Determining the Environmental Potentials of Urban Pavements by Applying the Cradle-to-Cradle LCA Approach for a Road Network of a Midscale German City

Mayara S. Siverio Lima [1,*], Mohsen Hajibabaei [2], Sina Hesarkazzazi [2], Robert Sitzenfrei [2], Alexander Buttgereit [3], Cesar Queiroz [4], Viktors Haritonovs [5] and Florian Gschösser [1]

1   Department of Structural Engineering and Material Sciences, University of Innsbruck, 6020 Innsbruck, Austria; florian.gschoesser@uibk.ac.at
2   Department of Infrastructure Engineering, University of Innsbruck, 6020 Innsbruck, Austria; mohsen.hajibabaei@uibk.ac.at (M.H.); sina.hesarkazzazi@uibk.ac.at (S.H.); robert.sitzenfrei@uibk.ac.at (R.S.)
3   Department of Mobility and Civil Engineering of Münster, 48155 Münster, Germany; abuttgereit@gmx.net
4   The World Bank, Washington, DC 20433, USA; queiroz.cesar@gmail.com
5   Department of Roads and Bridges, Riga Technical University, LV-1658 Riga, Latvia; viktors.haritonovs@rtu.lv
*   Correspondence: mayara.siverio-lima@uibk.ac.at; Tel.: +43-512-507-63109

Abstract: This study used a cradle-to-cradle Life Cycle Assessment (LCA) approach to evaluate the environmental potentials of urban pavements. For this purpose, the urban road network of the City of Münster (Germany) was selected as the case study, and comprehensive data for several phases were collected. The entire road network is composed of flexible pavements designed according to specific traffic loads and consists of main roads (MRs), main access roads (MARs), and residential roads (RSDTs). Asphalt materials, pavement structures, and maintenance strategies are predefined for each type of road and are referred to as "traditional" herein. Some pavement structures have two possible maintenance strategies, denoted by "A" and "B", with distinguished periods of intervention. To evaluate the impact of using recycled materials, we considered alternative pavement structures composed of asphalt materials containing a greater amount of reclaimed asphalt pavement (RAP). The study was carried out considering analysis periods of 20, 50, 80, and 100 years and using two indicators: non-renewable cumulative energy demand (nr-CED) and global warming potential (GWP). The results show that the use of higher amounts of RAP can mitigate negative environmental impacts and that certain structures and maintenance strategies potentially enhance the environmental performance of road pavements. This article suggests initiatives that will facilitate the decision-making process of city administrators to achieve more sustainable road pavement constructions and provides an essential dataset inventory to support future environmental assessment studies, particularly for European cities.

Keywords: urban pavements; asphalt mixtures; environmental impacts; sustainability

1. Introduction

The climate change and the current environmental crises have intensified the global pursuit for sustainability, pressuring governments and city administrators to promote more sustainable practices [1], and to seek solutions for the most relevant areas of concern such as the transportation sector, which is responsible for approximately 25% of Europe's greenhouse gas emissions and 15% of the global share [2,3].

The environmental impacts caused by the transportation sector come from distinct sources: road construction, maintenance and rehabilitation procedures, vehicles and user-related emissions, end-of-life of the structure [4], etc.

Particularities such as the pavement conditions and the deterioration over time directly influences the rolling resistance of the pavement, affecting the safety, noise level, CO_2 emissions, and fuel consumption of vehicles [5–9]. Therefore, decisions such as defining the

least impactful material to construct urban roads, the pavement design, and the periodicity of interventions have a higher impact on the overall impacts caused by roads [10].

A big share of the impact generated by the construction of roads is from the production of pavement materials and additional industrial processes, which make up 21% of the greenhouse gas emissions [6,11]. Many researchers agree that using recycled materials, by-products, and waste materials to build pavement structures helps mitigate environmental impacts and reduces the overall cost [6,8,12–16].

To support the decision-making process, Life Cycle Assessment (LCA) tools are often applied to help stakeholders to select environmentally appropriate materials, pavement designs, and rehabilitation practices within an optimized budget, without compromising the quality of the road pavement [17].

Studies have shown that LCA tools [15,16,18–21] can provide a long-term perspective by comparing different solutions and possibilities for urban pavements [10]. However, finding the best materials and structures and an "optimal" maintenance and rehabilitation strategy that can ensure acceptable road conditions, lower agency-user costs, and reduced environmental-social impacts [22] requires complex data analysis and is strongly influenced by local conditions.

In collaboration with a European Union project titled "SAFERUP! (Sustainable, Accessible, Safe, Resilient, and Smart Urban Pavements)", the Department of Mobility and Civil Engineering of the City of Münster aims to improve the sustainability of its urban roads by using LCA to evaluate existing asphalt materials, pavement structures, and maintenance strategies.

In order to assist Münster and other cities to embrace the Agenda 2030 and enhance the environmental performance of the urban road network, this study assesses the environmental impacts of Münster's road network—which is entirely composed of flexible pavements—using the cradle-to-cradle approach with closed-loop recycling. Therefore, all life cycle phases, such as raw material extraction, asphalt material production, transportation, pavement construction, maintenance procedures, deconstruction, and recycling processes were considered in the analysis.

In addition to the traditional pavement structures currently adopted in Münster, we simulated alternative options by selecting asphalt materials with the highest RAP content available at the asphalt plant to fabricate the distinct layers of the pavement. Different maintenance strategies were applied to either the traditional and alternative pavement structures and analysis periods of 20, 50, 80 and 100 years were considered.

Finally, this study aims to compare materials, pavement structures, and maintenance strategies that can be used to preserve the urban road network of cities and provide an extensive dataset to support future LCA studies.

2. Urban Pavements in Münster, Germany

In Münster, the pavements are designed according to the traffic load (Bk, "Belastungsklasse" in German) in terms of 10-ton axle passages (e.g., 10 to 32 million for Bk 32) and are categorized as main roads (MRs), main access roads (MARs), and residential roads (RSDTs).

The road department of Münster follows the German Guideline [23] "RStO 12: Guidelines for the standardization of pavement structures of traffic areas" that predefines certain pavement structures to be used, which are referred to as "traditional structures" herein and are abbreviated as "T".

The MRs and MARs are composed of four layers, while the RSDTs have only three. The asphalt materials used in the surface, binder, and base layers can either be stone mastic asphalt (SMA) or asphalt concrete (AC) and may partially be composed of RAP.

To assess the environmental benefits and limitations of using RAP, "modified structures", abbreviated as "M" herein, were constructed using asphalt mixtures with the highest content of RAP available.

The specifications, such as load class, materials, and thickness, of the analyzed pavements are listed in Table 1.

Table 1. Pavement structure analysis.

	TRADITIONAL STRUCTURES			MODIFIED STRUCTURES		
Type	**Load Class**	**Material**	**Thickness (cm)**	**Load Class**	**Material**	**Thickness (cm)**
Main Roads	Bk 32-T	SMA 8 S	3	Bk 32-M	SMA 8 S	3
		AC 22 BS	8		AC 22 BS + 30% RAP	8
		AC 32 TS	14		AC 32 TS + 60% RAP	14
		Unbound	45		Unbound	45
Main Access Roads	Bk 3.2-T1	SMA 8 S	3	Bk 3.2-M1	SMA 8 S	3
		AC 16 BS	5		AC 16 BS + 30% RAP	5
		AC 22 TS	10		AC 22 TS + 30% RAP	10
		Unbound	45		Unbound	45
		OR			OR	
	Bk 3.2-T2	AC 8 DS	3	Bk 3.2-M2	AC 8 DS + 50% RAP	3
		AC 16 BS	5		AC 16 BS + 30% RAP	5
		AC 22 TS	10		AC 22 TS + 30% RAP	10
		Unbound	45		Unbound	45
					OR	
				Bk 3.2-M3	AC 8 DS + 50% RAP	3
					AC 16 BS + 50% RAP	5
					AC 22 TS	10
					Unbound	45
Residential Roads	Bk 1.0-T	AC 8 DN	3	Bk 1.0-M	AC 8 DS + 50% RAP	3
		AC 22 TN + 40% RAP	10		AC 22 TN + 40% RAP	10
		Unbound	45		Unbound	45
		OR				Surface Layer
	Bk 0.3-T	AC 8 DN	3			Binder Layer
		AC 22 TN + 40% RAP	8			Base Layer
		Unbound	39			Unbound Layer

2.1. Asphalt Production

The asphalt mixtures were produced using primary raw materials, such as bitumen, diabase aggregates, and limestone as a filler, as well as using RAP. The bitumen can vary according to the mixture type: stone mastic asphalt (SMA) mixtures contain polymer-modified bitumen (PMB), whereas asphalt concrete (AC) is composed of 50/70 bitumen.

The asphalt plant located in Münster (Germany) is defined as batch-mixing plant and follows the cold-recycling method to produce asphalt mixtures with RAP.

The RAP is procured from pavements milled in Münster and is transported to the asphalt plant for further application in asphalt mixtures after initial treatment (crushing, sieving, and separation).

The asphalt plant produces approximately 150,000 tons of asphalt mixtures and 50,000–80,000 tons of RAP per year. Approximately 98% of the heating energy is obtained from coal and 2% from light fuel oil. The overall energy consumption of the asphalt plant is presented in Table 2.

Table 2. Annual energy demands of the asphalt plant.

Inputs of Asphalt Production		
Energy	667,500	kWh/year
Heat (Light fuel oil)	118,500	kWh/year
Heat (Coal)	11,551,500	kWh/year
Diesel	355,500	kWh/year

Because it is not possible to determine the individual energy consumption for the production of asphalt mixtures or for that of RAP, the energy required to produce each asphalt mixture was calculated using Equation (1) [24,25]. Additional information, such as the asphalt mixture recipe, densities, mixing temperatures, and other variables used in the

aforementioned formula are available in the supplementary material (Tables S1–S3) and in a paper published by Siverio Lima et al. (2020) [12].

$$TE = \begin{bmatrix} \sum\limits_{i=0}^{M} m_i \times C_i \times (t_{mix} - t_0) + m_{bit} \times C_{bit} \times (t_{mix} - t_0) + m_{rap} \times C_{rap} \times (t_{mix} - t_0) + \\ \sum\limits_{i=0}^{M} m_i \times W_i \times C_w \times (100 - t_0) + L_v \times \sum\limits_{i=0}^{M} m_i \times W_i + \sum\limits_{i=0}^{M} m_i \times W_i \times C_{vap} \times (t_{mix} - 100) \end{bmatrix} \times (1 + CL) \quad (1)$$

where:

C_{bit}: Specific heat coefficient of bitumen (50/70)—kJ/kg·°C
C_i: Specific heat coefficient of aggregates—kJ/kg·°C
C_w: Specific heat coefficient of water (10 °C)—kJ/kg·°C
C_{vap}: Specific heat coefficient of water vapor—kJ/kg·°C
C_{RAP}: Specific heat coefficient of RAP—kJ/kg·°C
W_i: Water content of aggregates—%
L_v: Latent heat of vaporization of water—kJ/kg
CL: Casing loss factor—%
t_0: Ambient temperature—°C
t_{mix}: Maximum temperature of aggregates and RAP—°C
m_{bit}: Mass of bitumen—kg
m_i: Mass of aggregates and filler—kg
m_{RAP}: Mass of RAP—kg
M: Materials

2.2. Construction and Deconstruction Processes

As mentioned earlier, Münster's urban pavements contain three (RSDTs) or four (MRs and MARs) layers, among which one is an unbound layer (subbase), and the others are built using asphalt materials.

The first stage of pavement construction involves spreading the gravel with a bulldozer to build the unbound layer. Subsequently, the two rolling processes with a single drum are performed, followed by a compacting process with a vibration plate to complete the construction of the subbase layer.

The construction of new asphalt layers begins with the spraying of a bituminous emulsion on the underlying layer to improve the inter-layer adhesion. Thereafter, the hot asphalt mixture is discharged and distributed. After the asphalt layer is placed, two rolling processes are executed with a single drum, and the asphalt layer is then compacted using a vibration plate.

Depending on the maintenance strategy, the pavement layers can be replaced separately or together. The asphalt layers are deconstructed with a mill cutter, and a hydraulic digger loads the unbound subbase onto a transport lorry. Figure 1 shows all the processes necessary for the construction and deconstruction of pavements.

The machines used to construct and deconstruct pavements are listed in Table 3. The specifications were obtained from the literature [26] to facilitate the modeling process.

Table 3. Machines used during the construction and deconstruction stages [26].

Process	Machine Type	Model
Spraying bitumen emulsion	Bitumen sprayer on a lorry	Atlas AE 6000
Paving	Asphalt paver	CAT AP 555 E
Rolling	Single Drum Smooth—Vibration compactor	CAT CS 74 C
Compacting	Vibration plate	Weber CR 10
Distribution	Bulldozer	CAT D5K LGP
Milling	Mill cutter	Wirtgen W 200
Loading	Hydraulic digger	CAT 345 D
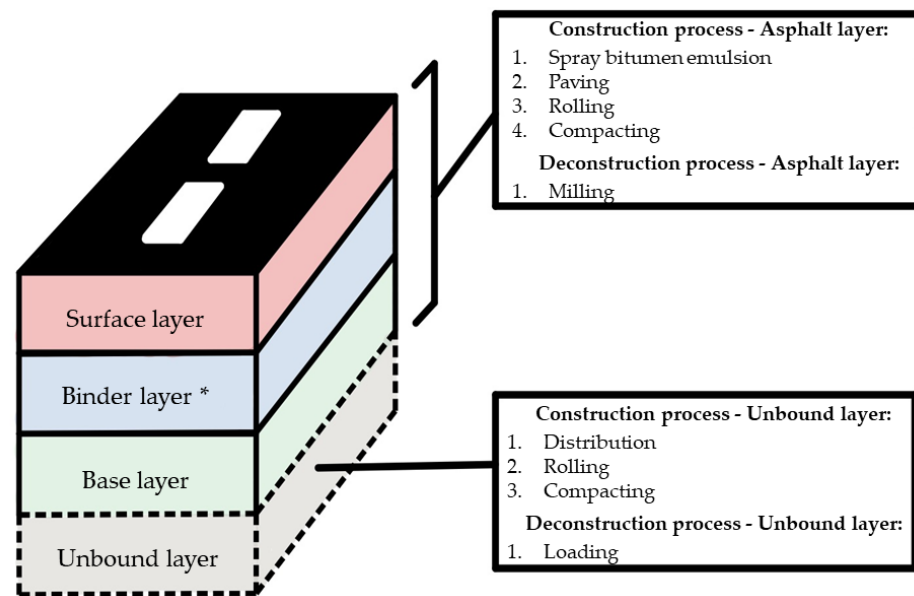
*Applied only to main roads and main access roads

Figure 1. Pavement construction and deconstruction processes.

2.3. Maintenance Strategies

The maintenance routine adopted by the city of Münster varies according to the pavement structure and the strategy defined to keep the pavement in acceptable condition, as shown in Table 4. In general, there are three main phases of pavement maintenance:

1. Deconstruction and construction of the surface layer (M1);
2. Deconstruction and construction of the surface layer and following layer, which can be either the binder layer for Bk 32 and Bk 3.2 structures or the base layer for Bk 1.0 and Bk 0.3 structures (M2);
3. Total deconstruction and construction of the pavement (M3).

Table 4. Maintenance strategies for pavements in Münster.

Classification	Load Class	Pavement Structure	Maintenance Strategies (Years)						
			A				B		
			M1	M2	M3	M4	M1	M2	M3
Main roads	Bk 32	Surface layer	15	30	40				
		Binder layer		30	40				
		Base layer			40				
		Unbound			40				
Main access roads	Bk 3.2	Surface layer	15	30	40	50	20	35	50
		Binder layer		30		50		35	50
		Base layer				50			50
		Unbound				50			50
Residential roads	Bk 1.0	Surface layer	40	80			20	40	60
		Base layer		80				40	60
		Unbound		80					60
	Bk 0.3	Surface layer	40	60	80				
		Base layer		60	80				
		Unbound			80				

Administrators in Münster use one maintenance strategy for Bk 32 and Bk 0.3 structures and one of two maintenance strategies for Bk 3.2 and Bk 1.0 structures, referred to herein as "A" and "B".

To understand the impacts of the pavement strategies over time, different lifetimes were simulated in this study: 20, 50, 80, and 100 years.

3. Life Cycle Assessment

3.1. Goal

This study was conducted to support the decision-making process used by the Münster authorities, based on an analysis of the environmental potentials of the urban pavements. The main goal of this study was to assess the environmental impacts of the asphalt materials, pavement structures, and road maintenance strategies adopted in Münster considering lifetimes of 20, 50, 80, and 100 years.

3.2. Scope of the Study

3.2.1. System Boundaries

The "cradle-to-cradle" approach with a "closed-loop recycling" method was employed in this study. Therefore, we assumed that 100% of the road materials obtained from the deconstruction were recycled within the same production chain and used in the production of new asphalt materials.

All life cycle phases, from raw material acquisition (A1) to the recycling process (C3), were considered in the analysis, except for the "use phase" processes related to vehicle operation, lighting, road cleaning, etc. In addition, services such as maintenance, repair, replacement, and refurbishment of pavements were considered.

The primary raw materials (diabase aggregates, limestone as filler, and bitumen) are procured from different suppliers located across Europe and transported to the asphalt plant to proceed with the manufacturing of asphalt mixtures.

The secondary raw material (RAP), originating from the milling of Münster pavements, is subsequently transported to the asphalt plant for treatment before being added into the asphalt mixtures. Because the asphalt plant is the initial and final destination of the RAP, no additional transportation is required between these steps. Further details, such as the cut-off point, are explained in Section 3.2.3.

The asphalt mixtures produced in the asphalt plant are transported to the construction site to build the pavements. Depending on the project design, classification, and maintenance strategy adopted, the road pavements are partially or entirely deconstructed during maintenance. Figure 2 shows the system boundaries and phases considered in the analysis.
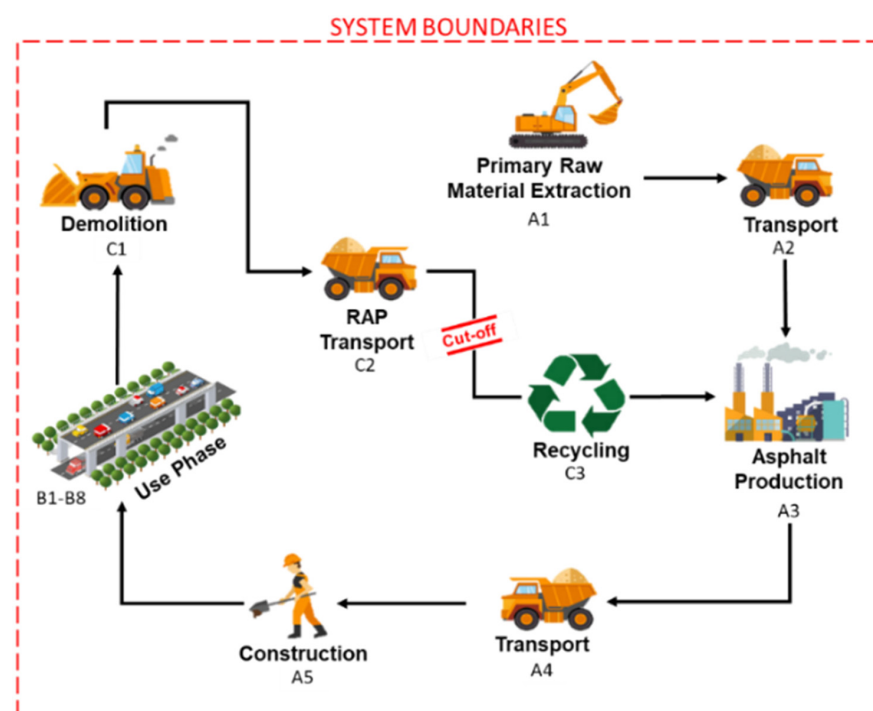

Figure 2. System boundaries of the study.

The terminology used to describe the life cycle stages in Figure 2 is defined in the EN 15804:2018 standard [27], as presented below:

- A1: raw material supply;
- A2: transport of raw material to the manufacturer;
- A3: manufacture of the asphalt mixtures at the asphalt plant;
- A4: transport of asphalt mixtures to the construction site;
- A5: construction of pavements;
- B1–B8: use, maintenance, repair, and replacement of asphalt layers;
- C1: demolition of pavement;
- C2: transport of milled asphalt pavement to the asphalt plant;
- C3: waste processing operations for reuse, recovery, or recycling (RAP production).

3.2.2. Functional Unit

The functional unit used in this study was 1 m^2 of road pavement.

3.2.3. RAP: Allocation and Closed-Loop Recycling

In this study, the RAP was considered as a secondary raw material rather than the end of life of the pavement. Thus, the environmental loads of the treatments performed on the RAP, such as crushing, sieving, and separation, were attributed only to the asphalt mixtures containing RAP.

Therefore, the cut-off point was set between the transportation of the milled pavement to the asphalt plant and the production of RAP.

Considering RAP as a secondary raw material implies reducing the use of the primary raw material. Thereby, all environmental loads involved in RAP production (crushing, sieving, and separation) are incorporated into the system, creating a closed loop of recycling. Meanwhile, the system boundaries of asphalt materials without RAP include all environmental loads associated with the use of primary raw materials until the deconstruction process and transportation back to the asphalt plant.

3.3. Life Cycle Inventory (LCI)

The primary data associated with the road network (i.e., pavement design) and the production of asphalt mixtures, such as raw material suppliers, recipes, and amounts of energy and water consumption, were collected through questionnaires answered by the asphalt producers and the road department of Münster.

The distances to transport either the primary (205 km for aggregates, 112 km for bitumen, and 205 km for filler) or secondary raw materials (25 km for RAP) were calculated considering the asphalt plant as the final destination. The materials are transported from the origin to the asphalt plant by a five-axle lorry vehicle (EURO 6) [28], that weighs around 14 tons and has a maximum load capacity of 26 tons. The fuel consumption varies from 0.18 L of biodiesel per kilometer when empty to 0.32 L of fuel per kilometer when fully loaded.

The relevant input and output data that the producer could not provide were obtained from the literature [13,26,29]. Some variables, such as the specific heat coefficient of materials and latent heat of vaporization of water of Equation (1) [24,25], were obtained from Santos et al. [25].

Information regarding the machines used for the construction and deconstruction processes was sourced from Gschösser (2011) [26] and modeled based on producer data [30–34], as shown in the supplementary material (Tables S4 and S5).

The mineral aggregates were modeled using the dataset for "crushed gravel", while "crushed limestone" was used as a filler dataset to create the asphalt mixtures. Because the required input data were not accessible, the RAP production (crushing, sieving, and separation) was modeled based on the "limestone production, crushed, for the mill" dataset available in Ecoinvent. Owing to the limitations of the software (which provides only an average input), all asphalt mixtures were modeled using the same dataset for bitumen.

All the inputs and outputs were modeled using SimaPro 9.0 (PRé Sustainability: Amersfoort, The Netherlands) [35] and the Ecoinvent 3.5 database (Ecoinvent: Zurich, Switzerland) [36]. The LCIs for all phases of the pavement's lifetime are listed in the supplementary material (Tables S1–S10).

3.4. Life Cycle Impact Assessment

To assess the environmental impact of road pavements, we adopted the GWP (kg CO_2 equivalent) indicator used in the Environmental Product Declarations (EPD 2018) [37] method and the non-renewable cumulative energy demand (nr-CED) parameters, which is based on the Cumulative Energy Demand method V1.11 in Ecoinvent version 2.0 [36] and is presented in MJ equivalent.

A Monte Carlo simulation was performed to verify the reliability of the environmental impact results using SimaPro software. In LCA, the uncertainty comes from the input data collected, which can be described by a specific distribution characterized by a standard deviation [38]. The standard deviation of each life cycle inventory entry is calculated by using the pedigree matrix method proposed by Ecoinvent [36,39], which is based on six factors (i.e., reliability, completeness, temporal correlation, geographical correlation, technological correlation, and sample size) [36,39]. Hence, a random value of uncertainty based on the reliability given by the data collection is specified to each inventory entry. The values attributed might vary from 1 to 5 and can be see within the supplementary material (Tables S1 and S4–S9). The calculations use a 95% confidence interval and perform 1000 runs to obtain an a probability distribution for each scenario [39].

In order to verify the impact of uncertainty, nine Monte Carlo simulations were performed comparing the GWP and nr-CED results of two 100 years lifetime pavement structures cases. The comparisons were defined taking into account the best- and worst-case scenario presented within each category.

4. Results

The environmental impacts in terms of GWP and nr-CED per square meter of road pavement are shown in absolute numbers in the supplementary material (Table S11).

Figures 3 and 4 show the overall environmental impact of the different pavement structures in terms of nr-CED and GWP over the pavement lifetime. In general, the higher the traffic load on the pavement, the higher the environmental impact.
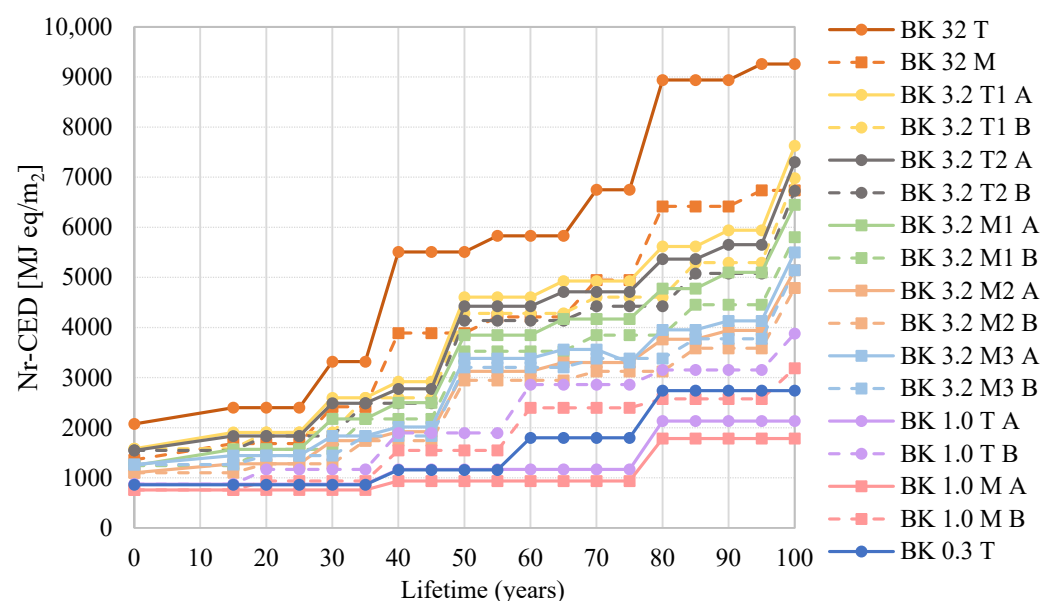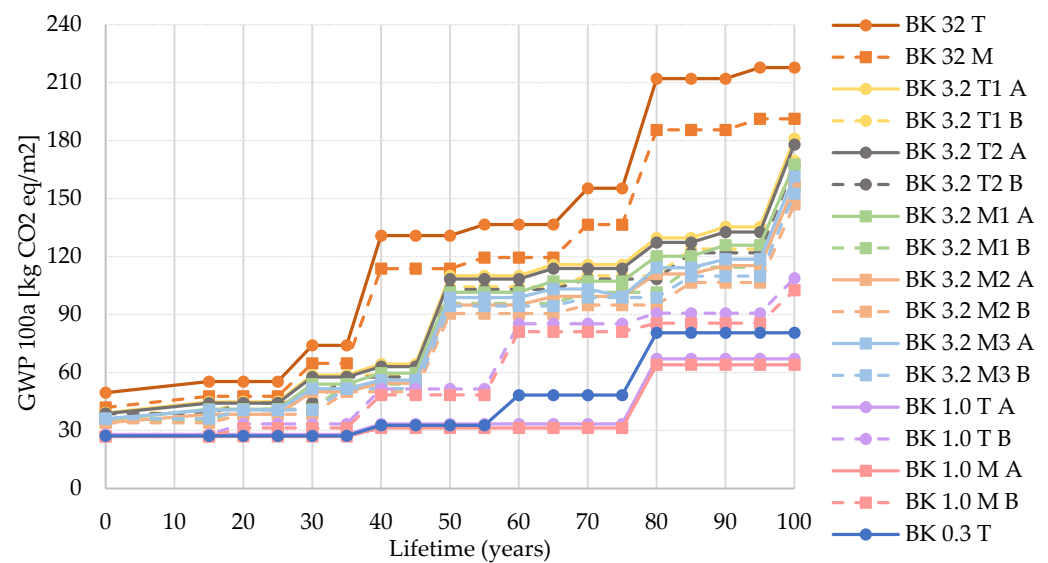

Figure 3. Nr-CED results over the years.

Figure 4. GWP results over the years.

The "modified" structures exhibited lower environmental impacts than the "traditional" structures did, in terms of both indicators and for all lifetimes evaluated. Therefore, using higher contents of RAP to produce asphalt mixtures for road pavement layers potentially reduces the environmental impacts (GWP and nr-CED) of pavement construction over the lifetime of the pavement.

The difference between the environmental impacts of the "traditional" and "modified" structures is emphasized with respect to the lifetime: the longer the lifetime, the larger the difference between the "traditional" and "modified" structures.

For the lifetime of 20 years, strategies "A" and "B" presented similar impacts for the Bk 3.2 structures in terms of nr-CED and GWP. In contrast, for Bk 1.0 T, increases of 25% in nr-CED and 16% in GWP were observed upon changing the maintenance strategy from "A" to "B", while for the modified structure (Bk 1.0 M), an increase of 19% in nr-CED and 14% in GWP was observed.

For the lifetime of 50 years, there was a larger difference between the impacts of MARs (Bk 3.2) and residential pavement structures (Bk 1.0) because of the maintenance strategy employed for the former. Unlike for the 20-year lifetime, there were only slight differences between the "traditional" and "modified" Bk 3.2 structures and between strategies "A" and "B".

For the lifetime of 80 years, maintenance strategy "B" used in Bk 3.2 structures, showed reduced impacts in terms of both indicators; average reductions of 17% in nr-CED and 15% in GWP were observed when strategy "A" was used for the same structures. The discrepancies between the "traditional" and "modified" structures and between strategies "A" and "B" are amplified due to the frequency of interventions in each case.

For the lifetimes of 50 and 100 years, the differences between the impacts associated with strategies "A" and "B" decreased by an average of 7.5% in nr-CED and 5.5% in GWP for the MAR structures (Bk 3.2).

For Bk 1.0 pavements, strategy "A" leads to potentially lower environmental impacts in terms of GWP and nr-CED than strategy "B" does over 20, 50, 80, and 100 years. Both Bk 1.0 T "A" and Bk 1.0 M "A" structures showed reduced impacts compared to the Bk 0.3 structure. The difference is amplified over the years, and it can be observed that Bk 1.0 T "A" had the lowest environmental impact among the traditional structures. Therefore, for longer service lifetimes, it is potentially better to construct Bk 1.0 T pavements using maintenance strategy "A" than to construct Bk 0.3 structures in residential roads. The use of Bk 1.0 pavement structures in Bk 0.3 traffic load areas would reduce the environmental impacts of residential roads as the pavements would last longer.

Figure 3 shows that the environmental impact of Bk 32 T structures, in terms of nr-CED in year zero, was 274% higher than that of the lowest-impact structure (Bk 1.0 M "A"). After 100 years, the difference between the impacts grew to 518%. Figure 4 shows that compared with Bk 1.0 M "A", the Bk 32 T structure emitted 184% more CO_2 in year zero and 340% more CO_2 after 100 years. The gap is due to the overall amount of material used and the constant rehabilitation procedures required for pavements with high traffic loads (i.e., Bk 32 T).

Using higher amounts of RAP to construct Bk 32 structures reduced the emission of CO_2 by 12% and the value of nr-CED by 27% over 100 years. The Bk 32 M structure presented lower or similar impacts in terms of nr-CED when compared with Bk 3.2 T1 "A", Bk 3.2 T1 "B", Bk 3.2 T2 "A", and Bk 3.2 T2 "B" structures.

Initially, all the MAR structures exhibited similar impacts. The longer the time, the higher the impact gap between the structures. The Bk 3.2 M2 "B" structure presented the lowest environmental impacts in terms of both the indicators, whereas Bk 3.2 T1 "A" exhibited the largest impacts. After 100 years, Bk 3.2 T1 "A" had a 37% larger impact in terms of nr-CED and 19% higher CO_2 emissions than Bk 3.2 M2 "B" did.

Among the residential pavement structures, the reduction in impact after 100 years was approximately 54% in terms of nr-CED and 41% in terms of GWP, when comparing the highest-impact structure (Bk 1.0 T "B") with the lowest-impact one (Bk 1.0 M "A"). Bk 0.3 showed similar environmental impacts as Bk 1.0 T "A" and Bk 1.0 M "A" did until the 55th year; thereafter, the interventions and the deconstruction and construction of the surface and base layers increased the impact gap between the structures.

4.1. Impact Contribution per Category

Figure 5 shows the average impact contribution per category. Because the asphalt plant provided only the total amount of energy consumed, instead of individual data the "production" category comprised both operations: the impact of the asphalt mixture production as well as that of RAP processing (crushing, sieving, and separation).
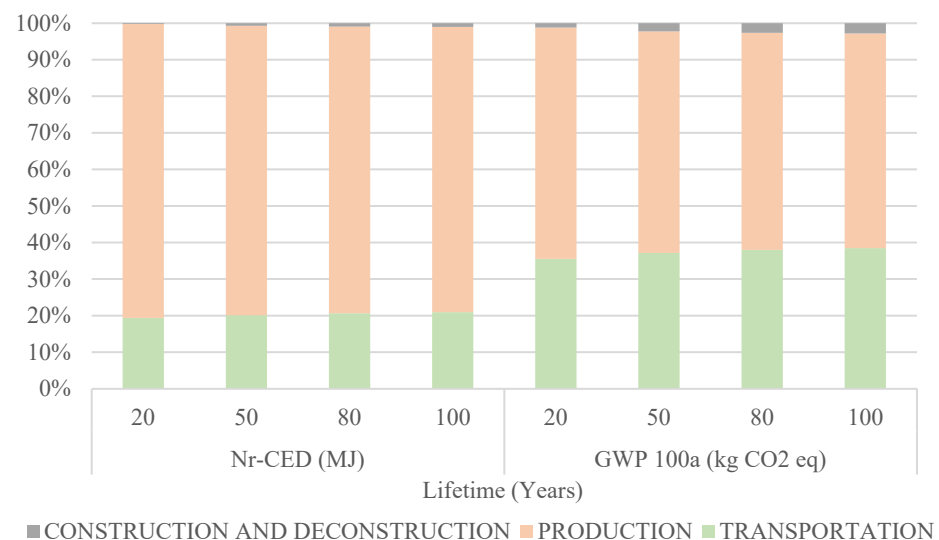

Figure 5. Environmental impacts divided into categories.

The "production" and "transportation" processes are the main contributors to environmental impact in terms of nr-CED and GWP. The "production" process is responsible for nearly 78% of the impact in terms of nr-CED and 55% in terms of GWP, due to the energy demand for heating the materials and the gas emissions during asphalt production.

In contrast, "transportation" contributes 20% in terms of nr-CED and 36% in terms of GWP; this impact is mainly due to the transportation distances covered by the aggregates (205 km), bitumen (112 km), and filler (205 km) from the suppliers to the asphalt

plant. Therefore, the "modified" pavement structures with higher amounts of RAP and modeled to perform similar to the "traditional" structures are most likely to have lower environmental impacts due to the reduced amount of virgin raw material used and the shorter transportation distances for the RAP (25 km).

Only a small share of the impact (1–3%) is attributed to the "construction and deconstruction" processes.

4.2. Monte Carlo Analysis

Figure 6 compares the two structures and shows the probability of one structure exhibiting higher (A ≥ B) or lower (A < B) environmental impacts than the other over an analysis period of 100 years.
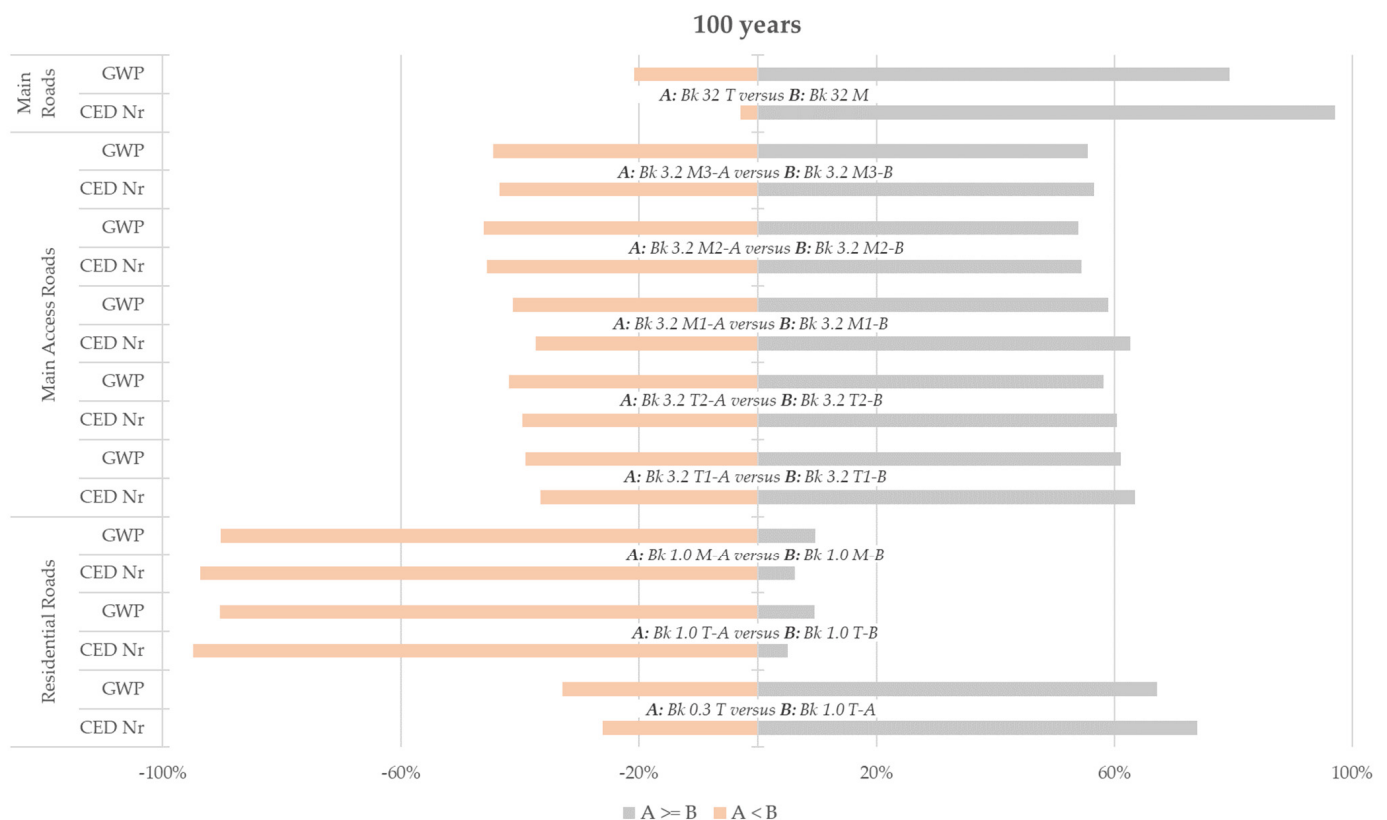
Figure 6. Monte Carlo simulation: 100 years.

The first analysis shows that "traditional" Bk 32 structures (Bk 32 T) are more likely to have higher environmental impacts than their "modified" counterparts (Bk 32 M). In this case, the maintenance strategies over the years are equal and the reduction in impact is due to the higher amount of RAP within the "modified" structure.

A comparison between maintenance strategies "A" and "B" of the Main Access Road pavements shows a slight probability of strategy "B" having a lower environmental impact than strategy "A" for Bk 3.2 structures. The reduced impact presented by the strategy "B" is related to the interval and periodicity of interventions defined: "B" demands the changing the top layer after 20 years and the following layers after 15 years, while the "A" requires the first intervention after 15 years and four interventions during the entire pavement lifespan.

The comparison between the strategies for Bk 1.0 structures shows a higher probability of "A" having minor impacts in terms of both indicators due to the reduced demand of interventions (2) over the entire life time of the pavement in comparison with "B" (3).

Regarding the use of Bk 0.3 or Bk 1.0 T "A" structures, Figure 6 shows that Bk 0.3 is more likely to have higher impacts than Bk 1.0 T "A" is over 100 years.

5. Conclusions

This study aimed to assist cities to embrace the Agenda 2030 and enhance the environmental performance of urban road networks by assessing the life cycle of urban pavements and the maintenance strategies adopted by administrators in Münster (Germany). Based on the results, the following conclusions were drawn.

- Combining layers containing the largest possible amount of reclaimed asphalt pavement (RAP) might reduce potential environmental impacts in terms of non-renewable cumulative energy demand (nr-CED) and global warming potential (GWP);
- The longer the simulated service life, the greater the difference in environmental impact between the "traditional" and "modified" structures;
- In general, the higher the traffic load on roads, the greater the environmental impact;
- The higher the reconstruction interval and lifespan of pavements, the lower the environmental impact;
- In residential areas, it might be recommended to build stronger structures and reduce the maintenance interval than the opposite;
- Approximately 98% of the environmental impacts over the pavement life cycle is due to the production of asphalt mixtures and materials transportation (i.e., raw materials, asphalt mixtures, and reclaimed asphalt pavement);
- Construction and deconstruction have a negligible influence on the overall impact of pavements during the service life;
- Maintenance strategies can strongly influence the environmental impact of urban roads. Therefore, pavement design, service life, and maintenance periodicity should be carefully evaluated.

This study showed that using reclaimed asphalt pavement to compose asphalt mixtures can potentially mitigate the environmental impacts of pavements over their lifetime because of the reduced use of raw materials, which reduces transportation distances. The results showed that the addition of 30% RAP in the binder layer and 60% RAP in the base layer within the pavement structures of main road categories might save 2521 MJ of energy and the emission of 26.5 kg of CO_2 equivalent over 100 years per square meter of pavement built.

Considering the worst- and best-case scenarios for each pavement category, it is estimated that the city of Münster could save 2235 MJ of energy and around 40 kg of CO_2 equivalent over 100 years per square meter of pavement by using the least impactful options to compose its road network. If applied across the entire road network of Münster, the emission savings could reach 376,000 tons of CO_2 after 100 years: this represents 0.00087% of the current annual emissions worldwide, or 10% of the annual emissions in Iceland. In addition, the amount of energy saved could reach approximately 5662 GWh—enough to supply a year of energy in countries such as Latvia, Luxemburg, or Honduras.

This investigation considered that all asphalt mixtures and pavement structures perform equally and have similar lifetimes. Even though the Monte Carlo simulation was used, future studies should consider the individual surface and mechanical performance of pavements and their durability when evaluating the maintenance strategies.

The suggested "modified" pavement structures may not be suitable for application as they do not account for local regulations. Moreover, the "traditional" pavement structures modeled in this study represent the conditions of Münster and may not apply to other areas.

Finally, it was shown that pavements with longer service lives have lower environmental impacts. Nevertheless, it is essential to define the ideal time for intervention and to maintain pavements to be in acceptable condition. Failure to achieve this can compromise users' safety and well-being, increase the risk of accidents, generate more noise, increase vehicle fuel consumption, and exacerbate the environmental impact of the pavement.

Although this study analyzed Münster's road network, it is essential to state that the assessed data represent the reality of many cities around the world—especially European cities—and provides relevant input data to support further life cycle assessment analysis to be made by other institutions in the future.

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