LIFE CYCLE ASSESSMENT MODELS FOR ROAD MARTERIALS AND HIGHWAY PAVEMENTS

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ABSTRACT

This study adapted the cradle-to-gate, cradle-to-grave and the cradle-to-cradle Life Cycle Assessment models for the environmental analysis of road materials and highway pavements. To show the usability of the different LCA models, the production of hot mix asphalt (HMA) and a typical concrete mixture for concrete pavements as well as an asphalt and a concrete highway pavement were analysed concerning the IPCC Global Warming Potential 2007 (100 years) indicator (GWP), the Non-renewable Cumulative Energy Demand (CED) and the Swiss Ecological Scarcity indicator (EcoScar). The results for the analysed case studies show that "asphalt products" due to the application of bitumen have a higher impact concerning the Non-renewable Cumulative Energy Demand, although they have a lower impact regarding the GWP and the EcoScar indicator as "concrete products". It is shown that reuse of recycled material does not always cause environmental improvements, due to the fact that the production of recycled concrete has a higher impact concerning the GWP indicator than the production of primary concrete. The study also demonstrates the substantially high influence of the material production processes and the high significance of the material transport to the building site.

1. INTRODUCTION

Life Cycle Assessment (LCA) is a methodology that observes and analyses a product or service over its entire life cycle in order to determine its environmental impacts. This LCA model, including all processes from raw material extraction until waste treatment after the product is not useable anymore or the service was performed, is called the "cradle-to-grave" model [1]. This model is mainly utilized to compare the environmental impacts occurring over the whole lifetime of products fulfilling the same function, in order to determine the environmental relevance of decision options [2].

However, for LCA studies with goals other than the comparison of product or service options, models using different analysis scopes than the cradle-to-grave model can be applied.

An LCA study using the "cradle-to-gate" model ends when the finished product leaves the production plant. This model is applied to determine the environmental potentials of production processes of one single product, whereby it is required that the optimized production condition does not have any influence on the environmental impacts of the use and end-of-life phase of the product [2, 3].

The "cradle-to-cradle" model is applicable to products that are recyclable for the most part, so that the cycle from the end-of-life phase to the production phase can be closed. This model is utilized to show the environmental performance of products that are applied to the same function after a recycling process [2].

This paper aims to adapt these three models for Life Cycle Assessments of road materials and highway pavements. To show the applicability of the different LCA models two types of road materials and two different Swiss highway pavement types were analysed concerning three different environmental indicators.

Firstly, the environmental potentials in the production of road materials used within typical Swiss highway pavements are determined by a cradle-to-gate LCA.

Secondly, the cradle-to-gate model was modified for the product “highway pavement”. Thereby, the road construction process was analysed in addition to the material production phase. Thus, this special LCA model for road pavements can be called “from-cradle-to-cut-ribbon”, due to the fact that all processes until the pavement is used by traffic the first time are included.

The application of the cradle-to-grave model requires the specification of a period of observation for the analysed highway pavements, because no average life span can be assigned to a road construction due to the fact that they are maintained frequently in order to keep the road section usable for traffic as long as possible. The period of observation should be chosen corresponding to the possible maintenance strategies for the analysed highway section. Since the road construction after the period under observation is not sent to a “grave”, the term cradle-to-gate is inappropriate for the application of this for road pavements. Depending on the chosen period under observation the model should be named for example “cradle-to-50-years”. In order to keep the context simple, and although it is not completely correct, in this paper this model will be named “cradle-to-grave”.

The reuse of reclaimed material after a maintenance action as a recycled material in the new built layers of the pavement can be described as a “cradle-to-cradle” model within a “cradle-to-grave” model, because the materials are reused for a product with the same function as the original product. This recycling scenario is also called “closed-loop recycling”.

2. METHOD

2.1. Goal and scope

The goal of an LCA study generally depends on what product is analysed, why and for whom the study is performed. Therefore, the goal of the LCA also defines the scope of the study, which is defined by the system boundaries and the functional unit [1].

The product to be analysed is described by the product system and its system boundaries. The system boundaries are set according to the applied LCA model and the goal of the LCA study. A process flow chart demonstrates all analysed processes within the system boundaries and the interaction between them [2].

All environmental impacts occurring over the analysed life cycle phases relate to the functional unit. A Life Cycle Assessment analyses or compares product systems. These systems fulfil a specific function and generate a certain benefit. Therefore, the benefit should be the basis for the choice of the functional unit, in order to assure the comparability of the systems [3].

2.1.1. Cradle-to-gate LCA for road material production

The goal of applying the cradle-to-gate LCA model for the production of different road materials is to determine the environmental potentials hidden in the production processes. Thus, the analysed systems include all production processes. The functional unit can either be defined as mass (one ton of material) or volume (one cubic meter of material), because the aspired benefit of the compared systems, i.e. the systems for the standard and the optimized material production, is to receive a certain amount of an applicable road material.

2.1.2. Cradle-to-cut-ribbon LCA for highway pavements

The aim of performing an LCA study for different highway pavements, including all processes until the highway is serviceable for traffic, is to combine the environmental potentials given by the production processes according to the amounts of materials needed for the different pavement types and to evaluate different construction processes for the several material layers. Hence, the system boundaries include all material production and pavement construction processes. The functional unit used for this paper is a highway pavement construction with a length of 10 km.

2.1.3. Cradle-to-grave LCA for highway pavements

Since the average life span of a road construction in general is not determinable, the highway pavement is analysed over a chosen period of observation. The goal of analysing different highway pavements over a certain time period is to determine the pavement and the maintenance strategy with the lowest environmental impacts. The different life cycle phases within the system boundaries, i.e. material production, pavement construction, phase of use, pavement deconstruction, recycling and waste treatment, occur depending on the analysis period and the chosen maintenance strategy. Therefore, it is recommended to do a sensitivity analysis for several analysis periods. The system boundary for this model is set after the last process occurring within the chosen period under observation. The functional unit is again a highway pavement construction with a length of 10 km.

2.1.4. Recycling Scenarios

Reclaimed road material can be reused for the production of new road material. After the pavement layer is deconstructed the reclaimed material needs to be upgraded to a usable recycled material, which can substitute primary material in the production of road material. For this study it is assumed that all road materials are 100% recyclable. Thus no waste treatment processes are analysed.

Reclaimed road materials do not necessarily have to be reused for the same type of material. For example, recycled concrete aggregates can be reused as an unbound subbase. Therefore, for LCA studies of road materials and highway pavements the “open-loop recycling” approach is applied. This approach analyses two different systems: System A, i.e. the system of the material or pavement layer that is deconstructed and can be reused for system B, i.e. the system of the new road material or pavement layer [3].

Concerning the allocation of the recycling processes that make material applicable for the reuse in System B the cut-off rule needs to be applied. This rule states that the “cut” between system A and system B needs to be at a defined point. Thus, all recycling processes until this defined point are part of System A, and all processes after this point belong to system B [2]. Since it is left to the judgment of the LCA conductor where to set this cut-off point, the two systems can get either more or less burdens from the recycling processes.

For the recycling of road material or pavement layers the cut-off point can be set at the beginning of the deconstruction process, after the deconstructed material was transported to the recycling plant or after upgrading to a usable recycled material.

Thus, concerning the cradle-to-gate and the cradle-to-cut-ribbon model the LCA conductor needs to make the decision, whether system B, the system of the new produced road material or pavement layer, includes all, a part or none of the recycling processes.

Regarding the cradle-to-grave model, the decision and the consequences concerning where the cut-off point is set between the systems become more complex, due to the fact that recycled material can be used for nearly all layers within a road pavement, and reclaimed material does not necessarily have to be reused for the same type of material.

Within a cradle-to-grave model, System B, the system of the production of new road material applied for the new built road pavement or rebuilt pavement layers during a maintenance action, is always part of the overall system of the analysed pavement. System A, the system of the material that is deconstructed, can be part of the overall system or part of an external system, i.e. the system of a material that is not embedded into the analysed pavement. This external system hast to be utilized, when the new built pavement contains recycled materials, and when the deconstructed layers do not provide the amount of recycled material needed for the layers rebuilt during a maintenance action.

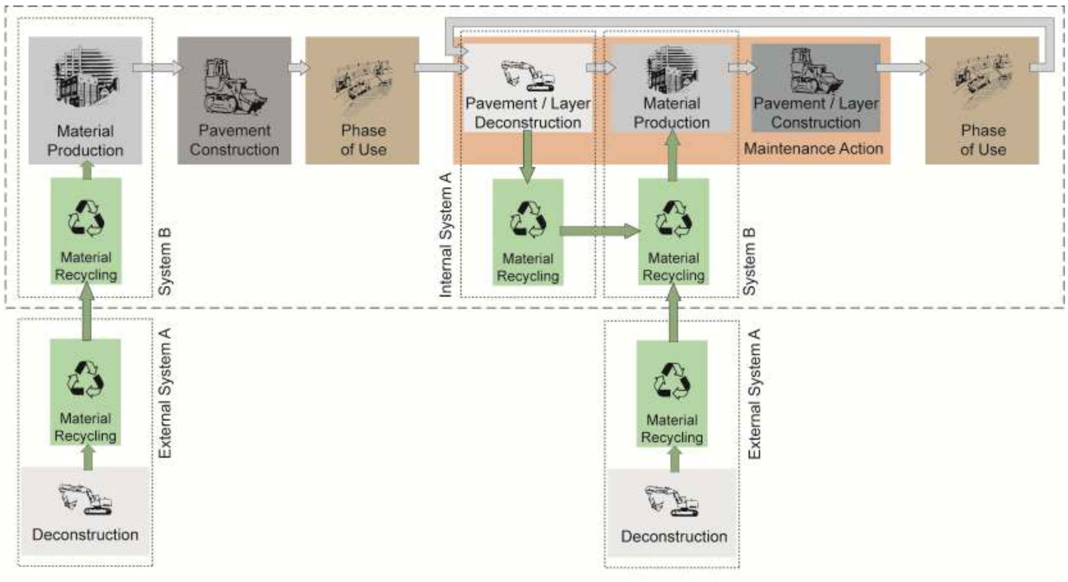

Figure 1 – Recycling scenarios

For the production of road materials used for rebuilt pavement layers during a maintenance action and containing reclaimed material from the analysed pavement no decisions concerning 'where to set the cut-off point' have to be taken, because all recycling processes are included in the overall system. This special case of open-loop recycling is called "open-loop as closed-loop recycling" [2] or can be seen as the application of the cradle-to-cradle model.

For the situation, when recycled material is applied in a new built road pavement or for rebuilt layers during a maintenance action, although the deconstructed layer does not provide enough recycled material, the LCA conductor has to choose between the same options as offered for the cradle-to-gate LCA, whether to include all, a part or no recycling processes.

For this paper, the cut-off point between the System A and the System B was set before the moment the up-graded recycled material leaves the recycling plant, because when an asphalt layer is deconstructed the mill cutter typically used converts the asphalt to granulates that can be reused directly for the asphalt production, i.e. the mill cutter is the recycling plant of the asphalt. Therefore, it was also defined that for the production of the other materials the cut-off point is set before the moment the concrete aggregates leave the recycling plant.

3. CASE STUDIES

The models described were applied for the analysis of three case studies. The first case study analyses two road materials concerning environmental potentials within their production processes by applying the cradle-to-gate model. The second one compares the standard with the optimized production and construction conditions for two Swiss highway pavements by performing from-cradle-to-cut-ribbon LCAs. The third case study analyses two Swiss highway pavements over a period of 50 years.

The results of all LCA studies are expressed by the IPCC Global Warming Potential 2007 (100 years) indicator (GWP) [4], the Non-renewable Cumulative Energy Demand (CED) [5] and the Swiss Ecological Scarcity indicator (EcoScar) [6].

3.1. Ecological potentials within road material production

This case study analyses the production processes of hot mix asphalt (HMA) and a typical concrete mixture for concrete pavements. The asphalt base course mixture AC B 22 H [7] was analysed representing the environmental potentials of asphalt production. The analysed concrete mixture is a bottom concrete mixture that was applied in praxis [8]. For both material types, the analysis of the standard material composition and production condition, as well as two optimized composition and production scenarios are shown in Table 1.

The combination and the quantification of all inputs and outputs occurring over the analysed life cycle phases are called Life Cycle Inventory (LCI). Data for the overall asphalt production was collected with a survey, covering 25% of all Swiss asphalt production companies. A questionnaire was compiled in cooperation with the Swiss Bituminous Mixture Industry (SMI) to gather data about production volumes, mixture compositions, the used energy for the production, internal transport processes, transport distances of the sub-suppliers, emissions, auxiliary materials and existing ecological potentials of the asphalt production [9]. Concerning concrete and therefore also cement and clinker production, data representing average Swiss production data provided by the Swiss cement industry's association was applied [10]. The data of the upstream chains, i.e. LCI data regarding the production of the raw and auxiliary materials, the transport processes, etc., were taken from the ecoinvent database [11].

The environmental potentials for the production of HMA can be achieved by replacing primary material with reclaimed asphalt pavement (RAP), by lowering the initial moisture of the aggregates from 4 % to 2 %, and by decreasing the mixing temperature from 180°C to 115°C with the application of low viscosity bitumen. The substitution of primary material with RAP can be performed “cold”, i.e. RAP is added to the heated aggregates, or “warm”, when RAP is heated up in a parallel process to the heating of the aggregates. The Swiss standard for hot mix asphalt [12] limits the amount of primary material that can be substituted for the production of asphalt base courses, i.e. 15 % for cold recycling and 30 % for warm recycling.

Environmental potentials for the bottom concrete production are given by substituting primary mineral aggregates with recycled concrete aggregates (up to 100%) and by applying a cement type containing a lower percentage of clinker (CEM II / B-T instead of CEM I) [13]. Since the cradle-to-gate LCA for the concrete production was performed with Swiss average data, no potentials for concrete production conditions could be determined.

The material compositions, production characteristics and the cradle-to-gate LCA results of the two analysed materials are shown in Table 1.

Table 1: Material compositions, production characteristics and cradle-to-gate LCA results

		Asphalt			**Concrete**		
		Standard	***Optimized 1***	***Optimized 2***	***Standard***	***Optimized 1***	***Optimized 2***
Material Identification		Hot Mix Asphalt Base Course - AC B 22 H			Bottom Concrete Mixture - C30/37; XF4, XC4, XD3		
Recycling							
Recycling Scenario		No Recycling	Average Recycling	Maximum Recycling	No Recycling	Maximum Recycling	No Recycling
Recycling Perecentage		0%	7.8 % Cold 13.9 % Warm	15 % Cold 30 % Warm	0%	100% Recyc. Conc. Aggr.	0%
Material Composition							
Filler	[kg/m^3]	153	107	84	-	-	-
Sand	[kg/m^3]	564	394	298	650	-	650
Gravel	[kg/m^3]	1580	1104	882	1262	-	1262
Recycling Sand	[kg/m^3]	-	-	-	-	597	-
Recycling Gravel	[kg/m^3]	-	-	-	-	1159	-
Reclaimed Asphalt (Cold added)	[kg/m^3]	-	110	360	-	-	-
Reclaimed Asphalt (Warm added)	[kg/m^3]	-	613	720	-	-	-
Cement CEM I	[kg/m^3]	-	-	-	343	-	-
Cement CEM II / B-T	[kg/m^3]	-	-	-	-	375	343
Bitumen	[kg/m^3]	102.0	71.0	55.0	-	-	-
Water	[kg/m^3]	-	-	-	144	194	144
Plasticizer	[kg/m^3]	-	-	-	3.5	2.5	3.5
Air-Entering-Agent	[kg/m^3]	-	-	-	2.5	2.5	2.5
Density	***[kg/m^3]***	***2399***	***2399***	***2399***	***2405***	***2330***	***2405***
Production Charakteristics							
Electricity, Medium Voltage	[kWh/m^3]	20.6	20.6			4.5	
Heat, Natural Gas	[MJ/m^3]	366.4	210.9			-	
Heat, Light Fuel Oil	[MJ/m^3]	366.4	210.9			-	
Heavy Fuel Oil, in Industrial Furnace	[MJ/m^3]	-	-			3.2	
Light Fuel Oil, in Industrial Furnace	[MJ/m^3]	-	-			13.7	
Natural Gas, in Industrial Furnace	[MJ/m^3]	-	-			1.4	
Diesel, Burned in Wheel Loader	[MJ/m^3]	26.6	26.6			23.3	
Transport, Barge	[tkm/m^3]	-	-			50.7	
Transport, Freight, Rail	[tkm/m^3]	-	-			7.0	
Transport, Lorry 3.5-20t	[tkm/m^3]	-	-			1.0	
Transport, Lorry 20-28 t	[tkm/m^3]	137.0	137.0			9.7	
Lubricating Oil	[kg/m^3]	7.2E-06	7.2E-06			0.012	
Tap Water	[kg/m^3]	0.02	0.02			-	
Steel, Low-Alloyed	[kg/m^3]	-	-			0.025	
Mixing Plant	[p/m^3]	6.0E-10	6.0E-10			4.70E-07	
Results							
IPCC GWP 100a kg	[kg CO2-eq/m^3]	180	125	114	308	248	233
CED Non-Renewable	[MJ-eq/m^3]	7481	5235	4316	1734	1471	1479
Ecological Scarcity (1000 Pt/m3)	[1000 Pt/m^3]	234	171	148	252	157	212

The results in Table 1 show that asphalt in general has a lower impact concerning the GWP and the EcoScar indicator, but has a substantially higher impact regarding Non-renewable Cumulative Energy Demand.

The results also demonstrate that an increasing percentage of RAP lowers the impact of the HMA production concerning all indicators.

The application of CEM II / B-T instead CEM I generally lowers the impact of the concrete production across all indicators. The use of concrete aggregates causes a greater need for cement within the concrete composition. Therefore the impact of the CEM II-recycled-concrete concerning the GWP indicator is higher than the impact of the mixture containing CEM II and primary material.

3.2. Ecological potentials of production and construction of highway pavements

This case study analyses one asphalt and one concrete pavement applicable for highway construction concerning environmental potentials given until the moment the pavement construction is finished by applying the cradle-to-cut-ribbon model.

A standard Swiss asphalt pavement contains a hot mix asphalt wearing course, base course and road base [7]. A subbase layer, which may consist of different materials, forms the base for these three asphalt layers.

Standard concrete pavements in Switzerland consist of 5 m x 5 m unreinforced plates connected to each other by anchors every 50 cm on all sides. It has become state-of-the-art to put an exposed aggregate layer atop of the concrete plates. The appearing joints between the plates are filled with a waterproof joint compound [8]. The concrete paving layers are placed on an interlayer of HMA in order to avoid material shifting in the subjacent subbase layer [8, 14], which may consist of different materials.

The superstructure of the two pavements can be seen in Figure 2.

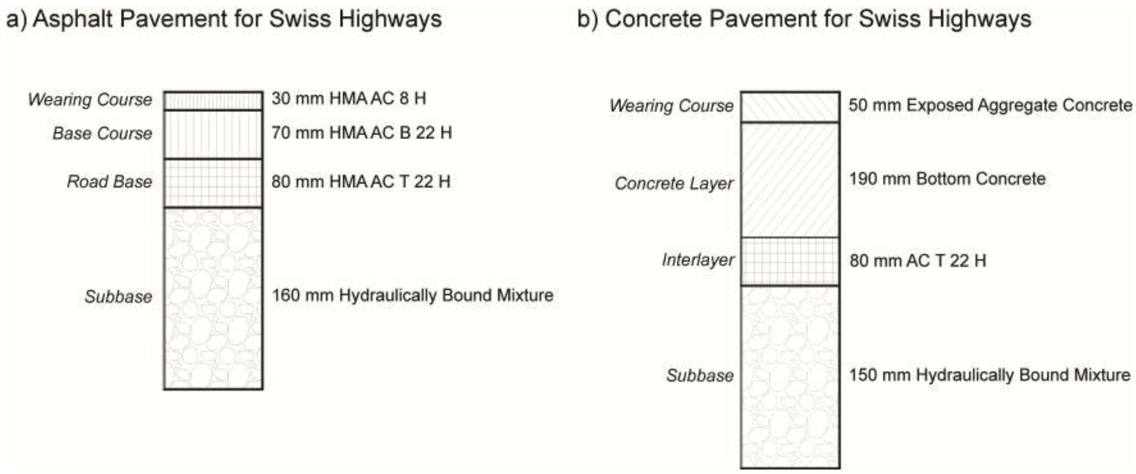

Figure 2 – Structure of the analysed Swiss Highway Pavements

In order to determine the environmental potentials for each pavement type, the application of materials produced in the standard and optimum way must be compared.

The standard materials are produced with primary raw material and under standard conditions.

For the production of optimum HMA, primary raw material should be substituted by the maximum amount of recycled materials stated in the Swiss standard for hot mix asphalt [12]. The optimal bottom concrete layer contains primary aggregates due to the fact that the mixture using recycled concrete aggregates has a higher impact concerning the GWP indicator and about the same impact concerning the Non-renewable CED. The top layer of both pavement types, i.e. the asphalt wearing course and the exposed aggregate concrete layer, have to provide several specific properties concerning driving comfort and safety. Therefore, the application of recycled material within these two materials is not permitted [8, 12].

For the production of optimal HMA mixtures optimized production conditions are assumed.

The standard hydraulically bound mixture is produced in a concrete plant using primary material. The optimum hydraulically stabilized subbase contains mixed recycled granulates instead of primary mineral aggregates. For both the standard and the optimum hydraulic mixture CEM II / A-LL [13] is applied.

Concerning the construction processes of the different layer, the environmental potentials are more difficult to determine due to the fact that the construction conditions vary depending on different factors such as geographical position, climate condition, etc. Furthermore, it has to be guaranteed that the finished construction fulfils the aspired technical requirements. Therefore, standard construction processes using building machines, considered to be state-of-the-art, were analysed.

The transport distance from the production plant to the building should in general be kept as low as possible. For this study an average transport distance of 25 km was assumed.

The results of the cradle-to-cut-ribbon LCAs can be seen in

Table 2.

Table 2 – Results of cradle-to-cut-ribbon LCAs

		Asphalt Pavement					Concrete Pavement				
		Weraing Course	*Base Course*	*Road Base*	*Subbase*		*Weraing Course*	*Concrete Layer*	*Interlayer*	*Subbase*	
		AC 8 H	*AC B 22 H*	*AC T 22 H*	*Hydr. Bound Mixture*	***Sum***	*Exp. Aggr. Concrete*	*Bottom Concrete*	*AC T 22 H*	*Hydr. Bound Mixture*	***Sum***
		30 mm	*70 mm*	*80 mm*	*160 mm*		*50 mm*	*190 mm*	*80 mm*	*150 mm*	
Standard Material Production											
IPCC GWP 100a kg	*[kg CO_2-eq/p.c.]*	1'235'180	2'589'678	2'970'076	2'449'486	**9'244'420**	3'846'925	12'488'338	2'970'076	2'296'393	**21'601'731**
CED Non-Renewable	*[MJ-eq/p.c.]*	57'583'631	107'347'959	122'857'200	19'657'835	**307'446'625**	21'768'463	77'872'118	122'857'200	18'429'221	**240'927'002**
Ecological Scarcity	*[1000 Pt/p.c.]*	1'558'454	3'359'695	3'852'345	3'737'560	**12'508'055**	2'958'574	10'459'704	3'852'345	3'503'963	**20'774'586**
Optimum Material Production											
IPCC GWP 100a kg	*[kg CO_2-eq/p.c.]*	1'029'472	1'635'008	1'428'531	2'281'082	**6'374'092**	2'900'751	9'552'045	1'428'531	2'138'514	**16'019'841**
CED Non-Renewable	*[MJ-eq/p.c.]*	54'312'975	61'933'029	34'704'054	15'627'042	**166'577'101**	18'575'584	67'963'550	34'704'054	14'650'352	**135'893'540**
Ecological Scarcity	*[1000 Pt/p.c.]*	1'449'641	2'120'937	1'461'195	1'597'512	**6'629'285**	2'448'562	8'876'967	1'461'195	1'497'668	**14'284'392**
Pavement Construction (without Transport)											
IPCC GWP 100a kg	*[kg CO_2-eq/p.c.]*	15'847	20'210	19'033	22'819	**77'908**	19'783	53'106	19'033	22'116	**114'038**
CED Non-Renewable	*[MJ-eq/p.c.]*	279'561	345'234	323'674	381'124	**1'329'594**	354'104	858'872	323'674	370'299	**1'906'950**
Ecological Scarcity	*[1000 Pt/p.c.]*	16'933	22'433	21'266	26'216	**86'849**	20'910	63'108	21'266	25'326	**130'610**
Material Transport to Building Site											
IPCC GWP 100a kg	*[kg CO_2-eq/p.c.]*	92'207	214'905	245'543	491'085	**1'043'739**	153'482	583'145	245'543	460'447	**1'442'617**
CED Non-Renewable	*[MJ-eq/p.c.]*	1'577'915	3'677'620	4'201'920	8'403'839	**17'861'294**	2'626'513	9'979'246	4'201'920	7'879'540	**24'687'219**
Ecological Scarcity	*[1000 Pt/p.c.]*	82'691	192'727	220'203	440'406	**936'027**	137'643	522'966	220'203	412'930	**1'293'742**
Total Standard Pavement											
IPCC GWP 100a kg	*[kg CO_2-eq/p.c.]*	1'343'233	2'824'792	3'234'652	2'963'390	**10'366'068**	4'020'190	13'124'589	3'234'652	2'778'957	**23'158'387**
CED Non-Renewable	*[MJ-eq/p.c.]*	59'441'107	111'370'814	127'382'794	28'442'798	**326'637'513**	24'749'081	88'710'236	127'382'794	26'679'059	**267'521'170**
Ecological Scarcity	*[1000 Pt/p.c.]*	1'658'079	3'574'855	4'093'814	4'204'183	**13'530'931**	3'117'127	11'045'778	4'093'814	3'942'218	**22'198'938**
Total Optimum Pavement											
IPCC GWP 100a kg	*[kg CO_2-eq/p.c.]*	1'137'525	1'870'122	1'693'106	2'794'986	**7'495'739**	3'074'016	10'188'296	1'693'106	2'621'078	**17'576'496**
CED Non-Renewable	*[MJ-eq/p.c.]*	56'170'451	65'955'884	39'229'648	24'412'005	**185'767'989**	21'556'202	78'801'667	39'229'648	22'900'191	**162'487'709**
Ecological Scarcity	*[1000 Pt/p.c.]*	1'549'265	2'336'097	1'702'664	2'064'135	**7'652'161**	2'607'115	9'463'041	1'702'664	1'935'923	**15'708'744**

The results in

Table 2 show that asphalt pavements generally have a lower impact on the GWP and the EcoScar indicator, which would be expected after calculating the potentials of the material production.

The relative reduction potential, i.e. the difference between the standard and the optimum pavement, is about the same for both pavement types regarding the GWP indicator. However, the asphalt pavement has a higher potential concerning the CED and the EcoScar indicator.

With regard to all indicators,

Table 2 also demonstrates the substantially high influence of the production processes and the high significance of the material transport to the building site. The influence of the construction processes is insignificant.

3.3. Environmental impacts of highway pavements over a 50-year period

The last case study analyses the previous cradle-to-cut-ribbon LCA analysed pavements over a period of 50 years.

Since processes and environmental impacts of the use phase (noise generation, rubber abrasion, difference in mileage due to pavement roughness, etc.) of the highway pavement are difficult to combine with the material production, construction and maintenance processes within one analysis, this study does not analyse processes occurring in the use phase of the road.

It is assumed that both pavements were newly built, utilising all given environmental potentials, i.e. the optimum pavements from the cradle-to-cut-ribbon study. Thus, this cradle-to-grave LCA shows the influence of possible maintenance strategies on the environmental performance of both pavement types.

The maintenance strategies applied were compiled based on data experienced and expert opinions, and can be seen as exemplary. Generally, the strategies should be determined by utilising an Infrastructure Management System (IMS) in order to select the best strategy corresponding to the pavement type, traffic load, the estimated budget for maintenance actions as well as climatic and geographic influences [15]. The average lifetime of an HMA wearing course is quantified as 12 to 20 years. HMA base course layers are on average applicable for 25 to 30 years and HMA road bases for 50 years. Hydraulically bound subbases have to be replaced every 50 years. Concrete pavement layer generally last for 30 to 40 years. Therefore, the maintenance strategies were chosen as shown in Table 3.

Table 3 – Maintenance strategies

	Replaced Layers	
Years	***Asphalt Pavement***	***Concrete Pavement***
15	Wearing Course	---
30	Wearing Course & Base Course	Exposed Aggregate Concrete & Bottom Concrete
50	Total Pavement	Total Pavement

Regarding the production of materials used for rebuilt layers during a maintenance action, it is assumed that they are produced under optimum conditions utilising all environmental potentials.

As mentioned before, the cut-off point for the allocation of the recycling processes is set before the moment the upgraded recycled material is transported from the recycling plant to the production plant due to the fact that asphalt layers are already upgraded to recycled material during the deconstruction process by the mill cutter.

Table 4 – Results of cradle-to-grave LCA

		Asphalt Pavement						Concrete Pavement					
		Material Prod.	*Decon-struction*	*Recycling*	*Pavement Constr.*	*Transport f. Constr.*	*Sum*	*Material Prod.*	*Decon-struction*	*Recycling*	*Pavement Constr.*	*Transport f. Constr.*	Sum
New Construction													
IPCC GWP 100a kg	*[kg CO_2-eq/p.c.]*	6'374'092	-	-	77'908	1'043'739	**7'495'739**	16'019'841	-	-	114'038	1'442'617	**17'576'496**
CED Non-Renewable	*[MJ-eq/p.c.]*	166'577'101	-	-	1'329'594	17'861'294	**185'767'989**	135'893'540	-	-	1'906'950	24'687'219	**162'487'709**
Ecological Scarcity	*[1000 Pt/p.c.]*	6'629'285	-	-	86'849	936'027	**7'652'161**	14'284'392	-	-	130'610	1'293'742	**15'708'744**
Maintenance 1													
IPCC GWP 100a kg	*[kg CO_2-eq/p.c.]*	1'029'472	26'585	-	15'847	184'413	**1'256'317**	12'452'796	75'038	773'843	72'888	1'473'255	**14'847'821**
CED Non-Renewable	*[MJ-eq/p.c.]*	54'312'975	413'075	-	279'561	3'155'830	**58'161'442**	86'539'134	1'147'561	14'429'718	1'212'977	25'211'518	**128'540'908**
Ecological Scarcity	*[1000 Pt/p.c.]*	1'449'641	31'984	-	16'933	165'382	**1'663'940**	11'325'529	93'372	867'659	84'018	1'321'218	**13'691'796**
Maintenance 2													
IPCC GWP 100a kg	*[kg CO_2-eq/p.c.]*	2'664'480	34'148	-	36'056	614'223	**3'348'907**	16'019'841	478'520	1'257'495	114'038	2'179'245	**20'049'139**
CED Non-Renewable	*[MJ-eq/p.c.]*	116'246'005	524'675	-	624'795	10'511'071	**127'906'546**	135'893'540	8'401'845	23'448'292	1'906'950	37'292'978	**206'943'605**
Ecological Scarcity	*[1000 Pt/p.c.]*	3'570'578	41'460	-	39'366	550'836	**4'202'241**	14'284'392	554'715	1'409'946	130'610	1'954'351	**18'334'013**
Maintenance 3													
IPCC GWP 100a kg	*[kg CO_2-eq/p.c.]*	6'374'092	92'895	515'895	77'908	2'087'478	**9'148'269**	-	-	-	-	-	-
CED Non-Renewable	*[MJ-eq/p.c.]*	166'577'101	1'423'636	9'619'812	1'329'594	35'722'588	**214'672'731**	-	-	-	-	-	-
Ecological Scarcity	*[1000 Pt/p.c.]*	6'629'285	160'588	578'439	86'849	1'872'054	**9'327'215**	-	-	-	-	-	-
Total Pavement													
IPCC GWP 100a kg	*[kg CO_2-eq/p.c.]*	16'442'135	153'628	515'895	207'720	3'929'854	**21'249'232**	44'492'477	553'558	2'031'338	300'965	5'095'118	**52'473'457**
CED Non-Renewable	*[MJ-eq/p.c.]*	503'713'183	2'361'387	9'619'812	3'563'544	67'250'783	**586'508'708**	358'326'215	9'549'406	37'878'011	5'026'876	87'191'714	**497'972'221**
Ecological Scarcity	*[1000 Pt/p.c.]*	18'278'789	234'032	578'439	229'996	3'524'300	**22'845'557**	39'894'312	648'087	2'277'605	345'238	4'569'311	**47'734'553**

The results in Table 4 show that, when pavements are analysed over 50 years, the asphalt pavement also has a lower impact on the GWP and the EcoScar indicator than the concrete pavements. With regard to the Non-renewable CED the asphalt pavement has a higher impact.

It also shows, that the highest environmental impacts are caused by the material production.

4. DISCUSSION

This paper showed the application of three different Life Cycle Assessment models for the environmental analysis of road material and highway pavements.

The results of all three LCA demonstrate that “asphalt products” have a higher impact concerning the Non-renewable Cumulative Energy Demand, although they have a lower impact concerning the GWP and the EcoScar indicator. These contrary results can be explained by the fact that the CED indicator also includes the feedstock energy. The feedstock can be described as a fuel that is used in a situation where it is not directly burned [16]. Thus, the use of bitumen within the asphalt represents a depletion of available energy resources.

It is shown that the cradle-to-grave model cannot be applied as for a normal product, because the average life span of a road construction is not determinable. Therefore, an analysis period has to be chosen. This paper analysed two different road pavements over a period of 50 years. In order to know the influence of the length of the analysis period for cradle-to-grave LCAs of road pavements, a sensitivity analysis, which assesses the pavements over different “periods of observation”, should be performed by upcoming research.

Furthermore, the influence of the cut-off rule should be analysed in future studies by setting the cut-off point at different moments of the deconstruction and recycling processes.

An uncertainty can be seen in the analysis of future maintenance actions, because development in material production and pavement construction processes is not considered. Therefore, it is recommended to perform a cradle-to-cut-ribbon LCA at the moment the maintenance action takes place, in order to control and to correct the results of the cradle-to-grave LCA, which was performed before the road was newly built.

The influence of the maintenance strategies should be analysed in future research projects. Thereby, it is recommended to analyse several strategies depending on different terms and conditions, which were defined with the help of an Infrastructure Management System.

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