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Review

Life cycle assessment of roads: Exploring research trends and harmonization challenges

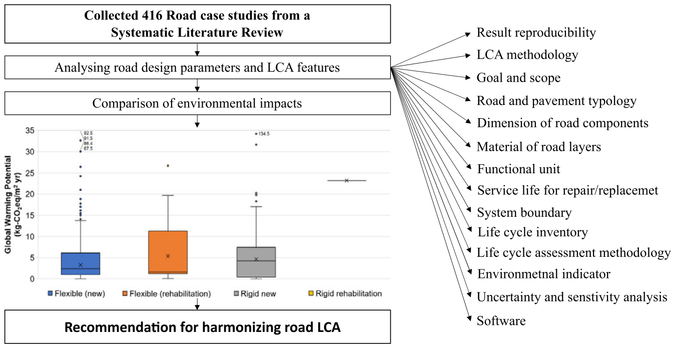
E. Hoxha [a], H.R. Vignisdottir [b], D.M. Barbieri [c], F. Wang [c,d], R.A. Bohne [c], T. Kristensen [b], A. Passer [a,]*

[a] *Graz University of Technology, Institute of Technology and Testing of Construction Materials, Working Group Sustainable Construction, Graz, Austria*
[b] *SINTEF, Institute Community, Working Group Infrastructure, Trondheim, Norway*
[c] *Norwegian University of Science and Technology, Department of Civil and Environmental Engineering, Trondheim, Norway*
[d] *Wuhan University of Technology, State Key Laboratory of Silicate Materials for Arc, Wuhan, China*

HIGHLIGHTS

- Systematic literature review on 417 road case studies
- Analyse of road design parameters and LCA features
- More than 90% of studies lack the information on road design parameters.
- More than 82% of studies are not transparent and results are not reproductible.
- Provide recommendation for a harmonized application of LCA

GRAPHICAL ABSTRACT



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ABSTRACT

The transparency, heterogeneity and hypotheses considered in the calculation of the environmental impacts of roads are still barriers to the identification of low-carbon solutions. To overcome this problem, this study presents an analysis of 94 papers obtained in a systematic literature review of the Scopus, Science Direct, Mendeley, Springer Link, and Web of Science databases. From a total of 417 road case studies, only 18% were found to be fully transparent, reproducible, and likely to present reliable results. The road design parameters of the speed limit were provided in 11% of the cases, and the average annual daily traffic data were provided in 42%. Limited data were found for the dimensions of road elements such as the number (77%) and width of lanes (33%), shoulders (15%), footpaths (5%), berms (1%) and foreslope (4%). The source of the life cycle inventory was presented in 57% of the case studies, impact assessment method was indicated in 22%, and the software utilized was listed in 50%. A lack of information was noted in the description of the types of materials employed in road projects. In addition, the large heterogeneity in the definitions of the functional unit, system boundary and in the reference study period of repair, replacement, rehabilitation or end-of-life for both flexible and rigid pavement does not support the identification of the most environmentally friendly solutions. Based on the results of the analysis, several recommendations for design parameters and life cycle assessment aspects are proposed to support a harmonized calculation of the environmental impacts of road projects.

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* Corresponding author.
E-mail addresses: endrit.hoxha@tugraz.at (E. Hoxha), alexander.passer@tugraz.at (A. Passer).

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Contents

1. Introduction

Global urbanization is triggering rapid improvement in various infrastructural construction methods, among which sustainable roads are recognized as a significant part. Worldwide, the transport sector is responsible for 32% of greenhouse gas (GHG) emissions, of which 74% are due to road traffic and construction processes (IEA, 2019). Furthermore, the global road network has a length of more than 16.3 million km (Nicodème et al., 2017), and the demand for road transport services is expected to increase by more than 50% by 2050 (Raposo et al., 2019). Meanwhile, policymakers and stakeholders should aim to significantly reduce GHG emissions to curtail global warming (IPCC, 2018).

Several technological shifts are currently being investigated, i.e., from vehicles driven by fossil fuels to electricity- or hydrogen-driven vehicles and from manually driven vehicles to platooning and autonomous vehicles. These new technologies, which comprise internal combustion engines for both light- and heavy-duty vehicles, are becoming increasingly competitive and can substantially reduce the environmental impact of road traffic (Raposo et al., 2019).

Consequently, the emission profiles of roads are changing from being transport dominated towards placing a much greater focus on the impact of construction processes. Thus, the next objective is to reduce the impacts from the materials and processes of construction, maintenance, and rehabilitation (Noshadravan et al., 2013; Santos et al., 2015; Yang et al., 2018; Santos et al., 2018). Although several authors have proposed new asphalt technologies (Huang et al., 2009; Sayagh et al., 2010; Anastasiou et al., 2015; Celauro et al., 2017; Wang et al., 2019), the best solutions have not yet been identified. Life cycle assessment (LCA) methods (ISO-14040, 2006; ISO-14044, 2006) have been widely applied in the construction sector to evaluate the environmental burdens of existing projects or to compare different solutions (Hoxha et al., 2017; Röck et al., 2020). However, regarding the general understanding of LCA and the neutral and transparent results needed for these comparisons, there is a broad range of different tools and methods for actually accomplishing the analysis. Due to these methodological choices, recent studies (Inyim et al., 2016; Jiang and Wu, 2019) have emphasized the knowledge gap in the difficulties of comparing the results of the road cases published in the literature, which does not allow the identification of solutions with lower impacts.

2. Research objectives

Motivated by this knowledge gap, the objectives of this study are to analyse the barriers preventing the robust comparison of road projects and to provide useful solutions for a harmonized application of LCAs. To that end, the transparency, variability and heterogeneity of inputs and the hypotheses of both road design parameters and LCA features are analysed. Based on the gathered data and analysis, recommendations are proposed that can represent the first step towards a future standardization of LCA methodology. The data were collected following the structured procedure of a systematic literature review (SLR) and a snowball approach (Higgins and Green, 2008; Wohlin, 2014). However, for a better justification of the objectives of this study, the next section analyses the previous literature reviews dealing with road LCAs.

3. Literature review

Previous review studies have discussed the use of LCAs to calculate the environmental impacts at the level of asphalt materials and road projects.

At the material scale, based on a reference unit of 1 ton, Anthonissen and Braet (2015) performed a critical review of the different technologies used to reduce the environmental impact related to asphalt concrete production. Moreover, the study considered reclaimed asphalt and low-temperature production. Virgin material savings and reduced transport distances minimize the environmental burdens of bituminous road construction works. Wang et al. (2020) assessed the energy consumption, the reduction in raw material use and the extension of the pavement service life related to rubberized asphalt. Compared to the production of traditional asphalt mixtures, the use of crumb rubber entail a significant reduction in terms of fuel consumption (20–25%), CO (−40%), CH_4 (−62%) and noise level. Tatari et al. (2012) evaluated the cumulative mass, energy, industrial exergy and ecological exergy for both warm mix asphalt (WMA) and conventional hot mix asphalt (HMA). The results showed that a decreased amount of atmospheric emissions should be evaluated in both the mixing phase and the supply chain (material production and transportation). Thives and Ghisi (2017) assessed the energy consumption and dioxide emissions for different types of binders. The GHG emissions are significantly lower (up to 70-80%) for bituminous asphalt mixtures than for mixtures related to Portland cement concrete. Although these studies provide guidance to reduce the environmental impacts of asphalt, they present discrepancies at the road scale and cannot be generalized. This is because the environmental impacts of roads are influenced by design parameters and LCA features. Design parameters, such as the bearing capacity, soil, weather conditions, average annual traffic, roughness, and deflection, define the geometric characteristics of roads and consequently the quantities of materials employed. In addition, LCA features such as the functional unit (FU), reference service life, system boundary, lifecycle inventory and impact assessment method are determinants of the environmental impacts of roads. Partial discussions of these parameters and aspects have been the subject of several publications.

At the road scale, Suprayoga et al. (2020) recently evaluated the degree of application of sustainability assessment to road infrastructure projects in terms of the environmental, economic and social pillars. Based on 31 analysed papers, they found that the ´project appraisal´ method covers the most extensive criteria and is recommended as the most suitable approach for decision-making. With a deep focus on LCA aspects, Inyim et al. (2016) investigated the environmental impacts of pavement construction. Given the heterogeneities found in terms of the FU, reference service life, environmental indicator and LCA approaches, they concluded that it was impossible to identify the most environmentally friendly asphalt technology. Hasan et al. (2019) stressed the critical need for adjusting the inconsistencies and research gaps in LCA by delving into all life cycle stages and as previously found in Balaguera et al. (2018) and Azarijafari et al. (2016) highlighted the benefits of energy saving and reductions in global warming potential (GWP) when the use of eco-design options is documented. Table 1 summarizes the LCA aspects discussed in the studies dealing with LCA at the road scale.

Table 1

Summary of the LCA features analysed in previous studies (CR-critical review; SLR-systematic literature review). (1) Inyim et al., 2016; (2) Suprayoga et al., 2020; (3) Azarijafari et al., 2016; (4) Hasan et al., 2019; (5) Balaguera et al., 2018; (6) Jiang and Wu, 2019.

Source		1	2	3	4	5	6	This study
Type of study		CR	SLR	CR	CR	CR	SLR	SLR
Database			2				1	6
Result reproducibility								X
LCA methodology							X	X
Goal				X	X		X	X
Scope	Road and pavement typology			X	X		X	X
	Motor lanes, shoulder			X			X	X
	Pavement thickness			X			X	X
	Functional unit	X		X	X	X	X	X
	Road lifetime	X		X			X	X
	Design parameters							X
	Footways, bicycle lanes, berm							X
	Material of each road layers							X
	Lifespan for repair							X
	Lifespan for replacement							X
	Lifespan for rehabilitation							X
System boundary	6 lifecycle stages for motor lanes	X			X	X	X	X
	15 lifecycle stages for 33 road components and processes							X
Software							X	X
Life cycle inventory				X	X		X	X
Life cycle impact assessment methodology								X
Environmental indicators		X	X			X	X	X
Uncertainties							X	X

In conclusion, previous authors recommended future studies for the standardization of the method adopted and its development considering the road characteristics. Given the LCA aspects discussed in previous review studies, this study presents a significant expansion in several directions. Starting from a SLR of the papers accessible in the Scopus, Science Direct, Mendeley, Springer Link and Web of Science databases, the analyses performed in this study are based on road design parameters and LCA features. The following design parameters were considered: speed limit, average annual daily traffic, climate zone and soil properties. Furthermore, data on the road type were retrieved such as the width of motor and non-motorized lanes, internal and external shoulders, footpaths, berms, foreslopes, thickness of wearing-, binder-, base-, and subbase-course. In addition, the type of asphalt used in different courses for new road projects and rehabilitation processes was considered. The FU and the corresponding information regarding their repair, replacement, rehabilitation and end-of-life (EoL) of both flexible and rigid pavement are evaluated in detail in this study. Furthermore, the analysis of system boundaries as defined by EN-15804 (2019), which breaks down the impacts on production (A1-A3), construction (A4-A5), use (B1-B6) and EoL (C1-C4), presents a significant recent expansion in the field. The data for the life cycle inventory, impact assessment method, environmental indicators and tools used for evaluation are analysed. Finally, the harmonized environmental impacts of flexible and rigid pavement for both new and rehabilitation processes are compared with each other. In addition to the comprehensive collection of data, the performed meta-analyses and the recommendations discussed for the harmonization of LCA application aligned with road characteristics represent the novelties of this study.

4. Materials and method

In the following subsection, the approaches of (i) the SLR and (ii) the data presentation, uniformization and analysis are described.

4.1. Systematic literature review

The objective of the SLR is to answer the following research question: How is LCA methodology applied for the evaluation of the environmental impacts of urban roads? To better determine the variety of aspects considered in the LCA studies eight additional research questions have been formulated:

- What are the approaches followed for the assessment of the environmental impacts of roads?
- What are the goals and scopes of the studies?
- What types of material are used for wearing, binder, base and subbase courses and the geometry of road cross-sections?
- What are the FU considered?
- What are the reference service lives for the repair, replacement and refurbishment of different layers of the road?
- What are the road components and materials considered in the system boundary of LCA studies?
- What are the databases, software and impact assessment methods used in LCA studies?
- What are the road pavements with lower environmental impacts?

To answer these questions, the search for relevant literature was performed through the combination of the following keywords: (Life cycle assessment OR Environmental impacts of) AND (roads) AND (Pavement OR Construction OR Infrastructure OR Maintenance). The inclusion criteria of the literature are limited to articles written in English and published in peer reviewed papers indexed in the Scopus, Science Direct, Mendeley, Springer Link and Web of Science databases. Grey literature, such as conference papers, theses, and reports was excluded.

Only the articles published after 2006, which corresponds to the date of the publication of the LCA standard (ISO-14040, 2006; ISO-14044, 2006), were considered to be relevant to the research questions. Studies published before 2006 were considered to be less pertinent regarding the methodology aspects, as they do not follow specific norms.

The relevant articles collected were then filtered through the screening of the titles, abstracts and through an examination of their full texts. In addition, a snowball approach was used for the identification of papers not collected through the literature review. The entire literature search and data extraction process lasted from June 2019 until January 2020. After excluding projects with tunnels or bridges, 417 scenarios of road case studies were ultimately collected. Fig. 1 summarizes the number of articles for each SLR step and the snowball approach.

4.2. Data presentation, uniformization and analysis

4.2.1. Data presentation

To display the results in a comprehensive way, the meta-analysis follows the indications of the EN-17472 (2020) and EN-15804 (2019) standards. The standards break down the environmental impacts according to the following life cycle stages: production (A1-A3), construction (A4-A5), use (B1-B6), EoL (C1-C4) and benefits (D) (Fig. 2).

In the case of roads, module A1 presents the environmental impacts of the processes associated with the extraction of material mainly from quarries. Depending on whether the pavement is rigid (i.e., cement concrete) or flexible (i.e. asphalt concrete), the raw materials used represent all types of aggregates, such as gravel, sand, filler cement or bitumen (Gschösser et al., 2012; Thives and Ghisi, 2017). The impacts due to the transportation of raw material to mix plants and asphalt production sites are included in module (A2) and (A3), respectively. The processes of asphalt production comprise the energy spent heating and mixing the aggregates. Altogether, these modules constitute the production stage, which is also referred to as cradle-to-gate. The impacts of the transportation of the materials used for wearing, binder, base and subbase courses to the construction site are included in module (A4). The environmental loadings for ground investigation (Zhang et al., 2010), demolition and site clearance (Chong and Wang, 2017; Krantz et al., 2017), excavation (Kim et al., 2012) and machinery or other processes required to build the road (Giani et al., 2015) are contained in module (A5).

The impacts related to the use of the road are considered in stages (B1-B6). Module (B1) refers to the processes of carbonization (Yu et al., 2013), leachate (Vidal et al., 2013), brake lining (Chen et al., 2016), tire abrasion (Verán-Leigh et al., 2019) and albedo (Yu et al., 2013). Module (B2) pertains to the impacts of road maintenance, such as road cleaning (i.e., dust or snow), traffic signals or lighting. The environmental impacts due to the repair of the joints (Umer et al., 2017) and pavement areas exhibiting cracks and minor damage (Choi, 2019) are included in module (B3). Module (B4) refers to the impacts of the replacement of the wearing course (Celauro et al., 2017), lighting, traffic signals, street finishing, cables or pipe networks (Keijzer et al., 2015; Trigaux et al., 2017). Road refurbishment is considered in module (B5). Refurbishment operations are necessary when road courses undergo substantial deterioration (Santos et al., 2015; Yang et al., 2018). Module (B6) includes the impacts associated with the electricity used from road components, such as traffic signals or lighting (Alzard et al., 2019) and the fuel consumed from vehicles (Santos et al., 2018; Xu et al., 2019).

The environmental impacts related to the EoL stage for pavement dismantling, transport to the processing plant, waste processing and elimination (i.e., landfill) are included in modules (C1), (C2), (C3) and (C4), respectively. If some materials are not eliminated but are recycled or reused in consecutive road use cycles, then the benefits are counted in module (D), i.e., the reuse of asphalt as recycled asphalt pavement (Farina et al., 2017; Gulotta et al., 2019).

4.2.2. Data uniformization

For the meta-analysis of the environmental impacts of the road case studies, the values of the indicators need to be harmonized based on a common reference unit. This can enable a comparison of the road scenarios investigated in different scientific papers. Only the absolute values of the GWP indicator are considered for in-depth analysis. In this regard, the reference unit kg-$CO_2e/m^2/yr$ is adopted in this study as expressed by the following equation:

$$GWP_n = \frac{GWP}{S \cdot RSL} \qquad (1)$$

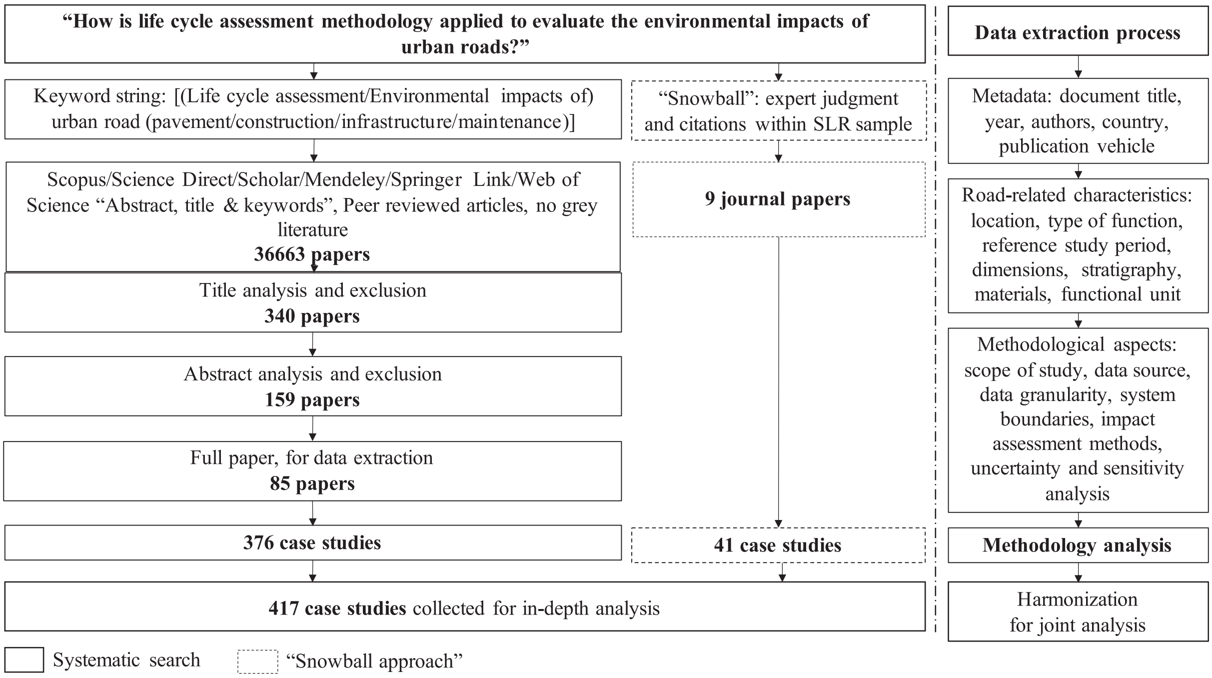
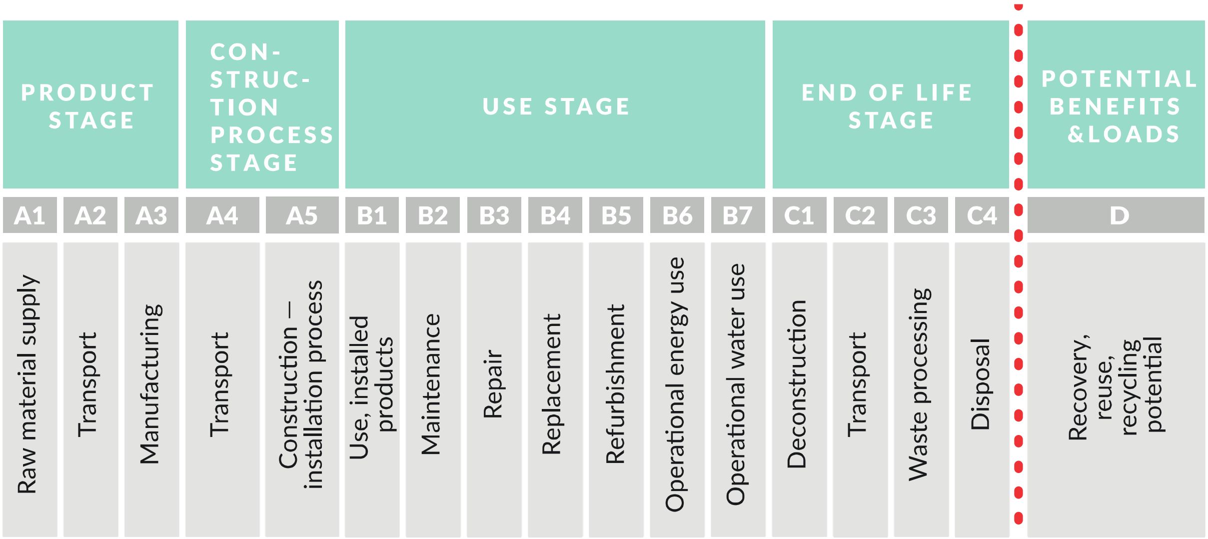


Fig. 1. Method for the literature search.



PRODUCT STAGE			CONSTRUCTION PROCESS STAGE		USE STAGE							END OF LIFE STAGE				POTENTIAL BENEFITS &LOADS
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Raw material supply	Transport	Manufacturing	Transport	Construction – installation process	Use, installed products	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction	Transport	Waste processing	Disposal	Recovery, reuse, recycling potential

Fig. 2. Life cycle modules according to the EN-17472 (2020) and EN-15804 (2019) standards.

where *GWP* presents the value of the global warming potential indicator (GWP), *S* represents the area or road, *RSL* is the reference service life, and GWP_n displays the normalized value of the GWP indicator.

However, the harmonization procedure shows discrepancies regarding the information available in the examined articles. For this reason, some hypotheses about the width of the road and its service life are considered. If the width of the road lane was missing, an average value calculated from other sources was speculated (see Section 5.2.2); the same procedure was followed if the information regarding the reference service life was missing (see Section 5.2.4).

5. Results

The publication of papers on road infrastructure projects has been steadily increasing. The largest share of the papers selected for data extraction, more than 65%, were published in the last 5 years. The spike in interest may be related to the requirements regarding road infrastructure for more resources embedded in the construction processes by 2050 (Raposo et al., 2019) which will consequently increase emissions. For this reason, the scientific work dealing with the minimization of impacts has undergone continuous improvement (Gulotta et al., 2019; Xu et al., 2019; Bressi et al., 2019; Gámez-García et al., 2019). The emphasis and guidelines from road authorities on both the documentation and goals of reducing GHG emissions enhance these effects (Keijzer et al., 2015). A full list of the papers considered for in depth data analysis are presented in the supplementay data.

5.1. Life cycle assessment methodology

Goals to reduce the environmental impacts of road infrastructure projects are difficult to set without a knowledge of the current level of emissions. The setting of goals and evaluation of new methods, technologies, and processes demand comparability among the options. The examination revealed that almost all the studies (98%) specified the location of the road considered. This information implicitly links to the code or standard used to design the road in compliance with national safety and quality requirements. The road typology and design parameters are the information used for defining cross-sectional feasibility, the components and their dimensions, and the quantity and quality of the material employed. Information on typology is provided in 70% of the reviewed papers, but there is a lack of consensus on the common definitions of roads. An urban road in China or the USA can be comparable with a highway in Europe. For this reason, the identification of urban road case studies was not possible, and in the meta-analysis, all road typologies were considered. Among the design parameters analysed, information on the climate zone is provided in 9.5% of the studies, soil support in 2%, speed limit in 11%, and average annual daily traffic in 42%. The lack not only of a common classification of road typologies but also of the transparency of the design parameters constitutes the first barrier preventing a robust ´apple to apple´ comparison of the studies. Furthermore, the evidence calls for further research on the calculation of the influence of design parameters on the quality and quantity of materials employed in road components and their courses and consequently, on the environmental impacts.

Regarding LCA methodology, ISO-14040 (2006) and ISO-14044 (2006) are the standard most commonly used for the calculation of road impacts, but other norms, such as EN-15804 (2019), ILCD (2010), and NEN-8006 (2004) were followed. Only 3 studies adopted the input/output approach, and 5 studies followed the hybrid approach. These approaches, which are generally used in the absence of information containing unit process data, are adopted for the calculation of the impacts of the cases situated in USA. However, the most significant result is that in 44% of the studies, the authors did not explicitly indicate the standard that they followed to assess the impacts. They mostly considered a simplified LCA methodology. The impacts were calculated as a multiplication of the quantities of materials by their respective global warming impact score. The simplified model applied previously in the building sector can lead to significant error of up to 20% (Kellenberger and Althaus, 2009). In the case of road projects, the degree of error associated with simplified methods is still unknown, and further studies are required. Furthermore, regarding the reproducibility of the results, only 37% (35 papers) presented fully transparent data among which 18 papers did not specify the standard or norm followed. Although the results of these studies can be fully reproducible, as mentioned above, their reliability is questioned. Finally, only 18% (17 papers) can be considered to be fully transparent and reproducible with reliable results. Based on this analysis and the results shown in Fig. 3, it is possible to conclude that the specification of the method can clarify the logic behind the calculation of the impacts and facilitate a standard presentation and interpretation of the results. However, the non-reproducibility of the results can also be due to a variety of other reasons, i.e., missing specifications regarding the FU, database, and inventory. By following the procedures of an LCA according to ISO-14040 (2006) and ISO-14044 (2006), the next sections highlight how the reviewed studies addressed road design parameters and LCA features.

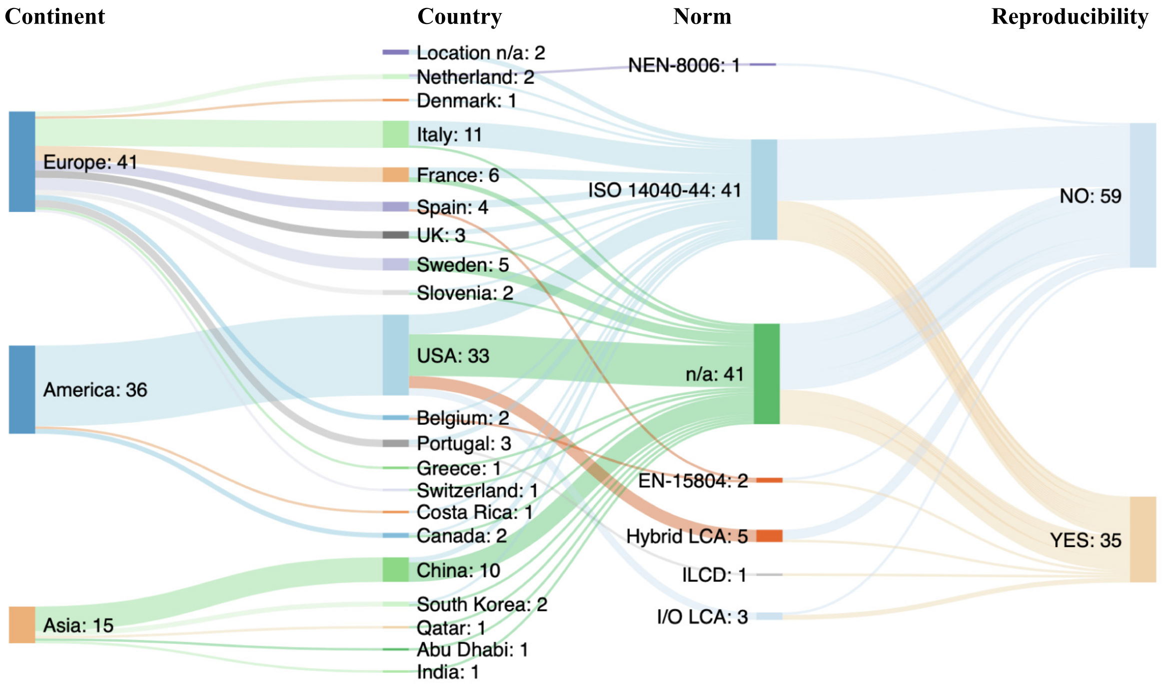


Fig. 3. Meta-analysis on the LCA methodology, reproducibility of the results and source of studies (continent; country; methodology; reproducibility of the results).

5.2. Goal and scope

The goal and scope of an LCA study is the basis for analysis and possible comparison with other investigations. In this non-technical stage of LCA, it is necessary to reflect on the intended objective of the study, a clear description of the products and their functionality, the FU, the reference study period, and the system boundary. The construction of this phase must be very clear because the final results depend on this step.

5.2.1. Goal of the study

The goal of the study describes the intended objective of the analysis, and it is especially important for the comparison and use of the results. For road LCA, the goal explains whether the study focuses on a new road stretch, whether the pavement type is rigid or flexible and whether the study seeks to identify emission hotspots, to understand the system, or to compare the environmental performance of the pavement. Based on the analysis of the data provided in the reviewed literature, slightly more than 50% of the studies aimed to develop a new solution for the reduction of impacts, while 49% performed a hotspot analysis for existing roads. Moreover, new materials or construction methods were commonly analysed, either to compare with traditional materials or methods or to identify and document emission hotspots. Understanding the different goals is therefore essential to be able to use the results correctly for improvement in other road construction projects. Information on pavement typology, shown in Table 2, is provided in 97.1% of the studies. This can be considered the most complete data provided in the reviewed papers and is therefore used to compare the environmental impacts of road cases. The data in Table 2 show that 74% of the articles analysed new road stretches, 24% focused on rehabilitation projects and 2% did not specify this contextual information. The majority of the studies (76.5%) analysed flexible pavement, which is the most common type of pavement used globally, while rigid pavement was analysed in 22% of the studies, and 1.5% did not state the pavement type. The data indicate a lack of studies analysing the rehabilitation of rigid pavement and identify a need for future research in this direction.

Table 2
Data on pavement typologies.

Pavement typology	Flexible	Rigid	n/a
New	52.8%	20.6%	1.0%
Rehabilitation	22.3%	1.4%	0.0%
Not specified	1.4%	0.0%	0.5%

5.2.2. Scope of the study

The scope of the system under study should include a description of the project, its functionality, the FU, and the system boundaries. Scope in this context differs significantly from that in product-specific studies, as roads can be disaggregated into many different components. A road can apply to only the motor lanes, either including or excluding the base, but it can also apply to electric installation, bicycle lanes, footways, or even the surrounding vegetation. For a comparison of road LCA studies, the inclusion or exclusion of each component needs to be described. Table 3 shows the percentage of the information provided to describe the road components. Although the total width of the road is provided in 69% of the cases, the dimensions of its components are missing in almost all of the studies. The most commonly available information is the width of the motor lanes, which is provided in 33% of the cases, and the least commonly available information concerns the berm, which is provided in 1%. Given the limited information and the high variability of road width components, the functional configuration of road cross-sections becomes unpredictable. Previous studies have shown that different functional configurations are possible for the same road width. By comparing several configurations, Gámez-García et al. (2019) found a difference of 30% in terms of the environmental impacts for the same road width. Another unexpected result of this analysis is the failure to obtain the course thicknesses. Information for the wearing course is provided in 82% of the cases, the binder in 31%, the base in 42% and the subbase in 28%. The limited cross-sectional dimensions available constitute a significant weakness for the reproducibility and comparison of road case studies. A failure to fully describe the road cross-section can be because of the authors' negligence or the non-consideration of secondary road components in the overall impacts under the assumption that their contribution is insignificant. However, for a better understanding of the environmental impacts of road

Table 3
Data on the scope of the reviewed papers.

Road properties	Available information about parameters	Details for available information			
		Min	Mean	Max	Unit
Speed limit	11%	50	95	120	km/h
Average annual daily traffic	42%	200	22372	70864	Unit
Length of road	81%	0,05	3,07	62	m
Total width of road	69%	2,5	12,7	40	m
Number of motor lanes	77%	1	3,1	9	Unit
Width of motor lanes	33%	3	3,55	4	m
Internal shoulder	11%	1	2,2	4,8	m
External shoulder	15%	0,2	2,2	3,65	m
Isolated belts	5%	0,75	1,3	2	m
Bicycle lanes	1%	2,35			m
Footways	5%	1,5	2,17	2,5	m
Berm	1%	1			m
Foreslope	4%	0,75	1,46	2,1	m
Depth of the lanes	72%	1,63	371	1660	mm
Wearing course	82%	2	111	356	mm
Binder course	31%	25	116	280	mm
Base	42%	15	212	1178	mm
Subbase	28%	100	226	929	mm

components, it is necessary in future research to identify the contribution of these aspects to the overall results.

Furthermore, the design parameters of the speed limit, carrying capacity, average annual daily traffic (AADT), and share of heavy-duty vehicles affect the repair and rehabilitation interval (Huang, 2004). These information are specified in only a few studies but has a substantial effect on the life cycle emissions of the road stretch. In addition, these studies are seldom included in the reviewed studies. However, a reduced need for repair and rehabilitation can significantly affect the overall emissions from a road stretch, and this information is therefore important to include (Birgisdottir et al., 2006). This analysis calls for further research on the calculation of the influence of the design parameters on repair, rehabilitation and replacement processes and consequently, on the environmental impacts of roads.

The depth and quality of the subbase and base can affect the need for the total rehabilitation of the road (Loizos et al., 2017; Barbieri et al., 2017). A stronger base that might need less repair and rehabilitation is likely to be more energy and emission intense during the construction phase (Torres-Machi et al., 2017). Detailed data on the thickness of road courses and the types of material employed are shown in Fig. 4. As previously indicated, most studies report the thickness of the wearing course, while only the studies that focus on aggregates report the subbase thickness. The wearing course represents the layer where the largest variety of material is tested. However, the lack of a clear description of the type of material used for the road layer should be identified. Some studies did not specify whether the HMA or WMA was modified or unmodified. In some studies, this issue is more important since they specified whether the asphalt was modified or unmodified but not whether it was HMA or WMA.

Some studies specified only whether the layers were flexible or rigid but did not provide specifications about the type of materials employed. The lack of information on the type of materials employed in road courses presents an additional barrier to reproducibility and consequently prevents a robust comparison of projects. The failure to specify materials is also observed in the studies that consider binder and base courses. Although several studies aim to develop and propose new solutions with lower impacts, the lack of material specifications makes them useless since they cannot be applied in future projects. Based on the results, we can conclude that the cross-sectional dimensions of the road and the materials specification must be detailed in the scope of the study. A lack of this information limits the comparability of the LCA results across studies, and therefore, their practical utility is questioned.

5.2.3. Functional unit

The functional unit (FU) is the basis for any LCA study and for comparability between projects. A vague definition of the FU can yield inaccurate results, and solutions with lower environmental impacts are therefore not identified (Weidema et al., 2004). Mao et al. (2017) compared the environmental impacts of 5 road typologies based on two FUs and show the influence of the FU on the identification of solutions with lower impacts. Considering 1 km as the FU, they found that an expressway had the highest environmental impacts. However, for an FU of 1m^2, this road typology presented the best solution. Fig. 5 shows the variety of FUs provided in the reviewed articles, with 1 km being the most commonly used. The studies adopting 1 km as the FU presented the FU as a 1 km snapshot of the system (25%), a 1 km/year (4%) or 1 km throughout the service life (17%). The results are also commonly presented for an entire road (17%), while FUs based on 1 m of the linear or areal portion of a road are less common (2.5%). Approximately 10% of the studies used the FU of the whole road stretch for the entire service life. The need for future research on the influence of the definition of the FU on the environmental impacts of roads should be emphasized. According to the Product Environmental Footprint guideline (Manfredi et al., 2012), a well-defined FU must answer to the questions: what, how much, how long and how well. Answering these questions can aid in sorting the information needed to increase the transparency of a study and guide the selection of the FU.

In the case of a road, the first question is linked to its dimensions. In general, the cross-section of a road changes with its length. A single road may consist of different widths, functionalities, components configurations or materials. The fact that the cross-section of a road changes with the length of the entire road must be considered as the first parameter of the FU definition.

The second question is linked to the definition of road configuration, its components and their dimensions. This aspect is missing in all of the FUs provided in the reviewed papers. As previously indicated, the same road dimension can have different functional configurations. Therefore, the specification of the number and width of lanes, internal or external shoulders, and other components of the road is necessary.

The reference study period of the road is the next parameter to be defined in the FU. This parameter is provided in almost all of the reviewed papers, but as will be shown later, its values vary significantly across studies. The last parameters describing the road quality are considered in a limited number of cases. Less than 5% of the studies described in the FU the AADT and the soil properties for which the road was designed, but other parameters, such climate or average slope, are missing. Although the definitions of these parameters are useful for a robust definition of the FU, they are insufficient since a road is composed of several components that are not necessarily linked to each other. For simplification reasons and project comparison, few studies offered the definition of the FU for each component of the road. This type of FU should be defined in a way that enables stakeholders to easily sum the impacts of all road components and obtain the full LCA of the road. This method would also work the other way, where the impacts of the road can be easily decomposed by component. In this way, part of the road can be compared from one study to another, and the entire road can be compared with cases examined by other authors.

5.2.4. Reference service life

The data collected from an in-depth analysis of the reviewed papers for both flexible and rigid pavement regarding the processes of repair, replacement, and rehabilitation are presented in Fig. 6. These parameters are crucial for a suitable definition of the FU since they strongly influence the environmental impacts. These data show that the repair of flexible roads is scheduled within 3–16 years of the road lifetime with an average value of 9 years. During the rehabilitation process, only part of the wearing course is repaired, which ranges between 20 and 60% of the total road surface. The next process is the full replacement (100%) of the wearing course. This can occur within 4–30 years, with

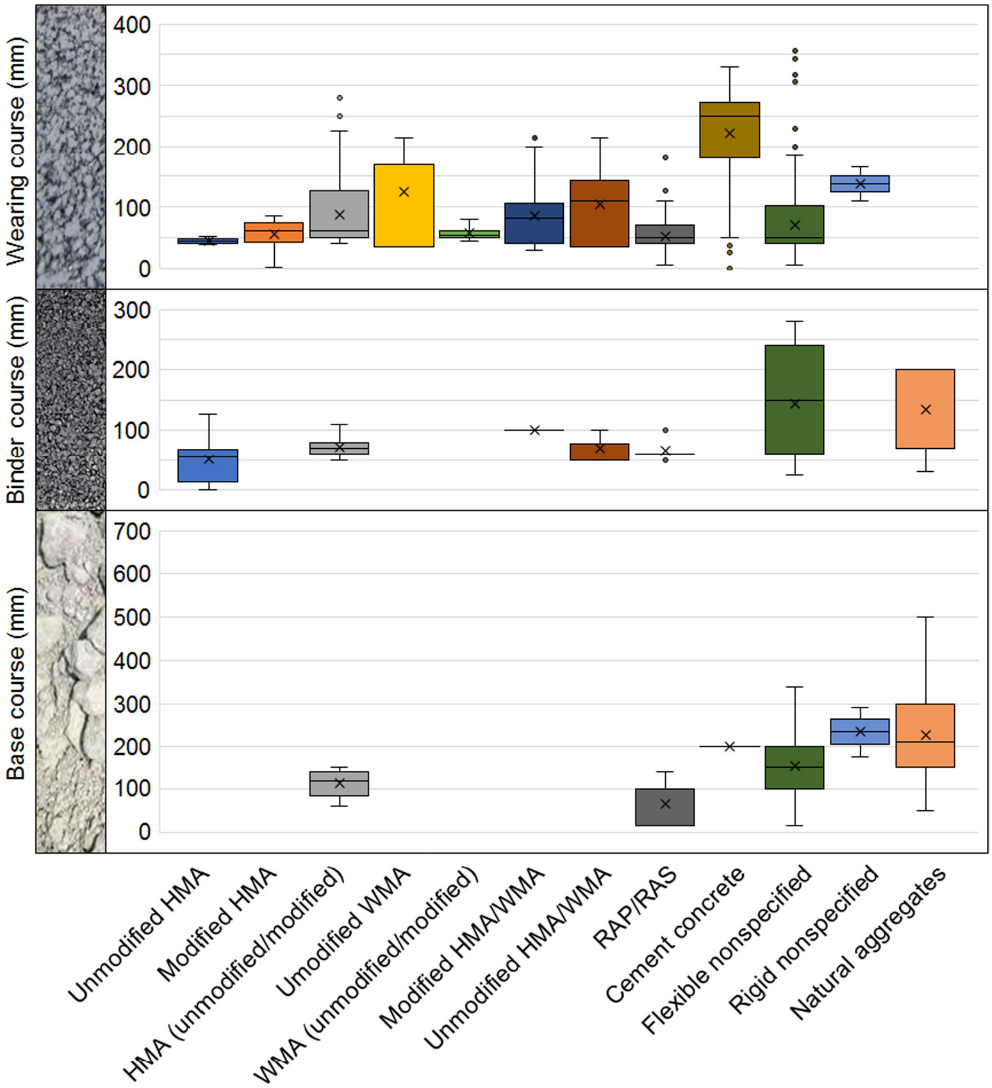


Fig. 4. Data of the materials used for the wearing, binder and base courses.

an average value of 12 years. The rehabilitation of roads with flexible pavement can occur within 10–50 years, with an average value of 29 years.

Due to its different construction technology, rigid pavement is subject to only repair and rehabilitation. The processes of replacement and refurbishment are the same and occur simultaneously. During the repair that is scheduled within 8–41 years (with an average of 19 years), only 1–5% of the road surface is repaired, considering joint resealing. The full rehabilitation of rigid pavement occurs within 15–40 years, with an average value of 33 years.

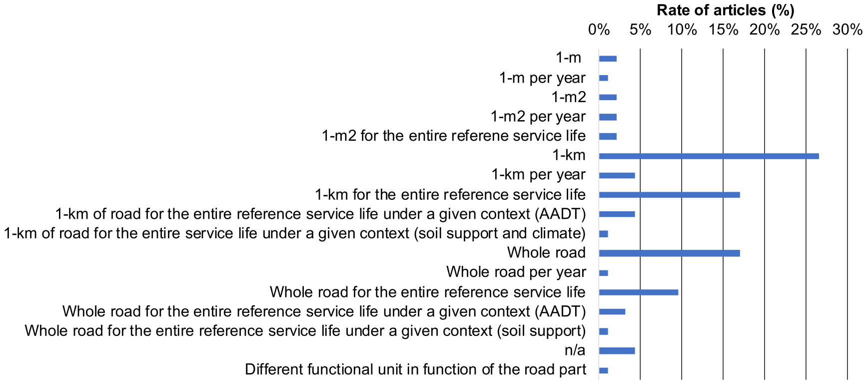


Fig. 5. Meta-analysis of functional units.

These values show that the scenarios for the repair, replacement, and rehabilitation of flexible or rigid pavement vary significantly across studies and are influenced by parameters such as the AADT, weather, soil properties, or road maintenance (Huang, 2004). As demonstrated above, these parameters are poorly described in several studies and their arbitrary definition may lead to solutions that do not necessarily have a lower impact. To overcome this issue, repair and rehabilitation should be supported by norms/standards for a more uniformized scenario for flexible and rigid pavement. In addition, homogenized scenarios are required when new asphalt technologies are proposed for lowering the environmental impacts of the road structure. Since new technologies are not tested in practice, it is difficult to predict their durability.

Based on the meta-analysis of the reference service life presented in Fig. 6, a recommended maintenance schedule is offered. For flexible pavement, the following maintenance schedule is suggested to estimate the effect of maintenance in LCA studies of roads:

Year 9: the repair of approximately 20% of the wearing course.

Year 12: the total replacement of the wearing course,
Year 21: the second repair of 60% of the wearing course,
Year 24: the next replacement of the wearing course, and finally.
Year 33: the total rehabilitation of the road.

Since rehabilitation corresponds to the replacement of all courses, it can be considered to be the reference service life of the road.

For rigid pavement, the following schedule is recommended:

Year 19: the repair of 5% of the wearing course,

Year 33: rehabilitation, which corresponds to the reference service life of the road.

Homogenizing the maintenance scenarios for both flexible and rigid roads, and considering the same reference service life allow a fairer comparison of case studies. In addition, for both road types, the processes of repair and rehabilitation are included at least once.

5.2.5. System boundary

The method followed in the analysis was not always specified; therefore, the system boundaries of the analysed studies varied for both flexible and rigid pavement. By examing the results for flexible pavement in Fig. 7, it is clear that most of the studies focused on the motor lanes, and these mostly included the product stage (97%) and the construction process (58%) stage. In a more limited number of studies (37%), the use stage was included through repair and rehabilitation measures. Finally, over 30% of the studies included the EoL stage for the motor lanes.

The results for the other components show that the inclusion of the different stages in the system boundary of the studies is lacking, although they involve large amounts of materials and can consequently present significant impacts. Furthermore, the underground electricity and water pipeline networks are poorly considered in the system boundary. Due to their lower lifetimes than road layers (Trigaux et al., 2017), the repair, renovation or rehabilitation of electricity or pipeline networks will involve in additional road repairs. Assessments of the impact of motor lanes without considering their correlation with other road components has a significant influence on LCA results. The analysis of the results shows the availability of data and the possibility of including all road components in the system boundary, but all studies fail to present a complete evaluation. This evidence calls for future studies to expand the system boundary to include all components in the analysis of the environmental impacts of roads.

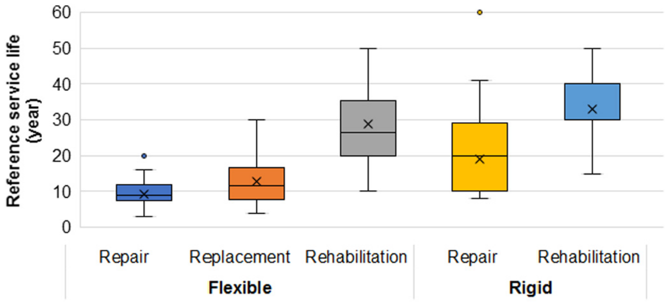


Fig. 6. Meta-analysis of the reference service life for the repair, replacement and refurbishment of flexible pavement.

Considering the results in Fig. 8, for rigid pavement, the studies seem to be more coherent with the EN-15804 (2019) standard, as a higher share of the studies generally follows the system boundary method presented there. It is also common to include EoL scenarios, but thist might be because concrete recycling has been traditionally used and because it is easy to dismantle into components. Motor lanes are also the main aspect investigated in the studies focusing on rigid pavement. However, a considerable share of the studies included shoulders (20%), non-motorized lanes (15%), and footways (15%). The clear difference in the inclusion of components between the studies on flexible and rigid pavements may be due to regional differences in how LCA practitioners define roads. Rigid pavement is more common in the USA, India, and China, where roads have heavier traffic loads, while Europe traditionally has flexible pavement, as its roads have lighter traffic (Mohod and Kadam, 2016). Even in the case of rigid pavement, none of the studies considered all of the road components in the system boundary.

The arbitrary inclusion and exclusion of road components in the system boundary decreases the reliability of the calculated results. To make a comparison of studies possible, the transparency of the components included in the system boundary requires attention.

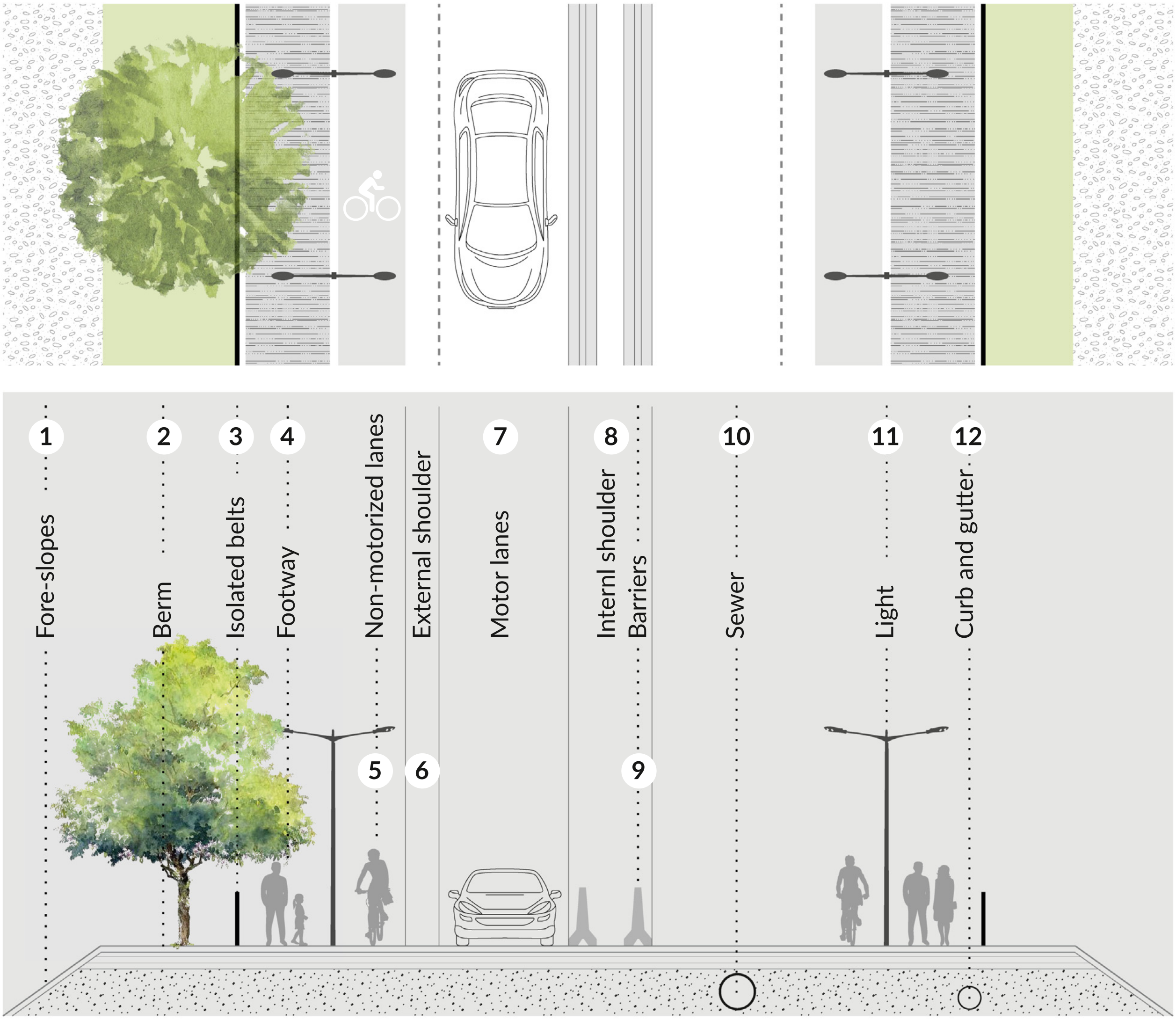
5.3. Inventory

The choice of inventory database can have a considerable impact on the results of an LCA study. Several databases are area-specific and should be chosen accordingly. The most common inventory databases used in the LCA studies on road infrastructure are Ecoinvent and Gabi, which are specified in 25% and 5% of the studies, respectively (Fig. 9). Both inventory databases contain global and regional specific datasets and can therefore be used internationally. In the studies reviewed, the use of input-output datasets was common or specified in 22% of the studies. However, the largest share of the studies did not specify the inventory database used in the research, and this was directly linked to study reproducibility. Previous studies in the building sectors have revealed differences of up to 26% in the value of the GWP among the life cycle inventory (LCI) databases (Lasvaux et al., 2015; Passer et al., 2015). Furthermore, the completeness, scope of the database and actuality represent additional criticisms (Martínez-Rocamora et al., 2016). For the environmental impacts of the asphalt itself, several studies considered only the environmental impacts of material extraction and neglected the impacts of asphalt production (Zhang et al., 2010; White et al., 2010; Tatari et al., 2012; Shi et al., 2019). However, the environmental impacts of the production stage can present approximately 50% of the total asphalt impact (Bressi et al., 2019). The temporal correlation of the database is provided in 5% of the studies but has a significant influence on the uncertainties of the environmental impacts of products (Ciroth et al., 2016).

Based on these criticisms, future research is required to calculate the gap between the limited impacts of asphalt technologies provided in the reviewed papers and the impacts found in a complete calculation.

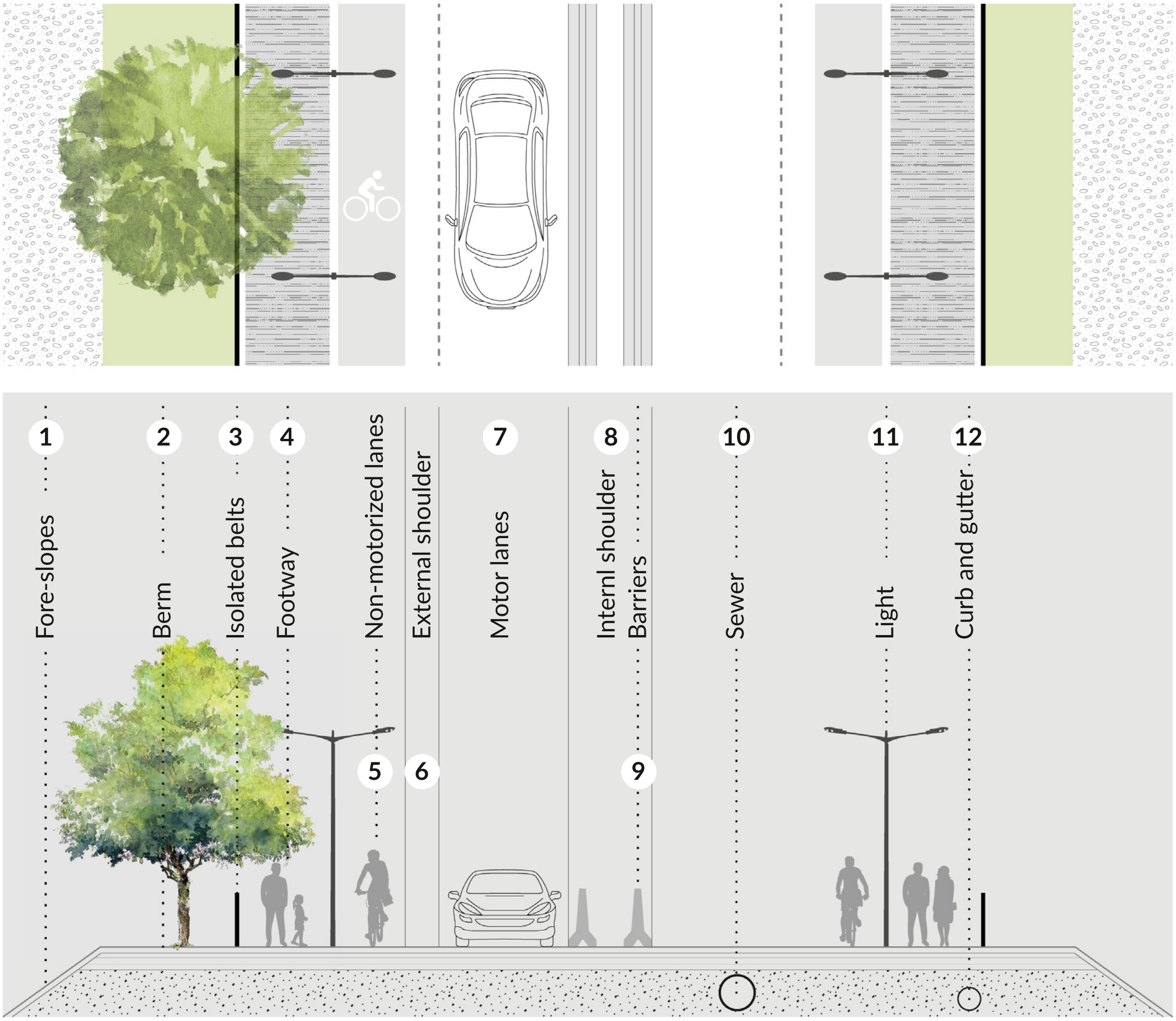
5.4. Impact assessment

Another LCA feature of the studies that are not reproducible is the lack of specification of the impact assessment methodology. By analysing different indicators, Cherubini et al. (2018) found differences of up to 44% among the values of the same environmental indicator



	Road components	1	2	3	4	5	6	7	8	9	10	11	12
Rate of scenarios considering life cycle stages in the system boundaries (%)	A1	7	1	4	5	6	18	97	9	2	2	4	1
	A2	7	1	4	5	6	18	97	9	2	2	4	1
	A3	7	1	4	5	6	18	94	9	2	2	4	1
	A4	6	1	-	4	5	16	58	6	1	2	1	1
	A5	7	1	-	4	5	14	53	4	1	2	1	1
	B1	-	-	1	-	-	-	5	-	-	-	-	-
	B2	-	-	-	-	-	1	3	-	-	-	1	-
	B3	-	1	-	-	1	9	32	3	-	-	-	-
	B4	-	-	-	-	-	10	37	8	-	-	1	-
	B5	1	-	-	1	2	3	21	2	-	1	-	-
	B6	-	-	-	-	-	1	24	1	-	-	2	-
	C1	-	-	-	1	1	9	36	2	1	-	1	-
	C2	-	-	-	1	1	12	34	5	1	-	1	-
	C3	-	-	-	1	1	9	31	2	1	-	1	-
	C4	-	-	-	1	1	12	34	5	1	-	1	-

Fig. 7. Meta-analysis of the system boundary of a new road with flexible wearing course (n=24) according to the EN-17472 (2020) and EN-15804 (2019) standards.



Rate of scenarios considering life cycle stages in the system boundaries (%)	Road components	1	2	3	4	5	6	7	8	9	10	11	12
	A1	1	2	10	15	15	20	100	15	5	5	5	5
	A2	-	1	10	15	15	19	99	14	5	5	5	5
	A3	-	1	10	15	15	19	99	14	5	5	5	5
	A4	-	1	-	10	10	16	67	12	-	-	-	-
	A5	-	1	-	10	1	9	59	3	-	-	-	-
	B1	-	-	-	-	-	-	13	-	-	-	-	-
	B2	-	-	-	-	-	-	-	-	-	-	-	-
	B3	-	-	-	5	5	12	44	10	-	-	-	-
	B4	-	1	-	-	-	13	26	12	-	-	-	-
	B5	-	1	-	5	5	2	16	2	-	-	-	-
	B6	-	-	-	-	-	-	34	-	-	-	-	-
	C1	-	-	-	5	5	2	30	2	5	5	5	5
	C2	-	-	-	5	5	12	40	12	5	5	5	5
	C3	-	-	-	5	5	2	31	2	5	5	5	5
	C4	-	-	-	5	5	12	38	12	5	5	5	5

Fig. 8. Meta-analysis of the system boundary of a new road with rigid wearing course (n=86) according to the EN-17472 (2020) and EN-15978 (2011).

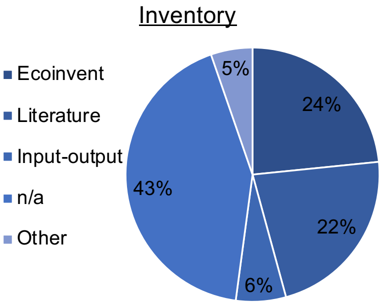


Fig. 9. Meta-analysis on the life cycle inventory.

calculated with different impact assessment methods. In 17% of the reviewed papers, the most commonly used methods are IPCC, CML, and ReCipe. However, the most unexpected result is the lack of information in 78% of the case studies, which makes the results unproducible and their comparison with other projects impossible. The software used for the analysis should in theory not have an effect on the results or the comparability of the studies, as different software can contain the same databases and impact methods, but in reality, the type of software can influence the results. Most of the studies used global warming (98%) as the main environmental indicator (Fig. 10) or the only indicator. Other important indicators were the cumulative energy demand (CED) (38%) and human toxicity (25%). Of course, the goal of each study significantly influences the choice of indicators, but in most LCA software more indicators are readily available. It is therefore recommended to expand the results and include more indicators such as PM emissions, human toxicity, eco-toxicity, and particles. Presenting these indicators in addition to global warming can increase the general awareness in scientific communities and strengthen the possibility for comparisons with future projects to track development.

5.5. Interpretation of the global warming potential

As one of the most relevant indicators under the scrutiny of public policies, GWP was considered in almost all the reviewed studies. The results of this indicator are presented in Fig. 11 for new and rehabilitated roads with rigid and flexible pavement. For new flexible pavement, several outliers are identified, and their values vary between 14 and 92 kg-CO$_2$e/m2/yr. Various reasons can be linked to the presence of outliers, but the analysis of studies (Alzard et al., 2019; Xu et al., 2019; Mao et al., 2017; Pasetto et al., 2017; Condurat, 2017; Bloom et al., 2016) with high environmental impacts of roads pinpoints the lack of information on the life cycle inventory. Although the influence of outliers is mitigated, the significant difference between the average (4.6 kg-CO$_2$e/m2/yr) and median (2.6 kg-CO2e/m2/yr) shows an asymmetrical distribution of impacts. The median indicates the possibility of developing road projects with impacts lower than 2.6 kg-CO2e/m2/yr. In the case of the rehabilitation of flexible pavement, only one outlier equal to 26 kg-CO2e/m2/yr is identified. The values are asymmetrically distributed since the average, which is equal to 4.7 kg-CO2e/m2/yr, significantly differs from the median, which is equal to 1.2 kg-CO2e/m2/yr. The median value shows the possibility of developing a rehabilitation solution for flexible pavement with impacts lower than the impacts of new roads. For new rigid pavement, few outliers are identified that vary from 20 to 135 kg-CO2e/m2/yr, and their presence is linked to the lack of information on the inventory used to assess the impacts (Mao et al., 2017). The values of the average (4.6 kg-CO2e/m2/yr) and the median (4.2 kg-CO2e/m2/yr) are slightly different from one another, which creates symmetric distribution of the impacts. The cases that assess the environmental impacts of the rehabilitation of rigid pavement are limited.

By comparing the average values, we can observe that the impacts of rigid pavement are 2% higher than impacts of flexible pavement, while the median is 165% higher. The significant differences between these solutions indicate that flexible pavement has lower impacts. However, criticism is warranted regarding the impacts of new and rehabilitation processes for flexible pavement. The average value of the environmental impacts is 3% lower for new cases than for rehabilitation. When comparing the medians, the value is 115% higher for new cases than for rehabilitation. Because of the lack of transparency, large variety, and heterogeneity of the inputs for the road design parameters and LCA features, a robust comparison of the impacts between new and rehabilitated flexible pavement is not possible. Despite these discrepancies, a

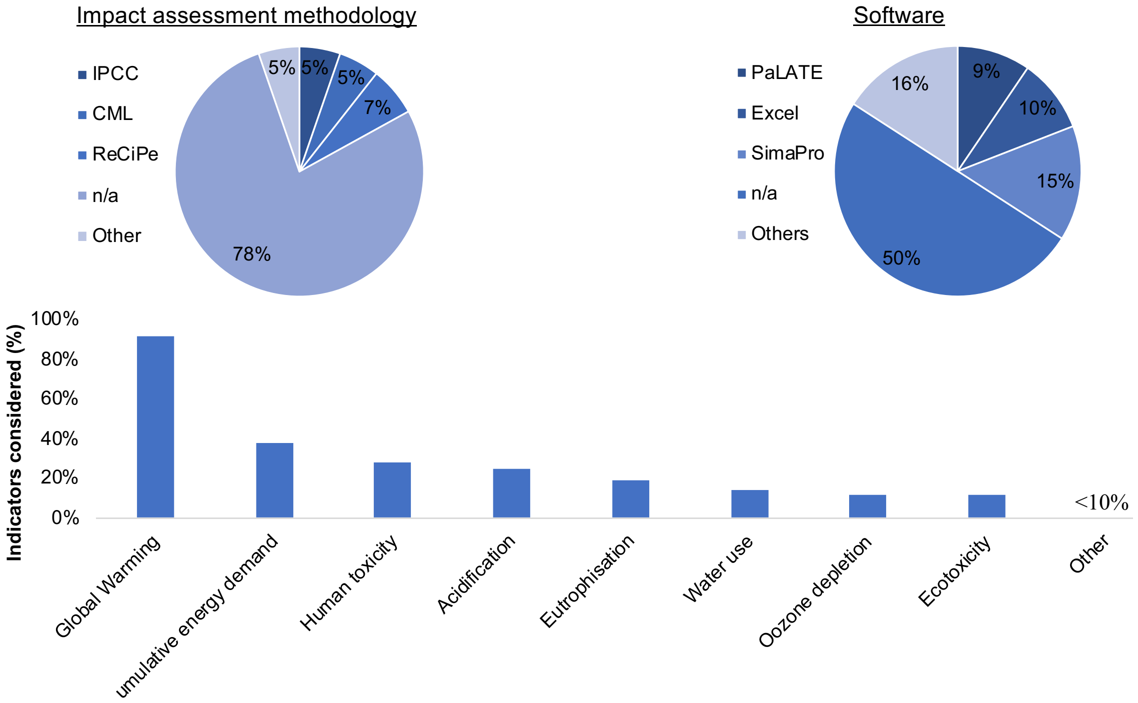


Fig. 10. Meta-analysis on the impact assessment methodology, environmental indicators and software.

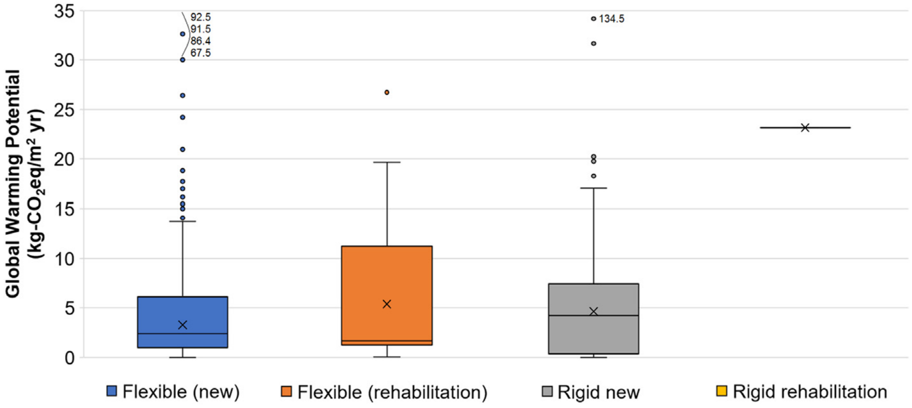


Fig. 11. Meta-analysis of the global warming potential indicator for road construction.

comparison of the median, which show that new pavement has higher impacts than rehabilitation processes, is more realistic. As discussed above in the case of new road projects, the impacts of production and construction processes and the processes of repair, replacement, or rehabilitation are accounted for. Therefore, the impacts of new flexible pavement are expected to be higher than the impacts of rehabilitation. However, a robust comparison with uniform hypotheses and input data is necessary for future research.

5.6. Sensitivity and uncertainty analysis

To increase the reliability of the results calculated and to strengthen the comparison between scenarios, an LCA analysis should include an uncertainty and sensitivity analysis (Morgan et al., 1990). According to the EU (2015) definition, an uncertainty analysis calculates the uncertainties of the outputs that are derived from the uncertainties of the inputs. The types of uncertainties in roads are the same as those in other sectors, and can be related to the input data, LCA model, user expertise level, and project design phase. The uncertainties of input data are related to the quantity of material, characterization factors, and service life (Hoxha et al., 2014; Hoxha, 2015). The uncertainty of the model is mostly associated with the impact of allocation (economic, mass or volume) at the production or EoL stage, cut off criteria, dynamic calculation, etc. (Yu et al., 2018; Hoxha et al., 2020; De Wolf et al., 2020). The uncertainties of the user expertise level involve the variability of the hypotheses considered in the assessment of impacts. The uncertainties of the project design phase encompass the various changes that the project undergoes during development to better suits the needs of habitant (Hollberg et al., 2020). In focusing mostly on the uncertainties related to the data, among the reviewed papers, 20% included uncertainty analyses in the assessment of the environmental impacts of roads. Xu et al. (2019) addressed the uncertainties linked to the quantity of vehicle fuel consumption. Huang et al. (2018) and Yu et al. (2018) considered in their analysis the uncertainties connected to the energy required for the production of asphalt material, while Tatari et al. (2012) and Kucukvar and Tatari (2012) examined the uncertainties associated with the quantities of asphalt ingredients. The uncertainties related to characterization factors were treated through a pedigree matrix in the studies of Vidal et al. (2013) and Giani et al. (2015). Furthermore, other studies considered the uncertainties of the reference service life of the maintenance and rehabilitation processes (Mao et al., 2017; Umer et al., 2017). The uncertainties regarding the methodological choice of the EoL allocation of impacts were analysed in the study by Yang et al. (2018). While Yu et al. (2018) addressed the effect of the time effect on the environmental impacts of roads. From these analyses, we observe a lack of studies that consider the full spectrum of uncertainties, which can be a subject for future research.

Concerning the definition of sensitivity analysis offered by the EU (2015), namely, the calculation of the contribution of the inputs to the total uncertainty in analysis outcomes, none of the studies considered this issue, which also make it a potential topic of future research.

6. Conclusion

This paper aimed to present an analysis of the road design parameters and LCA features of the available studies in the scientific literature. A critical overview of the studies in terms of transparency, heterogeneity and the variability of inputs creates the basis for recommendations for the future homogenization of LCA methodology. LCA has been used to compare products or processes with the aim of supporting the decision making process to reduce emissions without shifting the problem to other processes in the life cycle of the product. For road projects, this has been difficult to accomplish without conducting an extensive LCA. The process is time and resource consuming, and the sector would benefit from the comparability of past and future assessments to support the general reduction of emissions throughout the decision-making process. LCA is perceived as a standardized method, but, as the results show, this is not the case for roads.

6.1. Key findings

Overall, the results of the analysis of the studies selected for this review are that 82% of the studies are not sufficiently transparent, and the choices made regarding the road design parameters and LCA features lead to problems that complicate the comparison among different choices. This especially applies to the parameters of the ADDT, speed limit, location, weather conditions, soil support, average slope, FU, system boundary, data inventory, and method used for the analysis. Transparency and reproducibility are first dependent on the methodological choices. The studies indicate differences between regions, with European studies having higher transparency and being reproducible more often. The goal of the majority of the investigated studies (51%) focused on testing new solutions and materials, while others focused on hotspot analysis. Approximately 74% of the studies analysed new roads, while few focused-on operation and maintenance measures, which are a significant source of emissions, at least for flexible pavement. The reviewed studies varied regarding the scope of the included components. The features chosen were often not specified, and when they were specified, there was high variation. Information on the climate zone of the road was specified in 9.5% of the studies, soil support in 2%, the speed limit in 11%, and the AADT in 42%. The majority of the studies included information on the length of the stretch analysed, the width of the road (69%), and the thickness of the friction course (82%), while the binder (31%), base (42%), and subbase (28%) were poorly described. The most common FUs were 1 km, 1 km for service life, or the entire road project. Among the studies reviewed, over 17 different types of FU were identified. The variation in FU makes it difficult to compare solutions and therefore to select the best solution for emission reduction. The reference service life included the need for operation and maintenance measures and finally rehabilitation. The service life of flexible pavement in the reviewed studies was between 10 and 50 years, with 2 rounds of maintenance activities that have a significant environmental impact. Rigid pavement had a reference service life of 15–40 years, with only repair before total rehabilitation. System boundaries were often limited to the motor lanes for both flexible and rigid pavement. The studies considered limited processes at the production (97%), construction (58%), and EoL (30%) stages in the calculation of the impacts. This causes issues with comparisons between studies and clear statements according to standards. The most commonly used inventory databases were Ecoinvent and Gabi, and the most commonly reported environmental indicator was GWP. However, the largest share of the studies (43%) did not specify the inventory database or the impact assessment (78%) method used. This is the key reason why the results are not reproducible. Considering the influence of the features altogether does not allow a robust comparison of cases and consequently precludes the identification of the solutions with lower environmental impacts.

6.2. Recommendations

To guide the road infrastructure sector towards more sustainable choices, it is essential to increase the transparency and, thus, the reproducibility of the results. The ability to compare the results of different technological and material choices will enable road owners to reduce emissions throughout the lifetime of the road by providing accurate and usable information. We suggest that increased transparency can be achieved by providing/requesting a few essential parameters, such as a clear description of the road components linked to the FU and its aspects, the inventory database, and the impact assessment methodology.

The scope of the study must include a clear description of the dimensions of the entire road and its components. All information can be described in a figure of a road cross-section that contains the width and thickness of the road components and layers. The elements of barriers, pipes, or lighting systems that require more descriptive details can be specified in an additional figure. In the cases where the road has different cross-sections along its length, the cross-sections must be specified. Together with the cross-section, the design parameters for which the road and its components were designed must be specified. This method of description allows the road to be easily decomposed at the component or material level. Then, following the decomposition logic, an FU must be defined for each road component, and together, these should be correlated to the global FU of the entire road. The next step is the creation of subsystem boundaries, whose sum composes the system boundary of the road. The inventory data must be sufficiently precise to allow a clear link between the material flow of each road component and the associated global warming scores. In the end, the impact assessment method should be provided, and the environmental impacts for the indicators of the GWP, CED, particles, etc. of the road should be presented for the components and the road itself. This approach would allow a comparison among different road types and projects through the correct selection of the components. Furthermore, the results of this literature review demonstrate that analysing and presenting the impacts on a component-based FU is crucial to contribute to increased transparency and, more importantly, the usability of the results. We believe that the provision of this information would not affect the length of the papers published.

The possibility of comparison not only is important for LCA practitioners and individual projects but also can better guide the road construction sector towards lower emissions by assisting in the selection of materials and processes. The sector needs to follow a common direction to achieve the current ambitions of a 50% reduction in GHG emissions by 2050.

6.3. Future research challenges

The results of this SLR show different knowledge gaps that require further development. The road design parameters are poorly described in the goal and scope phase, but the thickness of road courses and consequently, the quantity and quality of the material employed are a function of these parameters. The first research challenge concerns the calculation of the influence of design parameters on the environmental impacts of roads for both flexible and rigid pavement. The results show a lack of studies that analyse the rehabilitation of rigid pavement. The reliability of the results presents another interesting research topic, which the studies fail to address in uncertainty analysis. Most of the studies use a simplified LCA approach, and consequently, the results present uncertainties. The calculation of the degree of uncertainties in the case of the simplified model is a subject that require further development. The analysis of the papers identified 18 FUs used in different studies. The calculation of the influence of these FUs on the LCA results provides another interesting research direction. Most studies limit the system boundary to the motor lanes of roads without offering a justification for the exclusion of other components. However, the literature provides all the data for considering these aspects in the calculation of impacts. A complete analysis of the environmental impacts of the road would identify the components with lower impacts that for simplification reasons, can be excluded or considered to be rational in other studies. Finally, none of the studies performed a complete uncertainty analysis of the input data in terms of the quantity of material used, global warming scores, and service life.

Declaration of competing interest

We acknowledge that the submission declaration of “Science of the Total Environment” journal has been complied with. We also confirm that all necessary permissions have been obtained. The authors declare that there is no conflict of interest regarding the publication of this article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.143506.

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