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A Top-Down Approach Based on the Circularity Potential to Increase the Use of Reclaimed Asphalt

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Abstract: Resource depletion and climate change, amongst others, are increasingly worrying environmental challenges for which the road engineering sector is a major contributor. Globally, viable solutions that comply with the principles of circular economy (CE) are being investigated that can replace conventional asphalt mixtures in a post-fossil fuel society. The use of reclaimed asphalt (RA) is a widely used and well-established method to reduce the environmental and economic impacts of asphalt mixtures while increasing their circularity. However, RA's market supply and demand have not yet been systematically analyzed and established. Moreover, the actual circularity potential and the opportunity of re-circulating RA in a closed-loop model have not yet been methodically defined. To address this, a three-layered framework to quantify and assess the circularity potential (Ω) of RA has been developed. To give stakeholders and legislative bodies a simple method to assess the opportunities available to them to become "more circular", a novel equation has been formulated. This takes the form of a three-level indicator that considers: technical aspects, the effect of the RA market, and the legislative restrictions. A case study in Germany was structured and undertaken to develop and verify the proposed approach. The results indicate that the available RA is insufficient to cover the needs of asphalt mixture production; even though RA production is significantly lower than the actual need of asphalt mixtures, it is not utilized in its entirety. An impactful step forward is the alteration of the regulations to support the higher utilization of RA in asphalt mixtures, and subsequently, the increased circular opportunity and potential of RA. Thus, Circularity potential (Ω) is a composite indicator that can support stakeholders, designers, and asset managers during the process of decision-making, to follow more circular operational, design, and asphalt pavement management patterns.

Keywords: circular economy; reclaimed asphalt; closed-loop; end of waste; asphalt; material circularity indicator

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1. Introduction

The civil engineering sector and, of course, the pavement engineering sector belonging to it, continuously exploit significant amounts of natural resources for the production, construction, and management of transportation infrastructure. Natural aggregates are one of the most highly exploited resources to produce asphalt mixtures and even unbound layers and earthworks, which in turn compose the main components of an asphalt pavement infrastructure. Moreover, undoubtedly large quantities of raw materials are extracted and exploited during the use and maintenance phase of pavement assets. For this reason, reclaimed asphalt (RA) exhibits a tremendous opportunity for the minimization of resource depletion and the re-use and/or recycling of materials that even when considered wastes can have an actual market value. For this reason, and due to the lack of a concise economic indicator for the potential of RA, and considering the economic value of RA, the development of a macroeconomic indicator of national relevance is strategically imperative and is proposed in this study. It is an indicator that corresponds to a national scale and can be described simply as a way of determining how advanced, in terms of the use of reclaimed asphalt in the pavement engineering sector, a nation is, and evaluates the viability of RA recycling and re-use within a circular economic environment. Given that the research indicates that in most European countries the available RA is not exploited completely, even if the need for the production of hot and warm mix asphalt is high, the suggested indicator can guide responsible authorities and stakeholders to realise the magnitude of the circularity potential that asphalt mixtures with RA have overall and nationwide. Three main drivers are considered: the impact of the regulation surrounding the use of RA in asphalt mixtures; the market effects or how much reclaimed asphalt is produced and used in a local economy; and the technical aspect, which, in this case, considers the mechanical performance of the asphalt mixtures containing RA in terms of the number of loading cycles before a mixture with RA fails due to fatigue. Given that this indicator has been named the "circularity potential" it could be described as being an inverse indicator, where lower values demonstrate that a nation has the potential to increase its circularity in the pavement engineering field. The goal of this indicator is to aid stakeholders and decision-makers to simply visualize the potential of a given nation to become more circular by promoting the use of RA. It can be characterized as a progress monitoring tool that can help the involved stakeholders to understand the potential in terms of CE implementation using RA and their progress with consistency and compliance to the national technical specifications. Finally, a case study will be presented to show the efficacy of the indicator.

1.1. Reclaimed Asphalt (RA)

Site-won asphalt consists of asphalt produced during the milling of asphalt road layers, slabs ripped up from asphalt pavements, and asphalt from reject and surplus production. The processing of site-won asphalt results in RA, which can be used as a constituent material for asphalt after being tested, assessed, and classified [1]. RA may be used as a constituent material for bituminous mixtures manufactured in an asphalt plant in accordance with the specifications for those mixtures. Thus, RA can be defined as existing asphalt pavement materials that have been removed during the resurfacing, rehabilitation, or reconstruction operations of asphalt pavements and accordingly processed [2,3]. All of the motorways within the EU member countries consist of asphalt pavements, which, as anticipated, suffer from various types of distress [4]. Their maintenance and rehabilitation are significantly impactful environmental, economic, and social processes. In order to minimize the impacts of these processes and move towards a more sustainable and circular approach, recycling of RA is a widespread practice within the road engineering industry [4–8]. Asphalt recycling first took place in 1915 [9,10], but it was not until the 1970s that it started gaining particular popularity and became a standard practice. This occurred during the period of the Arab oil embargo due to the significantly increasing cost of crude oil. Afterward, the construction practices started to systematically change in an attempt to utilize higher proportions of RA. This led to an extensive study about the incorporation of high percentages of RA in bituminous pavements. In 1979, a field demonstration project by the Federal Highway Administration of the United States was carried out in New Jersey, where they incorporated around 50% RA into asphalt pavements [9,11]. The use of RA became popular in State transport departments by the time the Superior Performing Asphalt Pavements (Superpave®) mixture design method was developed in the late 1990s [9]. The lack of guidance for the use of reclaimed asphalt in the production of hot mix asphalt by the Strategic Highway Research Program, led to the halt of high RA utilization by many departments [3]. However, by the end of the 20th century, guidelines for the utilization of RA within the Superpave® method had been developed; thus, allowing the recycling of asphalt pavements to become well-established.

In the United States, asphalt exhibits the highest recycling rates of any other material, resulting in lower overall material costs and allowing road owners to achieve increased roadway maintenance and construction activities within limited budgets [12,13]. Moreover, lately, and mainly due to the advancement of asphalt mixing plants, it has become possible to utilize higher proportions of RA during the asphalt production process. According to a 2017 survey, the European countries of Belgium, Finland, Great Britain, Hungary, and Slovakia were recycling more than 90% of the available RA in hot and warm mix asphalt production for surface layers [9,14]. Despite the success of these nations, Europe as a whole does not seem to be making adequate use of this resource. The annual average quantity of available RA within Europe is approximately 45.5 megatons, while the average annual proportion that is actually being utilized in asphalt production is only 23.2 megatons [14–23].

The main techniques facilitating the utilization of RA are hot in-plant recycling, hot in-place recycling, full-depth reclamation, cold in-plant recycling, and cold in-place recycling [5,24]. The percentage of RA incorporated in road pavements is usually limited to between 10% and 30%, despite the advantages that its use might imply and the increased levels of RA incorporation that can be achieved with the utilization of rejuvenators. This is mainly due to legislation limitations and technical issues, such as the variability of the RA properties, the lack of certainty about the performance of the mixture in the absence of experimental results on full-scale conditions, and the lack of complete understanding of the mechanisms taking place during the asphalt mixture's production [25–32]. For example, in Italy, the maximum allowed percentages of RA utilization are 30%, 25%, and 20%, for the base courses, binder courses, and surface courses, respectively [33,34]. In Germany, however, the maximum allowed percentage of RA that can be incorporated into different layers depends upon different characteristics of the RA itself and must be calculated. The maximum values are 100% for base courses and 50% for binder and surface courses [35]. The differences in the permitted maximum percentage of RA that can be used in each pavement layer are purely technical. The dimensions of these pavement layers, and their role in the pavement's functionality, limit the use of RA due to the changes it causes in the pavement's performance. Figure 1 shows a simple illustrative representation of a typical flexible pavement comprising three layers.

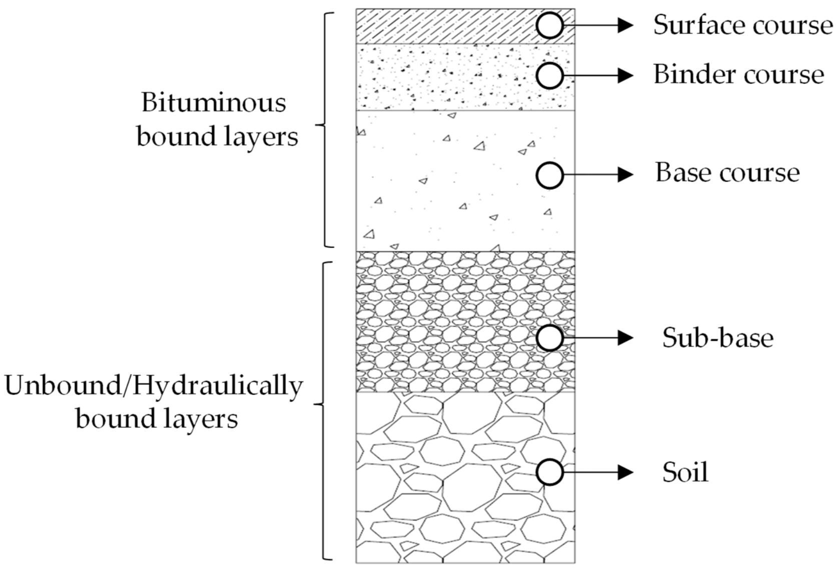

Figure 1. Typical cross-section of a flexible pavement.

As can be observed, surface courses are usually thinner and contain high-quality materials, as they are in direct interaction with the vehicles which use the pavement and, thus, the smoothness and stability of the pavement are of primary concern. Below the surface course, the binder course can be found. This works as a leveling course that is able to proportionally distribute the loads acting on the surface course onto the base course. The lowest layer is referred to as the base course, and it is the most important structural element of an asphalt pavement, absorbing all the energy transferred from the vehicles through the different layers and partially releasing it to the soil or structural element below. It can thus be deduced that RA is a brilliant example of material re-circulation within a product system. It has the potential to be 100% circular within a closed-loop system. RA exhibits a significantly valuable opportunity for the integration of CE practices in the road engineering sector. Regulations and technical standards, however, still pose a barrier to its full exploitation. Several studies have attempted to pave the way towards higher utilization of RA in asphalt pavements: the main conclusion of these studies is that higher utilization of RA is possible when attention is paid to the mixture design and the RA's properties so that a consensus between the laboratory mix design and the full-scale realization of the asphalt pavement can be achieved [36–43].

1.2. Circular Economy and Reclaimed Asphalt

The promotion of the circular economy (CE) and its principles in the road engineering industry involves the reduction of large amounts of energy and materials [44]; RA, therefore, exhibits a high potential for exploitation. By definition, CE is restorative and regenerative and aims to keep products, components, and materials at their highest utility and value at all times, i.e., it supports the "re-circulation" of materials and energy within the same (closed-loop process) or alternative product systems (open-loop process), and, thus, leads to the elimination of avoidable wastes [45]. In this context, RA is perceived as an ideal material that can re-enter the cycle of asphalt mixture production [46]. Although the concept of CE is not new, it still has not been widely and formally implemented in transportation infrastructure projects and specifically in asphalt pavements. The concept of CE made its first appearance as a proactive policy goal for numerous businesses and in political agendas in the late 1970s, mainly due to climate change and the acute concern of rising resource prices, raised by Carson and Boulding [47–50], and as aforementioned, it encompasses the principles of multiple schools of thought, such as industrial ecology and symbiosis, performance economy, biomimicry, cradle to cradle, blue economy, regenerative design, cleaner production, and natural capitalism [51,52]. However, when it comes to transport infrastructures, and more specifically asphalt pavements and RA, it becomes complex to encompass all the principles of CE in their life cycles, and thus no record of studies and approaches relevant to the quantification of their circularity has been recorded. Highways England, London's Waste and Recycling Board (LWARB), Ellen MacArthur Foundation, and Opportunity Peterborough are some of the institutions and companies that are driving towards introducing CE and its metrics within their agenda, hoping to influence a wider decision-making audience. Highways England, in collaboration with two of the most reputable construction companies worldwide, published an "*Approach and route map*" detailing how the implementation of CE can be achieved through their incipient strategies [53]. Moreover, LWARB has recently published London's CE Route Map, to accelerate the growth and development of CE across London, whilst setting out an ambitious plan of action, including the built environment and transportation infrastructure [54]. "*Cities in the Circular Economy: An initial exploration*" is a report published by the Ellen MacArthur Foundation. It highlights the challenges of the linear economy and promotes the advantages of implementing CE on an urban scale and within the built environment [55]. Opportunity Peterborough published the "*Circular City Roadmap*" in 2018. It is a resourceful plan and performance monitoring framework towards 2021, which sheds light upon the next steps to be followed for the realization of circular infrastructure, with the ultimate target being a "circular city" [56]. Some attempts have also been made by companies trying to specifically implement the principles of CE into the production of asphalt mixtures. Tarpaper recycling, along with Super Asfalt, have proposed the production of REC100. In addition, SYLVAROAD^{TM} RP1000 is an additive derived from crude tall oil (CTO) that can increase the levels of RA incorporated into the asphalt mixtures.

Hence, this paper discusses the development of a novel method for assessing the circularity potential of a given nation. The scope and objectives of this article are briefly presented before discussing the methodology surrounding and the development of the circularity potential indicator.

2. Scope and Objectives

This study has as its main scope to develop a decision-making support tool for stakeholders, contractors, asset managers, designers, and governmental bodies concerned with the road engineering industry, in an attempt to assist their transition towards more circular operating patterns through a three-layered method. In the developed method, three key parameters are taken into consideration. The actual and realistic supply and demand of virgin and recycled materials, the regulatory context of the region/country in which the tool is used, namely, the maximum allowed RA% utilization as dictated by local or national regulations, and finally, the mechanical performance of the investigated asphalt mixture with RA, in terms of expected service life; or in other words, its resistance to fatigue for the investigated case. The objectives that automatically emerge from the scope of this study are:

- The development and elaboration of indicators able to precisely describe the rules of the supply and demand of virgin and recycled materials in the road engineering industry, taking under consideration possible situations of recycled material surplus and/or shortage.
- The identification of the maximum allowed use percentage of RA in different asphalt mixtures, depending on their utility within the pavement. Different allowed percentages of RA are allowed for base, binder, and surface courses; and these percentages also change based on regions/nations.
- The quantification of the expected service life of the investigated asphalt mixture with RA and the comparison of said service life with the equivalent of an industry average asphalt mixture without RA, that offers the same utility in asphalt pavement.
- The development of a composite indicator that considers all the aforementioned parameters and describes the so-called circularity potential (Ω) of RA.
- The definition of an illustrative case study for an EU country, for which the necessary data will be collected and utilized in order for the viability of the methodology to be projected and the usefulness of the composite indicator to be established.

The three-layered approach of this framework can be more analytically seen in Figure 2, where all the key parameters considered for the development of this framework are illustrated.

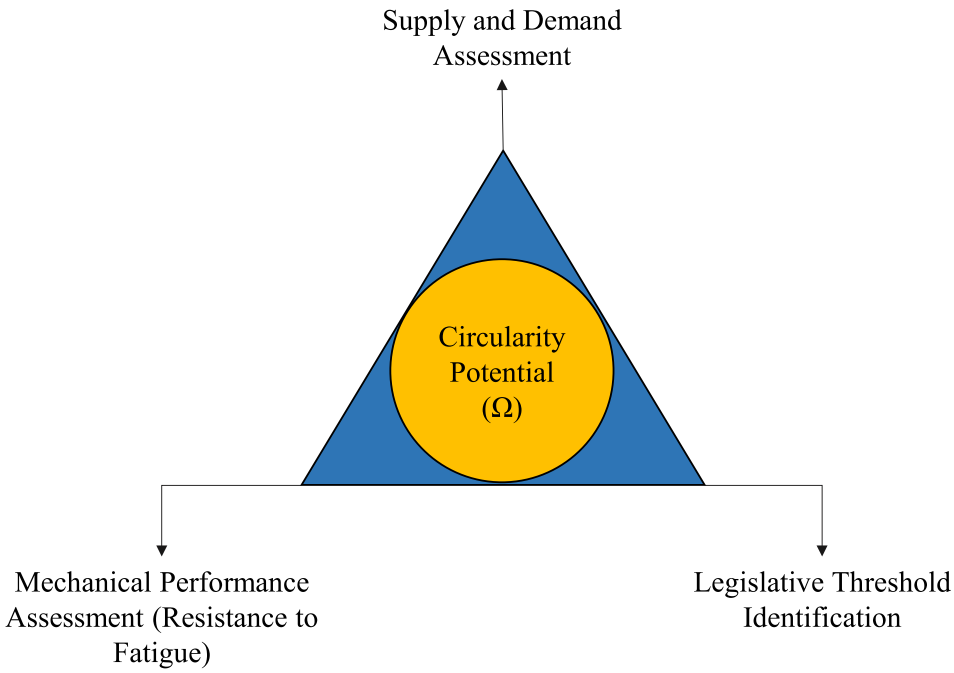

Figure 2. Key parameters considered for the development of the proposed framework.

Figure 2 shows the three primary factors that will be used to construct the three-layered composite indicator defined in Section 3.4. This composite indicator considers three fundamental drivers of the circularity potential of a given nation: the legislative aspect, i.e., what percentage of RA a government permits to be incorporated in the design of new or rehabilitated pavements; the technical aspect, also known as a mechanical performance indicator, which will drive technical decisions and will impose its own limits on the incorporation of RA if performance or safety is compromised by incorrectly increasing the use of RA; and finally the data related to the market, which imposes limits on the circularity potential of a nation due to the lack of RA available to substitute virgin materials. These three indicators have to be tackled by governments, who have the ability to commission studies to improve the mechanical performance of asphalt pavements that incorporate RA, to increase the supply of RA by mandating strict guidelines on the recycling and disposal of asphalt pavements, and, most straightforwardly, who have the ability to increase legislative limits on the incorporation of RA in asphalt pavements, in line with the best scientific guidance.

3. Methods

This section concerns the mathematical formulation used to obtain the key parameter. Each of the key indicators will be defined, and then their usage in the key parameter's formulation will be described. Finally, the key parameter will be analytically defined and briefly discussed. Prior to beginning the discussion regarding the analytical formulation to obtain the circularity potential, it is opportune to define the following parameters, which will be used throughout the subsequent analysis:

- Ω = circularity potential;
- L = legislative limit on the percentage of RA present in pavement construction;
- S_t = total supply;
- S_v = supply of virgin product;
- S_r = supply of recovered product;
- D_t = total demand;
- D_v = demand for virgin product;
- D_r = demand for recovered product;
- N_r = number of cycles at failure of an asphalt mixture containing RA;
- N = number of cycles at failure of an equivalent asphalt mixture without RA.

Given that many nations publish figures relating to the total amount of hot and warm mix asphalt produced each year, the total amount of RA available for use in new pavement construction activities, and the percentage of available RA used in construction activities; the above parameters can be straightforwardly defined. In the subsequent sections, each of the three indicators used to obtain the circularity potential will be defined in terms of the parameters listed above.

3.1. Supply and Demand Assessment

As previously stated, the supply and demand parameters can be populated using readily available data; this section provides guidance on how to populate these parameters and discusses the working theory behind the selection of these parameters. The total supply can be cast as the sum of the supply of the virgin materials and the supply of RA and the total demand can be cast as the sum of the demand for the virgin materials and the demand for RA, respectively:

$$S_t = S_v + S_r \quad (1)$$

$$D_t = D_v + D_r \quad (2)$$

For the subsequent analysis to be valid, the breakeven point, which is defined as the point at which there is a surplus RA available for use, must be reached; thus, one condition must hold true; the total supply must be greater than the total demand: $S_t > D_r$.

If this condition is met, the system is not balanced, but a breakeven point can be achieved; this contrasts with the conditions: $S_t < D_r$ or $S_t = D_r$.

In the first of these cases, the system is again unbalanced, but no breakeven point can be achieved as more production is not meeting demand and, therefore, all available RA is being used. In the second case, the system is balanced, but again, all available RA is being used and, thus, it would be impossible to reach the breakeven point.

Furthermore, it should be noted that while, in theory, S_v and D_v could have different values, in practice, these parameters are equal as asphalt is generally produced to order, and there will only be a surplus in very rare cases. Therefore, the total supply can be cast as follows:

$$S_t = D_v + S_r \tag{3}$$

Given that S_r and D_r are quantifiable values which, they can be related in the following manner:

$$S_t = \Delta + D_t \tag{4}$$

where Δ is the difference between the S_r and D_r values:

$$\Delta = S_r - D_r \tag{5}$$

Given these constraints, for the following analysis to be valid, Δ must be greater than zero. Δ could also be defined as the quantity of RA which remains unused and is likely sent to landfill, which, in a circular economic context, it is imperative to reduce. Thus, nations with a high supply of and low demand for RA will be seen as less circular than nations that have both a low supply and high usage, provided, of course, the breakeven point is not reached.

3.2. Mechanical Performance Assessment

The mechanical performance assessment can be categorized as a simple ratio between the number of cycles to failure of an asphalt mixture containing RA, to the number of cycles of an analogous product that does not contain RA ($\frac{N_r}{N}$). To find this value, data should be taken from previous studies which compare the mechanical performance of traditional asphalt pavements with asphalt pavements containing a quantity of RA. The mean ratio from a wide range of studies (preferably from the same geographical region) should then be used, allowing a general assessment of the circularity potential of any given nation, to be found.

3.3. Legislative Threshold Identification

The legislative threshold is defined as the maximum legally permissible percentage of RA in road construction. This is a crucial step in the analysis as there is no coherent rationale behind making recommendations that would not be sanctioned by governmental bodies. This indicator, naturally, has a maximum value of 100%, although in most cases, this is wholly unrealistic. As many nations place a limit on the maximum RA content that is allowed to be present in new road construction, this indicator is present to evaluate the potential effect that an increase of the legislative limit would have on the Circularity Potential indicator. This factor is calculated as the average maximum percentage of RA that could be incorporated in an asphalt pavement. The annual production of HWMA for each pavement layer is considered, and the legislative indicator is taken as the weighted average of these percentages by combining them with the legally allowed percentage of RA for each pavement layer. Figure 3, below, and Equation (6) serve to provide further explanation and clarity.

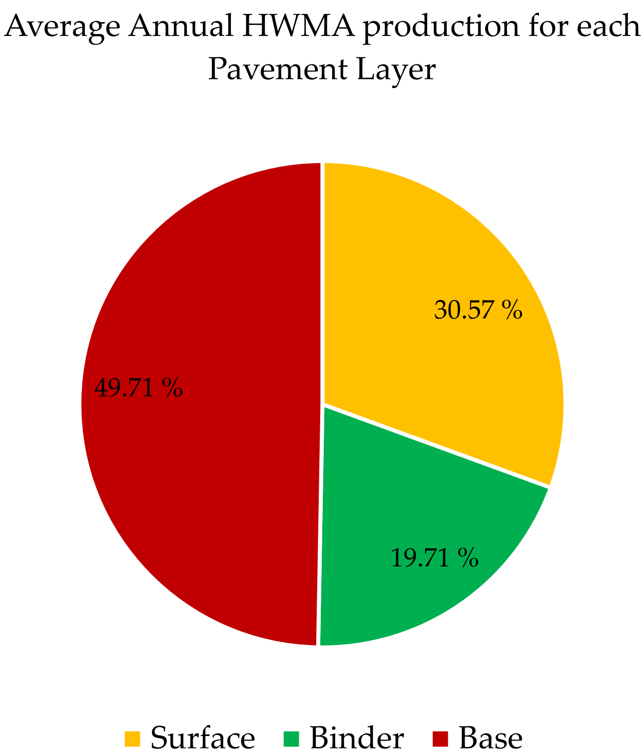

Figure 3. Average annual HWMA production for each pavement layer–generic data.

As can be clearly observed in the generic data above, the vast majority of the HWMA produced is used in the base layer; this layer also allows (in most nations) the highest incorporation of RA, increasing RA utilization across a pavement section. The surface layer then uses the second highest amount of the total RA produced, as the surface layer generally allows a lower incorporation of RA; this would reduce the weighted average. The final value (which will vary each year based on the production figures) is calculated using the equation below:

$$L = (P_s * LL_s) + (P_b * LL_b) + (P_{BA} * LL_{BA}) \quad (6)$$

where P_s is the production of HWMA for the surface course, LL_s is the legislative limit for RA incorporation in the surface course, P_b is the production of HWMA for the binder course, LL_b is the legislative limit for RA incorporation in the binder course, P_{BA} is the production of HWMA for the Base course, and LL_{BA} is the legislative limit for RA incorporation in the base course. The values used in Equation (6) above are all percentages which allows for the maximum, theoretical, total RA incorporation across all pavement layers to be found straightforwardly. In this analysis the percentage value is reported as an integer between 1 and 100 rather than as a percentage.

3.4. Composite 3-Layered Indicator Definition

Based on the previous sections, the data required to populate the circularity potential index can be derived. This indicator shows the potential circularity in the use of RA within a closed-loop system. The ideal scenario involves a nation that has very lax regulation on the use of RA in pavement design, high-quality production of asphalt mixtures containing RA, and a large stockpile of unused RA.

$$\Omega = \frac{1}{2}\log_{10}\left(L * \frac{S_r - \Delta}{\Delta} * \frac{N_r}{N}\right) \quad (7)$$

Within this indicator, each of the previously discussed elements is present within the brackets on the right-hand side where the legislative, market, and performance indicators are present. The indicator has a logarithmic operator present to normalize the magnitude of the indicator, and finally, this indicator is divided by 2 to maintain values higher than 1 for nations that can be seen as "mature", or which can be described as being relatively circular. Values lower than 1 indicate that a nation has a large circularity potential, i.e., that legislative bodies still can increase the use of RA in the pavement engineering sector by increasing technical standards and raising the legislative limits; for this reason, this indicator could be termed an "inverse indicator" as lower values represent a greater potential for exploitation. For mature nations that conform to high technical standards and permit a large percentage of RA to be used in asphalt mixtures, market forces are the only real drivers of change in the circularity potential indicator.

4. Structuring and Undertaking of a Case Study in Germany

4.1. Selection Criteria of the Case Study

Having established the methodological framework upon which the circularity potential indicator is based, a case study was structured and undertaken in order for the validity and usefulness of said framework and indicator to be proved. Firstly, when it came to country selection, the process followed was to identify the European country with the highest GDP at the moment. This strategic choice was made due to the fact that the GDP of a country can be characterized as a key parameter regarding the country's economic state and performance. In other words, the growth rate of real GDP is often used as an indicator of the general health of the economy, and in broad terms, an increase in real GDP is interpreted as a sign that the economy is developing well. In theory, a higher GDP can project a higher development rate of a country. Moreover, Germany is consistently reporting the percentage of RA used in a closed-loop manner for the construction and maintenance of asphalt pavements, on average accounting for 84% [14–23]. Thus, the current analysis has to be performed on the basis of a healthy and well-performing economy in which innovation and commitment to sustainability and circular economy are or should be well-established. The identified European country with the highest GDP is Germany, accounting for USD 3.806 trillion in 2020.

4.2. Quantifying the Circularity Potential of RA in Germany: A Case Study

To perform the required calculations for the quantification of the circularity potential (Ω) of RA in Germany and to also identify its trend over the last decade, the necessary data have to first be collected. For this reason, data relevant to the supply and demand of RA and hot and warm mix asphalt (HWMA) production, in Germany were collected through the concise publications of the European Asphalt Pavement Association, entitled "*Asphalt in Figures*". They are published yearly, and they contain, among others, precise information about the quantities of HWMA production, production of RA, and actual utilization rates of the produced RA. Furthermore, the next step was the identification of the allowed percentage of RA utilization in asphalt mixtures complying with the national regulatory context. In Germany, according to the German Asphalt Pavement Association, 100% of RA is allowed to be used in the base course, while up to 50% is allowed and suggested for the surface and binder courses [57]. Using data from EAPA again [14–23], the average production of HWMA per pavement layer in Germany was found; this value varied slightly over time; therefore, the legislative limit, when taking into account the change in production values will also vary over time as opposed to remaining constant. Combining these values with the regulations in Germany for the use of RA in each pavement layer, we find that a pavement section could contain a theoretical maximum of between 74% to 75.5% RA. Finally, to quantify the ratio N_R/N, data from reputable literature sources were gathered. An extensive collection of literature sources was undertaken and, thus, the average ratio of N_R/N for surface courses with 30% RA was calculated based on different experimental studies undertaken over the years 2004 to 2021 [58–77].

As shown in Table 1, in the majority of cases, asphalt mixtures incorporating RA tend to remain serviceable for a greater number of cycles when compared to those which do not;

this data may be skewed as all data is taken from laboratory examples that aim to evaluate the long term mechanical behaviors of these mixtures during cyclic fatigue testing, but, nevertheless, the data serves as a useful guide on the mechanical performance of these mixtures. Finally, all the data collected have been summarized and tabulated in Table 2.

Table 1. Values of N_R, N, and N_R/N collected from the literature for asphalt mixtures with 30% RA.

N_R	N	N_R/N
4375	1000	4.38
10,000	6500	1.54
10,000	1200	8.33
2000	2000	1
120	120	1
30,000	32,000	0.94
118,537	83,032	1.43
206,556	99,123	2.08
409,366	409,265	1
409,324	409,190	1
58,590	23,270	2.52
61,495	26,495	2.32
9320	19,510	0.48
12,295	10,785	1.14
11,000	10,000	1.1
14,000	11,000	1.27
1387	1033	1.34
1651	1033	1.6
1387	1156	1.2
1651	1156	1.43
167,803	112,763	1.49
3641	4461	0.82

Table 2. Tabulated data required for the quantification of Ω for the RA in Germany over the last 10 years.

	Germany										
	2011	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
HWMA production [Mt]	50.0	41.0	41.0	39.0	39.0	41.0	42.0	41.0	40.0	38.0	38.0
Available RA [Mt]	14.0	11.5	11.5	10.9	11.0	12.0	13.0	13.0	13.4	13.8	13.8
Used RA [Mt]	11.8	10.0	10.4	9.8	9.9	10.4	10.9	10.7	11.0	9.7	9.7
S_t [Mt]	64.0	52.5	52.5	49.9	50.0	53.0	55.0	54.0	53.4	51.8	51.8
D_t [Mt]	61.8	51.0	51.4	48.8	48.9	51.4	52.9	51.7	51.0	47.7	47.7
Δ [Mt]	2.2	1.5	1.2	1.1	1.1	1.6	2.1	2.3	2.4	4.1	4.1
N_R/N						1.79					
L	75.5	75.5	75.5	75.5	74.5	75	75.5	74.5	74	74.5	74.5

As can be deduced from the methodology deployed in Section 3 and the data presented in Table 2, S_t corresponds to the total HWMA production plus the total available RA. Moreover, D_t expresses the total demand for HWMA; thus, it corresponds to the sum of the total HWMA production, and the total RA used. Δ that was also defined in Section 3, projects the difference between the total supply and demand. Hence Δ is equal to the total supply minus the total demand: $\Delta = S_t - D_t$. Knowing this, the quantification of Ω, became possible via the implementation of the defined formula (6).

5. Results and Discussion

Having collected and systemized all the required data, the quantification of the circularity potential indicator became possible. The data collected was utilized within the previously described formulae, and the results can be seen in Table 3. Moreover, in Figure 4, for a clearer picture of the situation, the results have been illustrated in a graph, where also the current trend of the circularity potential can be seen for a 10 year time frame.

Table 3. Tabulated data required for the quantification of Ω for the RA in Germany over the last 10 years and the results of Ω. The color scale is set per row and for Ω per year, in which red represents its lowest values (lower circularity potential) and green the highest values (higher circularity potential).

	Germany										
	2011	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
HWMA production [Mt]	50	41	41	39	39	41	42	41	40	38	38
Available RA [Mt]	14	11.5	11.5	10.9	11	12	13	13	13.4	13.8	13.8
Used RA [Mt]	11.8	10	10.4	9.8	9.9	10.4	10.9	10.7	11	9.7	9.7
St [Mt]	64	52.5	52.5	49.9	50	53	55	54	53.4	51.8	51.8
Dt [Mt]	61.8	51	51.4	48.8	48.9	51.4	52.9	51.7	51	47.7	47.7
Sr − Δ	11.8	10	10.4	9.8	9.9	10.4	10.9	10.7	11	9.7	9.7
Δ [Mt]	2.2	1.5	1.1	1.1	1.1	1.6	2.1	2.3	2.4	4.1	4.1
NR/N	1.79										
L	75.5	75.5	75.5	75.5	74.5	75	75.5	74.5	74	74.5	74.5
Circularity potential [Ω]	1.43	1.48	1.55	1.54	1.54	1.47	1.42	1.40	1.39	1.25	1.25

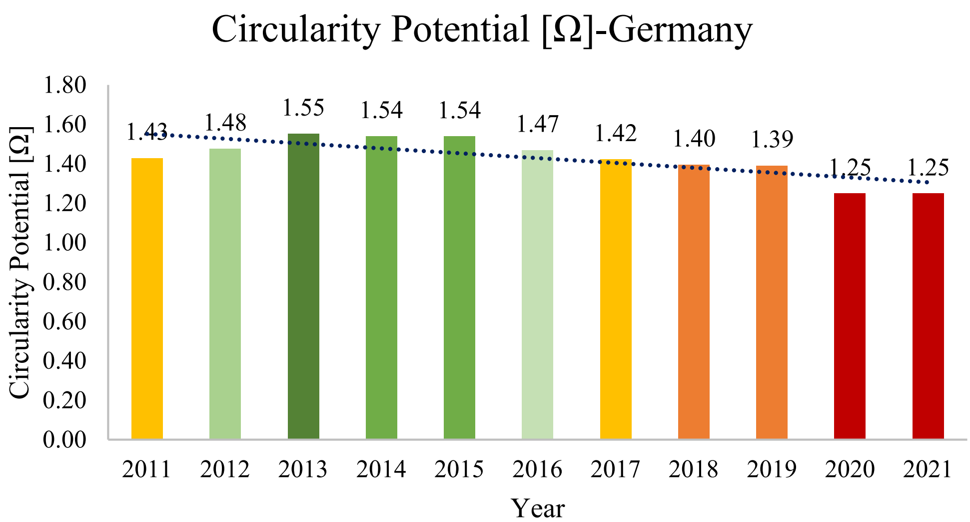

Figure 4. Circularity potential [Ω] values over the period 2011–2021 and its trend over the same period. The color scale is set per bar and for Ω per year, in which red represents its lowest values (lower circularity potential) and green the highest values (higher circularity potential).

Surprisingly, it can be seen from the obtained results that the circularity potential for RA in Germany over the period 2011–2021 fluctuated significantly and has been constantly decreasing in recent years. The highest values for Ω were achieved in 2013, 2014, and 2015 when a significantly higher circularity of the RA in Germany was detected.

Unfortunately, the same observations can be seen in Figure 4, where the plot indicates a decreasing trend for the circularity potential of RA in Germany. Starting at 1.43 in 2011, it climbed up to its maximum of 1.55 in 2013, and then started declining over the years to reach 1.25 in 2021. The boom in RA use after 2011 can partially be explained by the introduction of a new set of rules and standards that were published in 2011 by the German Asphalt Pavement Association (dav), where it is clearly stated that "All highway authorities are required by law as a matter of priority to promote recycling of reclaimed road construction materials; this also includes the separation of reclaimed asphalt and other reclaimed road construction materials." [57]. Thus, an increase in RA use over the years can also be seen due to [78,79]:

- improvements made in separate recovery (milling, possibly re-crushing, and storage);
- improved technologies for increasing quantities added;
- increasing focus on recycling in rules and standards and construction contracts;
- comprehensive distribution and improvement of reclaimed asphalt feeding technologies [57].

The constant decrease of Ω after 2013 is influenced entirely by "market forces", in that the legislative and technical aspects over this period remain relatively constant. The influence of these market forces is likely due to higher quantities of RA being produced while the percentage of RA being used for the production of HWMA remains constant, as can be seen in Table 3, where it can be clearly observed that, over time, the Δ value increased. This results in an ever-increasing quantity of "unused" RA. In Germany, however, this quantity of RA which has been termed "unused", is, in fact, "downgraded", i.e., used in other operations such as in unbound pavement layers and in backfilling operations. As such, the HWMA and the resultant RA in recycling operations was not a closed-loop system but rather an open-loop, which, although in the same sector, comprises alternative, downgraded pathways for the end of waste resources.

There is, however, an alternative explanation. It is possible that the road construction industry in Germany is currently operating at maximum capacity since the total motorway construction in kilometres is not increasing, according to official Eurostat data. This potentially indicates that RA was not utilized for the construction of new asphalt pavements but instead for maintenance activities, which require significantly fewer construction materials. In this case, RA was probably stockpiled and utilized in different applications that are out of the scope of a closed-loop model. As stated in the methodology, in a "mature" economy such as that found in Germany, which has already made great strides towards becoming more circular, the only real driver of change (in the context of the circularity potential indicator) are market forces. Therefore, the only way to ensure that this indicator returns consistently high results is the use of all RA in a closed loop.

6. Conclusions

In this study, an attempt was made to establish a three-layered framework to quantify and assess the circularity potential of RA. Firstly, the market supply and demand were defined through a set of developed equations, along with the RA's possible opportunity for circularity, which is individually based on the regulatory context of the country under examination. Finally, the mechanical performance of the mixture with RA under examination has been included as a parameter in the equation, defining a three-level multi-indicator. To develop and verify the proposed approach a case study in Germany has been structured and undertaken. The results indicate that the available RA is not enough to cover the needs of asphalt mixture production, and even though the RA production is significantly lower than the actual need of asphalt mixtures, it is not utilized in its entirety. Moreover, it was exhibited that the RA market was not mature enough to accommodate an increase in the available RA. In other words, there was more available RA than it was actually needed or that was allowed to be utilized in pavement construction and/or maintenance. It is possible that the road construction industry in Germany is currently operating at maximum capacity since the total motorway construction in kilometres is not increasing, according to official Eurostat data. When the length of German motorways starts to consistently increase, the circularity potential decreases. This would indicate that the use of RA is mostly focused on the maintenance of existing pavements and not in the construction of new asphalt pavements. This is also supported by the fact that during the period 2012–2015, the total length of German motorways was relatively stable and the circularity potential was significantly increased, indicating that the available RA was utilized as RA now in mainly maintenance activities, which requires significantly fewer construction materials. In this case, RA was probably stockpiled and utilized in different applications that are out of the scope of a closed-loop model.

An impactful step forward is the alteration of the regulations to support the higher utilization of RA in asphalt mixtures and, subsequently, the increased circular opportunity and potential of RA. Circularity potential (Ω), thus, is a composite indicator that can support stakeholders, designers, and asset managers during the process of decision-making to follow more circular operational, design, and asphalt pavement management patterns. It becomes apparent that a novel approach must be adopted by the involved stakeholders in the road engineering sector. Tools and indicators such as the developed one have to be taken strongly under consideration so the principles of circular economy can start being embedded in the core of pavement engineering. Stakeholders and governmental bodies must put pressure on introducing new legislation supported by scientific evidence that high percentages of RA can be incorporated in the construction of new asphalt pavements while providing equal performance characteristics to the said pavements. More budget should be allocated towards the familiarisation of key stakeholders with the extraordinary opportunity that RA is presenting towards the implementation of a circular economy. This would also suggest following an approach that can lead to a combined sustainable and circular development in the pavement engineering sector by implementing systematically defined holistic closed-loop approaches. Finally, in a broader scope, expanding further from this investigation that was specifically carried out for the road engineering sector and understanding that the concept of circularity potential (Ω) can be successfully generalized, it can confidently be deduced that it can also be successfully utilized in various energy and material intensive sectors. Circularity potential (Ω). It can be a significantly advantageous tool that, if implemented in various, mature sectors of industrial production, can provide a sturdy steppingstone towards developing and implementing well-tailored policies, regulations, and best practices that can directly and/or indirectly push for the holistic transition towards a real and monitored circular economy.

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