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Life cycle assessment (LCA) to evaluate the environmental impacts of urban roads: a literature review

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Abstract. With the ratification of the Paris climate agreement to avoid the uncompensated effects of climate change, 197 countries will have to dramatically reduce their greenhouse gas emissions in half by 2030. In the case of the urban space, roads are responsible for the consumption of 105M tons of bitumen and 115M tons of the world's greenhouse gas emissions. For this reason, the reduction of the environmental impacts of road construction is becoming an urgent necessity. So far the vast majority of the Life cycle assessment (LCA) has been used to evaluate the environmental burdens of existing roads and new asphalt solutions. However, due to the different LCA methodological choices, recent studies have highlighted the difficulties in comparing the results of cases published in literature. Driven by this knowledge gap, the aim of the present study was to identify key aspects missing in the assessment of urban roads. Through a Systematic Literature Review (SLR), 47 publications have been selected for further investigation. An intensive analysis of these documents clearly demonstrate the heterogeneity of the applied LCA methodological choices as well as the selected approaches regarding i.e. the goal of the studies, functional unit, system boundary, database and stratigraphy of the road pavement. Aiming to harmonize the LCA methodology, we have identified key aspects that require solutions for a robust LCA application. The results are expected to be useful for the National Road Administration (NRA) in assessing the environmental impacts of future urban road projects. As a response to the Paris climate agreement targets, the application of harmonized methods regarding LCA should lead to a more robust and structured process in terms of identifying low carbon urban road solutions and contributing to the SDGs respectively.

1. Introduction

Worldwide, the annual consumption of bitumen for asphalt road pavement leads to the emission of around 115 million tons of CO_2-eq [1], and the minimization of it is becoming urgent. Life cycle assessment (LCA) methods have been widely applied in the construction sector and have been used in order to evaluate the environmental burdens of existing roads and new asphalt solutions. The results of the LCAs support decision-making in favor of more climate and environmentally friendly production and therefore help to achieve the UN Sustainable Development Goals (SDGs) number 12 (responsible consumption and production), 13 (climate action) and last but not least, 11 (sustainable cities and communities). However, due to methodological choices, recent studies highlighted the difficulties to compare the results of cases published in literature that do not allow the identification of the solutions with lower impacts.

Motivated by this knowledge gap, the HERMES project aims to analyze effective ways of assessing the impact of both present and future urban road systems, and to identify the eco-friendliest road pavement [2]. For this reason, the key aspects missing in the assessment of urban roads are presented in this paper. The most pertinent case studies addressing methodological issues for the assessment of environmental impacts are then identified and critically analyzed through a systematic literature review.

2. Systematic literature review

The systematic, structured procedure of the Systematic Literature Review (SLR) [3] for the comprehensive identification of the most relevant documents is presented in Fig 1. The search was limited to peer-reviewed papers published in Scopus, Science direct, Mendeley, Springer Link, and Web of Science database. In the first step, the combination of several keywords was used for the identification of the most adequate papers. Then they were filtered in three phases: (1) based on the title, (2) based on the abstract and (3) after reading the full paper. In the end, the papers focusing on the flexible road pavement were selected and the data of the case studies were extracted and analyzed in detail.

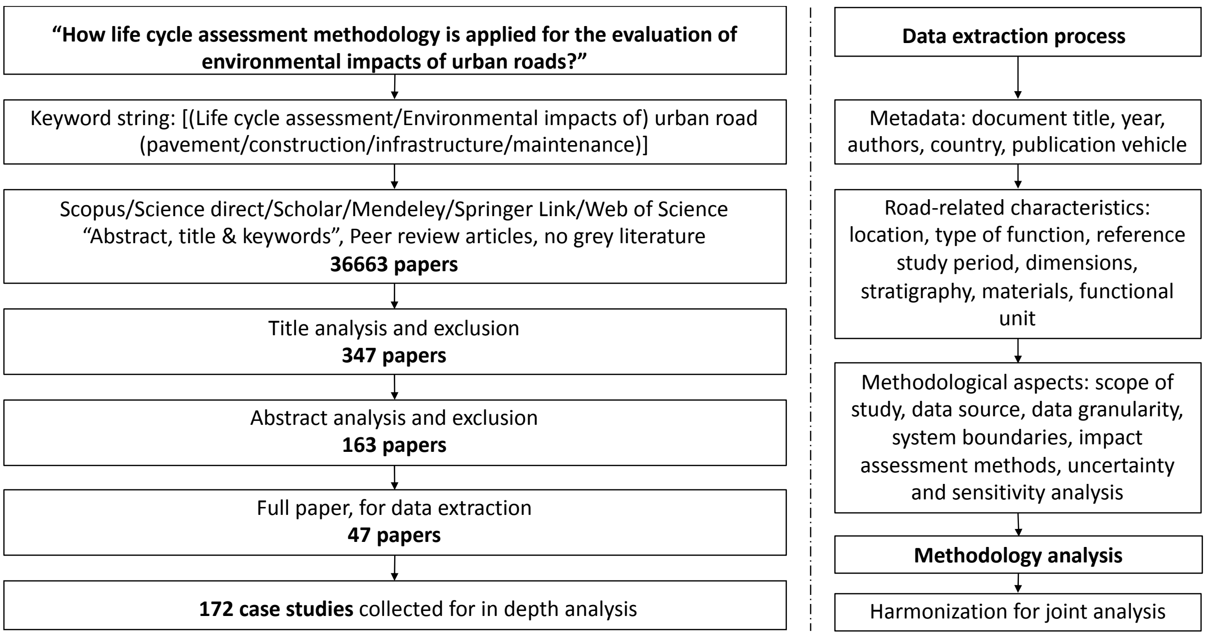

Figure 1. Method for literature search.

3. Results

3.1. LCA methods

The LCA approach for evaluating the environmental impacts of road construction and maintenance varies significantly. The results presented in Fig 2 show that the method used for conducting the LCA is not often specified, while the most common method when specified was ISO 14040-44 [51] which is applicable internationally. Other methods mentioned were, Eco-LCA, EN-15804 [52], and NEN 8006. Eco-LCA was developed by Ohio State University, Center for Resilience, and focuses on ecosystem services. EN-15804 is a European standard that focuses on sustainable construction work. Finally, NEN 8006 is a Dutch standard that mainly focuses on building information, including materials. Disclosing the standard or method used for the study should not be crucial for the compatibility of the results. However, a well-structured study is likely to reveal the method used because of general transparency and choices made while organizing the study.

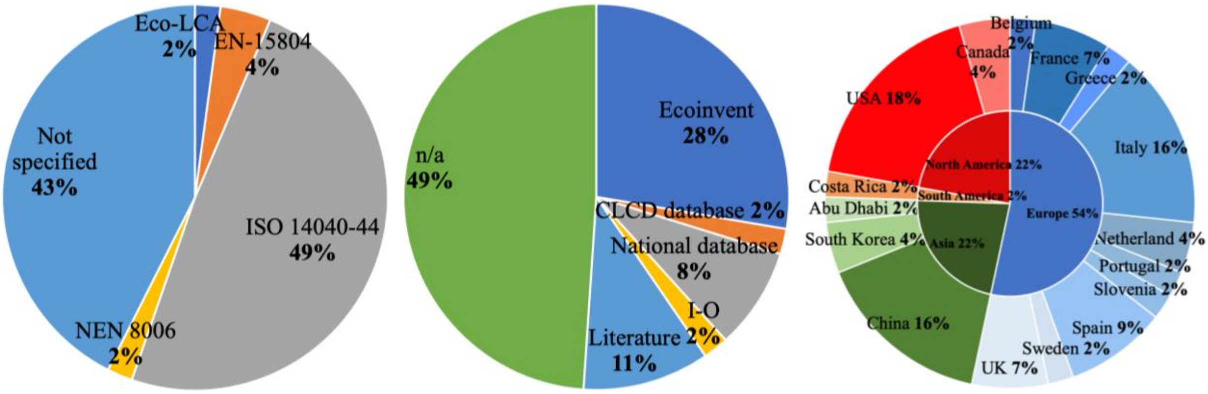

Figure 2. Meta-analysis of the LCA methodology, database and location of the roads.

The bases of an LCA include the emissions, inventory data, the specification of the database, and more specifically, the impact assessment methods. Almost half of all the studies examined did not specify the database used for the evaluation of the impacts. Of those who did specify the database, the ecoinvent was the most commonly used. Information from the national database only accounts for 8% while those from the literature were specified in 11% of the studies. The location of the studies can be quite important as it is affected by regional and national regulations as well as the climate that no only affects the need for groundwork, but it also affects the future need for maintenance. Furthermore, materials for road construction, and especially for asphalt, may differ substantially depending on the climate zone the road is in. The majority of the LCA studies on road construction and pavement were conducted in Europe with a large share from Italy. Both North-America and Asia have a share of 22% of LCAs on roads while other regions are barely represented. Italy, China, and the USA each represent 8% of the studies examined.

3.2. *Functional unit*

The functional unit is the very basis of any LCA study and is therefore also the basis of comparative analysis. The results of the studies (see Fig 3) included in this paper highlighted the challenges of comparing the results of both road construction and pavement in LCA. However, it was found that there are some key aspects many of the studies included in their definition of the functional unit. According to the SLR, the main aspects of the functional unit are both the dimensions (length, width and stratigraphy) and the time period. Over 50% of the studies presented the results per km road, while 13% used 1 m of the road. The most common width of the road varied between 4-lanes, 2-lanes, and 1-lane with a share of 28%, 21%, and 23%, respectively. Eleven percent of the studies used 1 meter as the width and the majority of those were effectively reporting on a square meter of road. Looking at the time aspect of the analysis, 18% did not disclose the time assumed for the study. Given the importance of the lifetime in LCA, the share of 18% is high. The studies that disclosed the lifetime most widely used a year as the basis for the assessment while the remaining 70% ranged from a 10- to 100-years perspective, with a relatively even distribution. There is a fundamental difference between a functional unit of a road and a product. A kilometer of a road with a certain width requires different input in the form of earthworks and materials, depending on the characteristics of the ground as well as the weather. Furthermore, the dimension of the road is controlled by a variety of aspects, including but not limited to speed, average annual daily traffic, and both vertical and horizontal alignment. All the studies accounted for the friction course in their investigation. Most of the studies also took the binder into account.

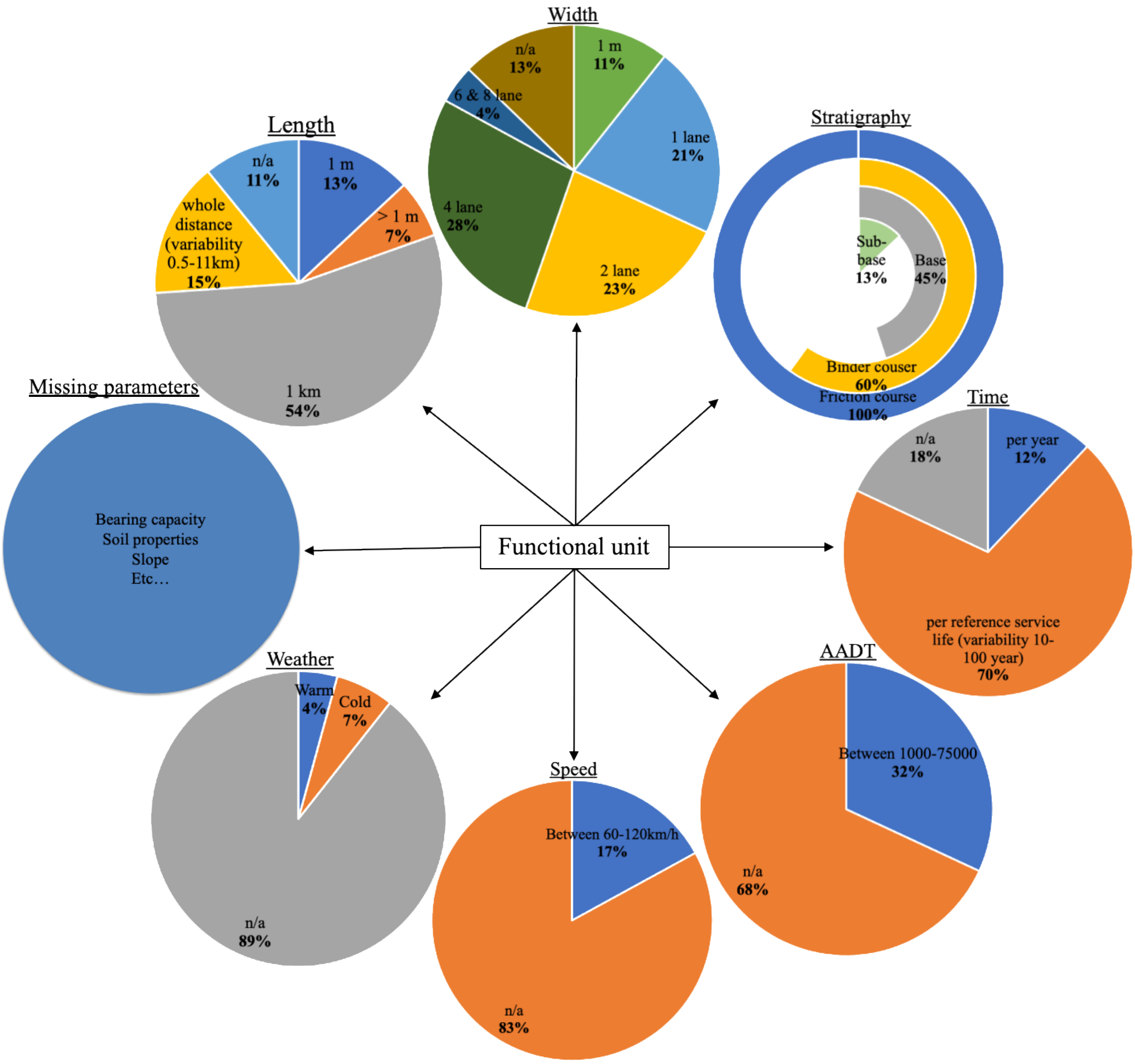

Figure 3: Meta-analysis of the functional unit (AADT: annual average daily traffic).

These aspects are easier to account for in a functional unit and compare to other studies. Many of the studies further specified about the thickness of each of these layers. However, only around 45% of the studies took the base-layer into account. Even fewer, or only 13%, of the studies examined the entire road structure including the subbase. The most difficult part to standardize is the inclusion of the base and subbase due to the variation in ground stability.

3.3. System boundary

The system boundaries should be clearly defined for a better comparison with other well-defined LCA studies. The results presented in Fig 4 show that the production and extraction of raw materials, as well as their transportation, are included in almost 90% of the studies. However, the construction itself is only included in approximately 50% of the studies. Construction is a relatively time-consuming part of a road's life cycle and it requires heavy machinery and a substantial amount of energy.

PHASES INCLUDED IN THE BOUDANRY		Results in %	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
Production	Raw material supply	**89%**	x	x		x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x			x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
	Transport	**89%**	x	x			x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x			x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Manufacturing	**87%**	x	x			x		x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x			x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Construction	Transport	**51%**	x	x			x	x	x		x			x	x		x		x		x	x	x	x							x		x	x			x	x		x	x			x			x		x
	Construction	**49%**	x	x			x	x	x		x			x	x		x			x	x	x	x	x							x		x	x			x	x		x				x			x		x
Use	Use	**15%**	x						x															x																		x		x			x	x	
	Maintenance	**17%**		x					x	x				x		x																												x			x	x	
	Repair	**15%**			x								x				x																									x			x		x	x	
	Refurbishment	**2%**																																										x					
	Replacement	**51%**		x				x	x	x			x			x	x	x	x	x	x	x		x		x	x	x			x	x					x	x		x	x						x	x	
	Operation	**28%**	x		x								x	x							x						x	x				x										x	x		x		x	x	
End of life	Demolition	**26%**						x	x				x	x					x					x				x					x				x	x		x	x								
	Transport	**26%**						x	x				x	x					x					x				x					x				x	x		x	x								
	Waste processing	**23%**						x					x	x					x					x				x					x				x	x		x	x								
	Disposal	**23%**						x					x	x					x					x				x					x				x	x		x	x								

Figure 4: Meta-analysis of the system boundary (life cycle stages according to EN-15804 [52]).

The use phase, including the use of vehicles as well as the operation and maintenance of the road, is seldomly represented. The phase of vehicle use is only considered in 15% of the studies. This is a variable that is commonly excluded as it varies a lot and includes a technology that is rapidly changing and does not depend on construction. Operation and maintenance activities are also often excluded except for the replacement of the road. As mentioned earlier, the replacement often only applies to the friction layer and it is therefore not surprising that the replacement activity is also quite common.

4. Conclusion

The results of this study identified the missing key aspects of the LCA methodologies used to calculate the environmental impacts of flexible road pavements. Transparency in LCA studies and heterogeneity regarding the norms/standards, functional unit, database and boundary of the system make it difficult to compare the results between studies. More than 40% of the studies did not provide any information on the norm/standards or of the databases utilized in the LCA studies, making the reproducibility of the results impossible. While the heterogeneity of the norms/standards and the databases used to calculate the impacts were derived from the different studies that provided this information, the different results cannot be compared.

When the functional unit used in LCA methods is different and sometimes incomplete, it becomes more difficult to compare the studies. A meta-analysis of functional units shows that its compound parameters are completely missing in more than 10% of the studies and the rest varies between studies. In more than 80% of the studies, the AADT, speed, weather, bearing capacity and slope of the road are not provided. According to ISO-14040 [51] standard, it is not possible to compare products with different functional units since all inventory data and impact evaluations are standardized.

Based on a meta-analysis of the system boundary, it can be concluded that almost all the studies evaluating the environmental impacts of the production phase and other life cycle stages are considered only in less than 50% of the studies.

In conclusion, we highlighted the urgent need to define the aspects of LCA in order to strengthen the robustness of the impact assessment and comparison of solutions. For this reason, the definition of these parameters is a very important aspect of this study.

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