Review of Methodology for Life Cycle Assessment and Life Cycle Cost Analysis of Asphalt Pavements

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Different approaches continue to be used to evaluate the environmental and financial impacts of road pavements throughout their life cycle. This paper aims to provide a methodological review of published studies of asphalt pavement Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA) and make recommendations for future studies. The results indicate that LCA studies limitations are related to functional units (FUs), chosen life cycle phases, maintenance schedules decision, and uncertainty. In comparison, the use of LCCA is limited to assessing maintenance strategies, is largely focused on agency cost, and usually ignores the possibility of current or future uncertainty. Accordingly, it is recommended to incorporate both LCA and LCCA, define a standard set of FUs, include the complete life cycle (including for new materials), consider pavement performance predictions in determining realistic maintenance schedules, include both short- and long-term costs and environmental impacts, and emphasise on probabilistic analysis of uncertainty.

Keywords: Economic analysis, Environmental analysis, Life cycle assessment, Life cycle cost analysis, Asphalt pavement

1. Introduction

The growing acceptance of sustainability principles has encouraged the more efficient use of energy and materials across the world, including in the field of highway engineering. Pavement construction has increased significantly, especially in developing countries, due to ongoing road development to support economic growth (World Bank, 2011). The consequent increase in emissions and environmental impact has led to the requirement for sustainable and economical technology development. Numerous asphalt technologies have been developed to lower the environmental impact of its use, including high recycled contents and warm and cold mix materials (Almeida-costa & Benta, 2016; Aurangzeb, Al-qadi, Ozer, & Yang, 2014; Mazumder, Sriraman, Kim, & Lee, 2016; Mohammad, Asce, Hassan, Asce, & Vallabhu, 2015; Piao, Bueno, Poulikakos, & Hellweg, 2022; Filippo G. Praticò, Giunta, Mistretta, & Gulotta, 2020; Rodríguez-alloza, Malik, Lenzen, & Gallego, 2015; Rubio, Martínez, Baena, & Moreno, 2012).

LCA and LCCA are used to evaluate life cycle environmental impacts and costs of a product or service during its lifetime. However, different methodologies are employed to evaluate the environmental and economic effects of current pavement technologies. Santero et al. (2010) provided a critical literature review for pavement LCA, including recommendations for future research. A review of pavement LCCA has been conducted by Babashamsi et al. (2016) where they highlighted the applicability and shortcomings of LCCA methods and processes. Since then, the number of research studies in this area has increased and methodology has developed. This review aims to re-evaluate the methodological frameworks used in LCA and LCCA studies of asphalt pavement by emphasizing the research developments since these previous two reviews were conducted. Key challenges and research opportunities for LCA and LCCA of asphalt pavement are summarized, and suggestions for improving the robustness and utility of these studies are presented.

2. Life Cycle Assessment

2.1. Application of LCA Framework to Asphalt Mixtures

Pavement LCA is a systematic environmental impact appraisal tool for a product, technique, or service over its lifetime, including for construction products, and has four iterative steps, as presented in Figure 2.1 (ISO, 2006b)The first stage is the definition of the goal of the study (including definition of the product or material) and its scope (including the use of the product or functional unit (FU), and the system boundary including life cycle stages included and analysis period). The second stage is the life inventory (LCI) analysis of inputs (e.g. resources) and emissions (to the environment). The third stage assesses the environmental impact produced by the resource use and emissions found in the inventory, in environmental impact categories, derived from an impact model, as defined in the scope. The last stage is the interpretation to analyze the results.

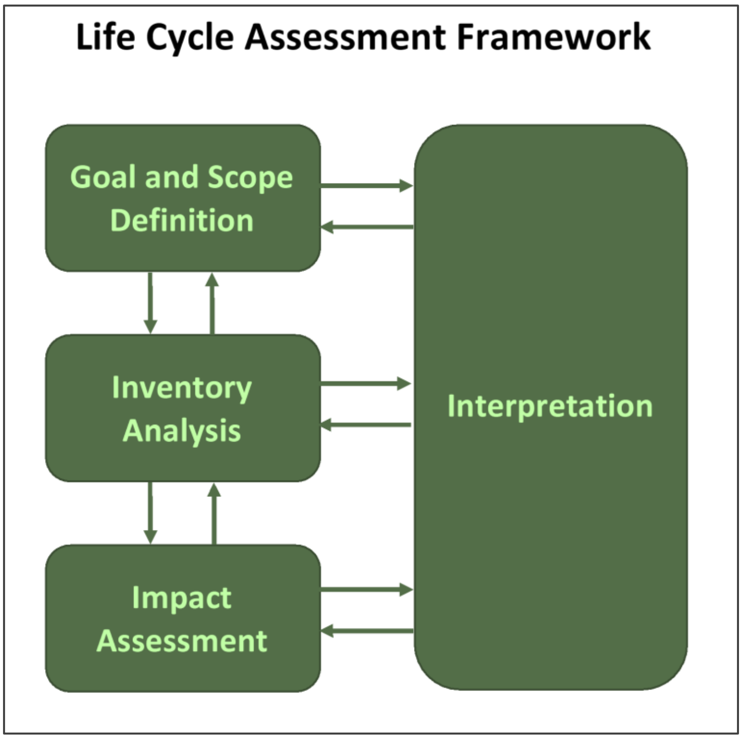

Figure 2. 1 Life cycle assessment (LCA) framework according to ISO 14040 (ISO, 2006b)

Table 2.1 records these details for a selection of LCA studies of asphalt materials or pavements and demonstrates that there are significant differences between the studies.

Table 2. 1 Synthesis of LCA studies of asphalt materials or pavements

Study	Goal	Materials or Pavements	Declared Unit	Life cycle stages	Impact categories (model)	Analysis Period	Geographical scope
Butt, Mirzadeh, Toller, & Birgisson (2014)	Enable improvements of the asphalt pavement LCAs by describing methods to consider feedstock energies and warm mixture additives and polymers.	Warm mix asphalt (WMA), Styrene-Butadiene- Styrene Polymer (SBS), wax	1 km of SC	Material production, construction, maintenance and rehabilitation, end of life	Feedstock energy (developed)	20 years	Stockholm, Sweden
Noshadravan, Wildnauer, Gregory, & Kirchain (2013)	Assess LCA uncertainty	Hot mix asphalt (HMA), jointed plain Portland Cement Concrete (PCC)	1 km of SC, BSC	Material production, construction, maintenance and rehabilitation, end of life	GWP (IPCC)	50 years	Missouri, USA
Vidal, Moliner, Martínez, & Rubio (2013)	Assess the environmental impacts of alternative pavements	Recycled asphalt pavement (RAP) with zeolite-based WMA	1 km of SC	Material production, construction, use, maintenance and rehabilitation, end of life	CC, ODP, HT, PoxF, PMF, IR, TA, EFw, MECO, ALO, ULO, NLT, WRD, MD, FFD,CED (Recipe midpoint and endpoint, CED)	40 years	Spain
Araújo, Oliveira, & Silva (2014)	Assess the environmental impacts of pavement alternatives	Polymer Modified Bitumen (PMB), RAP	1 km of SC, BC, BSC	Materials extraction and production; construction, use, maintenance, end of life	EC, GWP (Huang, Bird, & Heidrich, 2009)	20 years	Europe
Yu, Jiao, Ni, & Yang (2014)	Assess the environmental impacts of alternative materials	Waste plastic–rubber asphalt, SBS	1 tonne of SC	Material production	Ec, GHGs (IPCC)	-	China
Blankendaal, Schuur, & Voordijk (2014)	Assess the environmental impacts of pavement alternatives	WMA	1 m^3 SC	Material production, construction	CC, HH, ODP, HT, PoxF, PMF, IR, TA, EFw, TE, Ftox, ME,	-	Netherlands.

					ALO, ULO, NLT, MD, FFD (ReCiPe endpoint)		
Giani, Dotelli, Brandini, & Zampori (2015)	Assess the environmental impacts of pavement alternative	WMA and cold in-place recycling	1 km of SC, BC, BSC	Material production, construction, use, maintenance and rehabilitation, end of life	GWP, CC, ODP, TA, EFw, ME, HT, Poxf, PMF, TE, Ftox, MECO, IR, ALO, ULO, NLT, WRD, MD, FDP(IPCC, ReCiPe 2008, CED)	30 years	Italy
Farina, Zanetti, Santagata, & Blengini (2017)	Assess the environmental impacts of pavement alternative	RAP and Crumb rubber	1 m of SC	Material production, construction, maintenance	GER, GWP (GER; IPCC, 2006; Recipe method)	18 – 20 years	Turin, Italy
Samieadel, Schimmel, & Fini (2018)	Assess the environmental impacts of alternative material	Swine manure bio binder	1 tonne	Material production	GWP(IPCC 2006)	–	North America
Teresa M. Gulotta, Mistretta, & Praticò (2018)	Assess the environmental impacts of pavement alternative	SBS; quicklime (QL); cellulose fibers; waste plastics, crumb rubber,	1 m^2 of BC	Material production, construction, maintenance and rehabilitation, end of life	GER, CF (GER, ILCD)	-	South Italy
Puccini, Leandri, Tasca, Pistonesi, & Losa (2019)	Assess the environmental impacts of pavement rehabilitation alternative	Crumb Rubber from end-of-life tires Base Warm Mix with RAP	400 m and 464.5 m of SC, BC, BSC	Material production, construction, maintenance and rehabilitation, end of life	ODP, GWP, Mineral resources, Energy resources (ecological scarcity method)	72 years	Italy
Bressi, Santos, Marko, & Losa (2019)	Assess the environmental impacts of pavement alternative	Tire Crumb Rubber asphalt	1 km of BC	Materials production, construction	CC, FFD, EFw, Ftox, HT, MECO, ME, PMF, TA, ODP, TE, WRD (ReCiPe at midpoint level)	-	Empoli (Tuscany), Italy
Cao, Leng, Yu, & Hsu (2019)	Assess the environmental saving of pavement alternative	WMA with waste tire rubber	1 km of SC	Material production, construction, use, end of life	EC (Ecoinvent database)	20 years	Hong Kong

T. M. Gulotta, Mistretta, & Praticò (2019)	Assess the environmental impacts of pavement alternative	SBS, quicklime (QL), cellulose fibres (FB), mineral filler (FIL), waste plastic, crumb rubber	1 m^2 of SC, BC, BSC	Material production, construction, maintenance, end of life	GER, GWP, AP, Eu, PoxF (CED, EPD 2016)	20 years	South Italy
Filippo G. Praticò, Giunta, Mistretta, & Gulotta (2020)	Assess the environmental impacts of pavement alternative	RAP, crumb rubber, and waste plastics	1 m^2 of SC, BC, BSC	Material production, construction, maintenance and, end of life	GER, CC, ODP, HTc, HTnc, PMF, IRhh, Ire, POCP, AP, EUT, EFw, ME, WRD, MFD (ILCD midpoint 2011)	20 years	Italy
Hasan, Whyte, & Al Jassmi (2020)	Assess the environmental impacts of pavement alternative	Recycled construction waste, RAP, WMA, blast furnace slag	3.5 km of SC, BC, BSC, SB	Material production, construction, maintenance and rehabilitation	GWP, ODP, POzF, PMF, POxF, AP, Eu, EFw, ME, TE, Ftox, MECO, HT, LU, MFD, FFD, Water consumption (ReCiPe midpoint method)	30 years	United Arab Emirates
Vega A, Santos, & Martinez-Arguelles, (2020)	Assess the environmental impacts of pavement alternative	Recycled concrete aggregates	1 km of BC	Materials production, construction	ODP, GWP, IR, PSF, AP, Eu, HHC, HHN, HHP, Ec, FFD (Traci v2.1)	10 years	Colombia
Tokede, Whittaker, Mankaa, & Traverso (2020)	Assess the environmental impacts of pavement alternative	lignin binder	1 tonne of SC	Material production	GWP (IPCC)	–	Australia
Landi, Marconi, Bocci, & Germani (2020)	Assess the environmental impacts of pavement alternative	Cellulose-reinforced HMA, ELT fiber-reinforced HMA	1m^2 of SC, BC, BSC	Material production, construction, maintenance	CED, GWP, ALO, CC, FFD, Ftox, EFw, HT, IR, , ME, MECO, MD, NLT, ODP, PMF, PoxF, TA, TE, ULC, WRD (CED, IPCC)	30 years	Italy
Guest, Zhang, Maadani, & Shirkhani (2020)	Assess the environmental impacts of pavement alternative.	HMA, RAP	1m^2-year, 1 km-year, 1 ESAL-km, 1 person km of SC	Material production, construction, use, maintenance and rehabilitation	CC, PoxF, TA, PMF (not given)	40 years	Ottawa, Canada

F. Wang et al., (2021)	Assess the environmental impacts of pavement alternative	Self-healing asphalt, steel slag, WMA	1 km of SC, BC, BSC	Material production, construction	EC, GHG (n/a)	–	China
Khater, Luo, Abdelsalam, Ma, & Ghazy (2021)	Assess the environmental impacts of asphalt mixture alternative	Asphalt mixtures using composite admixtures of lignin and glass fibers	1 km of SC	Material production, construction	ADP, AP, Eu, GWP, ODP, HT, Ftox, MECO, TE, PoxF (CML2001)	–	China
Piao, Bueno, Poulikakos, & Hellweg (2022)	Assess the environmental impacts of pavement alternative	Rubberized semi-dense asphalt mixture	1 km of SC	Material production, construction, use, end of life	GHG, CED, HT & Ec (IPCC 2013, CED, USEtox Ecological Scarcity)	10 years	Switzerland
Abdalla, Faheem, & Walters (2022)	Assess the environmental impacts of pavement alternative	RAP, Off-spec Fly Ash (OFA), Food Waste Bio-oil (FWBO)	1 Ton of SC	Material Production	ODP, GWP, PSF, AP, Eu, HHC, HHN, Ec (TRACI v.2.1)	-	Philadelphia, USA
Yue, Abdelsalam, Khater, & Ghazy (2022)	Assess the environmental impacts of pavement alternative	Lignin fiber and diatomite powder modified asphalt mixtures	1 km of SC, BC	Material production, construction	GWP, ADP, AP, Eu, HT, TE, Ftox, MECO, PoxF, ODP (CML 2001)	15 years	China
Tushar, Santos, Zhang, Bhuiyan, & Giustozzi (2022)	Assess the environmental impacts of pavement alternative	ELTs crumb rubber asphalt mixture	1 Ton of SC	Material production	CC, ODP, TA, ME, HT, PoxF, PMF, TE, Ftox, MECO, IR, ALO, ULO, NLT, WRD, MD, FFD (ReCiPe midpoint and endpoint methods)	30 years	Victoria, Australia.

* SC: Surface Course; BC: Binder Course; BSC: Base Course; GWP: Global Warming Potential; ADP: Abiotic depletion ; ALO: Agricultural land occupation; AP: Acidification Potential; CC: Climate change; CED: Cumulative energy demand; CF: Carbon Footprint; Ec: Ecotoxicity; EC: Energy Consumption; EFw: Freshwater Eutrophication; Eu: Eutrophication; EUT: Terrestrial Eutrophication; FFD: Fossil Fuel Depletion; Ftox: Freshwater Ecotoxicity; GER: Global Energy Requirement; HHC: Human Health Cancerous; HHN: Human Health Noncancerous; HHP: Human Health Particulate; HT: Human Toxicity; HTc: Human toxicity—cancer effects; HTnc: Human Toxicity—non-cancer effects;

IR: Ionizing Radiation; IRe: Ionizing Radiation E (interim); IRhh: Ionizing Radiation HH; LU: Land Use; MD: Metal Depletion; ME: Marine Eutrophication; MECO: Marine Ecotoxicity; NLT: Natural Land Transformation; ODP: Ozone Depletion Potential; PMF: Particulate Matter Formation; POCP: Photochemical Ozone Creation Potential; PoxF: Photochemical Oxidants Formation; PozF: Photochemical Ozone Formation; PSF: Photochemical Smog Formation; TA: Terrestrial Acidification; TE: Terrestrial Ecotoxicity; ULO: Urban Land Occupation; WRD: Water Resource Depletion;

2.2. Goal and Scope

The goal of an LCA describes the purpose of the study. This step will assist in emphasizing which issues the study will address. For example, the goal clarifies whether the research will focus on looking at emission hotspots, process optimization or comparing the environmental burden of alternative asphalt materials or pavements. The goal should be reflected in the scope of the study. The scope involves the definition of system boundaries, analysis period, and FU, which includes the asphalt mixture and pavement design and acts as a reference for the whole project (ISO, 2006b). Table 2.1 shows that the scope can be very different from study to study. For instance, there are no fixed life cycle stages, although the stages have been defined in the international standard, ISO 21930 (ISO, 2017), also referenced by EN 15804 (BSI, 2019). EN 15804 and ISO 21930 lay the foundation for Product Categories Rules (PCR) and EPDs for building products and established principles regarding system boundaries and for the past three years, LCA practitioners have predominantly relied on these two standards for reference (Rangelov, Dylla, Mukherjee, & Sivaneswaran, 2021; Strömberg, 2020). Depending on the study's purpose, the system boundaries may include only some or all life cycle stages. Therefore, it is necessary to specify whether each stage was included in or excluded from the pavement LCA in order to compare them. The consequences of decisions at the included life cycle stages on the impacts of excluded stages cannot be assessed.

The definition of this phase must be very clear because the final results depend on this step. As shown in Table 2.1, there is a wide range of goal and scope definitions taken in asphalt LCA studies, employing different life cycle stages, functional units and analysis periods.

2.3. Functional Unit

ISO 14040 defines the FU as “quantified performance of a product system for use as a reference unit” (ISO, 2006b). The functional unit defines the physical unit and performance requirements in the study. For pavement LCA, the functional unit may be a length of pavement with a defined geometry (e.g., a certain number of lanes and shoulders of a specified size) that fulfils the requirements over a specified period. According to The FHWA's LCA Framework (Harvey et al. 2010) , functional unit can be characterized by identifying application, location, physical boundary, performance standard, and analysis period. For pavement systems, the functional unit should represent the physical dimensions and quantified performance of the pavement, including the traffic load.

In LCA, the FU is important since selecting different FUs may result in different outputs and conclusions for the same study (Dale & Kim, 2014). As shown in Table 2.1, LCA studies have various different FUs, which are presented in more detail in Table 2.2. The most commonly used FU in the asphalt LCA studies is 1 km length of constructed pavement (Araújo et al., 2014; Bressi et al., 2019; Cao, Leng, Yu, et al., 2019; Vega A et al., 2020; Vidal et al., 2013), however this is not a complete FU because they differ between roadway classifications (interstate, urban, rural) and hence carried traffic, the number and widths of the lanes, as well as difference in pavement thickness.

Other studies use unit area of 1m^2 as the FU, but again these FUs have different characteristics including pavement thickness (Gulotta et al., 2018; Landi et al., 2020; Praticò et al., 2020). The unit measured of weight or volume can also be applied to use. As this FU has been practically used in LCA studies with 1 ton unit (Abdalla et al., 2022; Samieadel et al., 2018; Tokede et al., 2020; Yu et al., 2014) The benefit of this FU unit is that regardless of the road width differences the result of case study could still be compared, nonetheless it can only be applied for cradle-to-gate study.

Table 2. 2 Functional Unit used in past studies

Study reference	FU	Lane width (m)	Shoulder width (m)	Roadway type	Traffic*
Bressi et al. (2019)	1 km of four lane road	3.5	NA	rural roadway	NA
T. M. Gulotta et al. (2019)	1 m^2 of two-lane road	9,5	NA	NA	NA
Araújo et al. (2014)	1 km of two-lane road	3.5	1	NA	22,565 AADT
Cao, Leng, Yu, et al. (2019)	1 km of road	-	NA	highway	9,355 AADT
Vega et al. (2020)	1 km lane	3,5	NA	highway	5,000,000 ESAL
Vidal et al. (2013)	1 km of two-lane road	13 in total	NA	NA	1000 AADT
Gulotta et al. (2018)	1m^2 of two-lane road	5,7	NA	urban road	NA
Farina et al. (2017)	1 m of two-lane road	4,75	NA	extra-urban road	NA
Heidari, Heravi, & Esmaeeli (2020)	1 m of six lane road	3.6	1	NA	30,000 AADT
Praticò et al. (2020)	1m^2 of two-lane road	4,75	NA	NA	NA
Samieadel et al. (2018)	ton	-	NA	NA	NA
Tokede et al. (2020)	Ton of two-lane road	3,6	NA	sub-urban	NA

Yu et al. (2014)	tonne	-	NA	NA	NA
Landi et al. (2020)	1m^2 of six lane road	15 in total	NA	NA	NA
Khater et al. (2021)	1 km	1,0	NA	highway	20,000 vehicles/day
Piao et al. (2022)	1 km lane	7,0	NA	urban roads	300 – 1000 ESAL

* AADT: Annual Average Daily Traffic. ESAL: Equivalent Standard Axle Load.

It would be difficult to compare the results of these studies due to the differences in the functional unit (FU) considered. In their review, Santero et al. (2010) mentioned that a standard FU framework was needed and this has not changed since they published their paper. Although more studies have encompassed key defining FU characteristics of the pavement such as type and location, there is still no standardized set of FUs that can precisely define the pavement structure and traffic and enable different studies to be compared directly.

2.4. System Boundary

Referring to ISO 14040, system boundary definition involves the selection of activities and processes included within the life cycle stages of the pavement (ISO, 2006b). The system boundary may include all stages or only part of the life cycle as shown in Figure 2.2, including material production processes, construction, use stages, maintenance, recycling, and end of life processes.

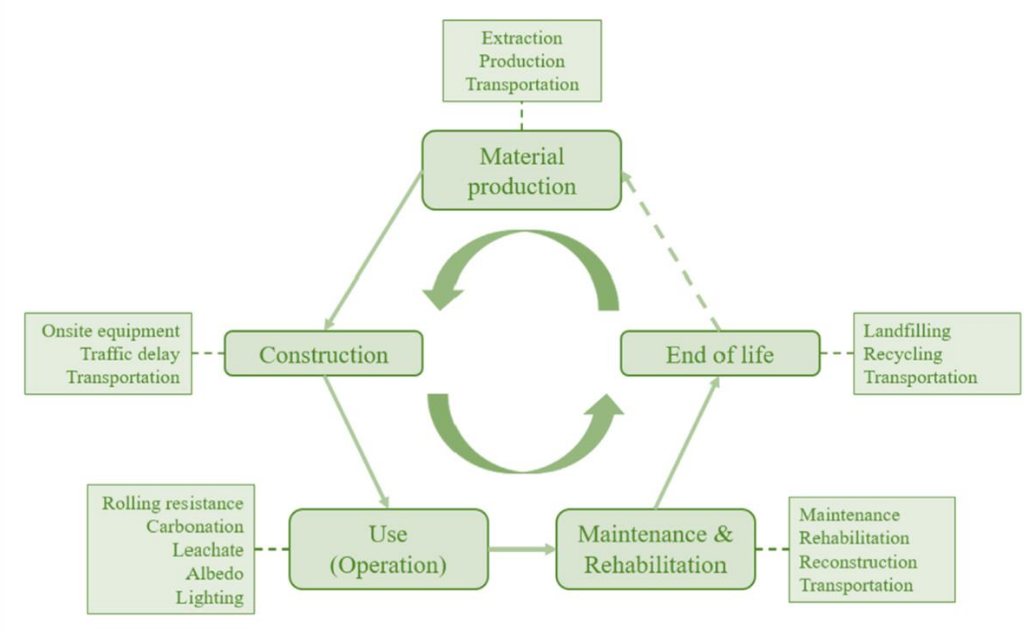

Figure 2.2 Generic pavement life cycle (Santero, Masanet, & Horvath, 2011a, 2011b)

In LCA, there is no fixed system boundary. Studies with different goals may require different stages to be included (Butt, Toller, & Birgisson, 2015). For example, when comparing two asphalt materials, the goal may be to compare only the production stages (cradle-to-gate) or may be extended to the construction stage or the complete life cycle, which will result in a more comprehensive result but also has a higher level of complexity requiring scenarios to be developed for future maintenance and recycling etc. Uncertainty analysis can be employed to help in the analysis of studies incorporating scenarios of future performance (Abed et al., 2023). For a life cycle study, the stages beyond production should only be omitted where the performance of alternative materials can be expected to be the same.

From Table 2.1, it is evident that materials production is the only phase included in every asphalt pavement LCA reviewed in this study. The material production stage will enable studies to focus on the aspects of the life cycle that are regarded as most relevant in estimating the ecological and sustainability potentials of the materials used. Many studies considered that for a new mixture, for which there is limited data available on the impacts, a cradle-to-gate analysis is appropriate since the extraction and processing of raw materials plays an important role for development of a new product. For instance waste plastic–rubber asphalt (Yu et al., 2014), bio-modified binder (Samieadel et al., 2018), and lignin binder (Tokede et al., 2020). However, this opinion is not necessarily correct since in terms of the pavement life cycle, different materials will have an effect on other stages as a result of the mixture performance and maintenance need during its service life, or end-of-life considerations (such as recyclability).

The construction phase has also received a lot of attention from researchers. It involves activities such as material transport, laying and compaction works. Some 20 out of 23 studies reviewed in this paper included this phase. Moreover, many have investigated LCA only up to this stage (Blankendaal et al., 2014; Bressi et al., 2019; Khater et al., 2021; Vega et al., 2020; Wang et al., 2021). Nonetheless, excluding a durability factor can have a significant impact on the entire life cycle impacts. The omission of life cycle stages beyond construction should be accompanied by supporting evidence (e.g., laboratory data indicating the comparable durability of alternative materials).

In contrast, the impacts from the use stage are usually ignored, which may lead to misleading and unreliable findings. This was stated by Santero et al. (2010), and the situation has not changed considerably since then. In fact, many studies have considered all other stages but the use stage (Gulotta et al., 2018; Hasan et al., 2020; Praticò et al., 2020; Puccini et al., 2019), while only a few studies have included the use phase (Araújo et al., 2014; Cao, Leng, Yu, et al., 2019; Giani et al., 2015; Guest et al., 2020; Piao et al., 2022). These studies indicate that pavement use makes a major contribution to life cycle environmental impacts. (Louhghalam et al., 2015; Trupia et al., 2017) investigated rolling resistance models to identify the governing parameters that drive the excess fuel consumption. In these studies it concluded that pavement-vehicle interaction (PVI) in use generates extra fuel consumption in vehicles, and factors such as the structural and surface properties of pavements change during service. This results in increased emissions.

Therefore, it is suggested to pay more attention to the pavement use phase, which can have a significant contribution to environmental impacts; although including the use phase will require predictions for pavement deterioration rates and therefore, result in higher uncertainty.

With regard to the maintenance, phase to ensure adequate pavement conditions throughout the life cycle, half of the papers examined in this article included this activity in their analyses. However, most of them considered maintenance activity without reference to the performance of the mixtures analyzed. For example, Vidal et al. (2013) assumed that maintenance is conducted every 15 years, while Gulotta et al. (2019) and Praticò et al. (2020) scheduled maintenance after half of the lifespan. Farina et al (2017) did schedule maintenance considering historical performance. However, such methods do not consider future possibilities that can alter prescribed maintenance programs, for instance, changes in deterioration rates due to traffic growth or climate change which can be expected to modify future maintenance schedules.

In another case, Landi et al. (2020) estimated the service life of each layer to predict maintenance activity by considering laboratory fatigue test result. Regardless, one laboratory performance parameter cannot justify the deterioration characteristics of a road pavement system as a whole. Very few employ a method to predict pavement deterioration parameters, as has been carried out by Guest et al. (2020) and Qiao et al., (2015) using mechanistic-empirical calculations. This approach can predict performance by calculating pavement characteristics and its corresponding conditions such as traffic level. Subsequently, the distress types and levels can be compared to a trigger value, at which point a maintenance event is scheduled. Moreover, the introduction of new pavement materials and technologies will affect the maintenance and rehabilitation process, and therefore needs a more comprehensive study (e.g. Kalman, 2022)

The last phase occurs when the road reaches the end of its useful life. Many researchers have also considered and analyzed this stage, using different approaches or options. For instance Gulotta et al. (2019) and Noshadravan et al. (2013) assumed that the pavement is completely demolished, which almost never happens in practice. Praticò et al. (2020) included waste treatment activity for the material that is disposed. Other research has used the cut off approach, where the destinations of recyclable materials are not modelled all the way to where they recirculate into new production, which means that the recyclable materials are “cut off” from the product system (Cao et al. 2019; Puccini et al., 2019). These differences in assumptions and treatment options at the end of pavement life introduce bias in the results and complicate the comparative assessment of case studies.

2.5. Life cycle inventory and allocation methods

According to ISO 14044, the second stage after goal and scope definition is performing an LCI analysis and its allocation method, as depicted in Figure 2.1. The LCI analysis involves the extensive data collection process associated with life cycle phases within the specified system boundary. Data serves as the fundamental foundation for LCA, and gathering these data represents a critical stage in the process, which is often anticipated to be the most time-consuming and resource-intensive aspect of the LCA. Therefore, several commercial and public databases can be accessed by LCA practitioners. Currently, numerous databases are employed in the pavement LCA. USLCI, EIO-LCA, Ecoivent and Athenai are among the databases used in the review studies, with the majority of the studies relying on the Ecoinvent database as a source of secondary data (68%). In addition to inventory databases, the reviewed studies also used various literature as data sources, such as Eurobitume (Eurobitume, 2012, 2020) and (Stripple, 2001) for asphalt material data. However, according to (T. Wang et al., 2012), which conducted an LCA analysis using four different databases, a significant increase of 25% in the variation of the environmental burden was observed due to adopting different databases. Hence, utilising a localised and up-to-date database appears to be imperative (Azarijafari, Yahia, & Ben Amor, 2016). Specific product information, such as in Environmental Product Declarations (EPD) will provide more relevant and transparent results (Rangelov et al., 2021). An EPD is a third-party verified and standardised document that provides transparent information about the environmental impacts of a product, calculated using the LCA method following predefined rules, known as Product Category Rules (PCR) (ISO, 2006a). For construction products and materials, EPDs are standardised by ISO 21930:2017 and EN 15804:2012+A2:2019. Currently, EPDs of bitumen or asphalt mixtures are becoming increasingly available. However, the production of EPDs has mainly been a bottom-up effort initiated by material producers with no single PCR. Furthermore, different PCRs developed and applied by the various program operators show a lack of harmonisation in the scope and assumptions, resulting in a lack of consistency between EPDs (Rosario, Palumbo, & Traverso, 2021). This highlights not only the necessity of the use of EPDs but also the need for a harmonisation of PCRs in the long term. This lack of harmonization could be overcome to some extent by the production of PCR and EPD systems by industry-representative or client bodies, as demonstrated in the USA by the National Asphalt Pavement Association (NAPA, 2023)

The allocation method employed in a LCA can significantly influence the results, as it determines how impacts are distributed among different processes or products (Huang, Spray, & Parry, 2013). In a pavement LCA study, for instance, impacts can be allocated to co-products of a single process (e.g., bitumen and other products at an oil refinery) based on their mass or economic value. Allocation at end-of-life (EOL) recycling can follow a number of methods, including the cut-off, loss of quality, closed-loop, ‘’50/50’’ and substitution methods. For the studies reviewed, the cut-off approach is the most commonly used for the waste treatment/recycling process. According to this method, recycling benefits were attributed to the life cycle of the recycled product (Cao, Leng, Yu, et al., 2019; Hasan et al., 2020; Vega A et al., 2020). Other methods which were also employed include the mass approach (Bressi et al., 2019), “50-50” (Yu et al., 2014), and system expansion (Piao et al., 2022). From this standpoint, these variations in the allocation method can add complexity to the assessment of LCA results. Therefore, pavement materials and co-products should be properly allocated according to rules that are appropriate for the process and fate of the involved materials and ideally, as stated in PCR.

2.6. Impact Assessment

The environmental performance of a pavement can be evaluated using a variety of different metrics, calculated on the basis of different impact assessment methods. As can be seen from Figure 2.3, the majority of the studies employed global warming potential (represented by GW, CC or GHG in Table 2.1) (80%) as the primary environmental indicator (Araújo et al., 2014, Hasan et al., 2020; Puccini et al., 2019; Tokede et al., 2020). Another widespread impact category analyzed in the studies is energy consumption (52%) which is considered representative of the environmental burden (Cao et al., 2019). Energy use impact can be analyzed with different impact indicator models, for example, Cumulative energy demand (CED) (Teresa M Gulotta et al., 2018; Landi et al., 2020; Piao et al., 2022; Vidal et al., 2013) Global energy requirement (GER) (Gulotta et al., 2019; Praticò et al., 2020). Furthermore, GHG or GWP and energy consumption are often used together to estimate the environmental impact of the pavement life cycle (Araújo et al., 2014; Kang, Al-Qadi, Ozer, Ziyadi, & Harvey, 2019; Samieadel et al., 2018; Vega A et al., 2020; Yu et al., 2014).

In addition, the pavement life cycle also involves other impacts such as land use, fossil resources depletion, acidification, and eutrophication (Giani et al., 2015). Consideration of these impacts is essential to have a more comprehensive view of the potential environmental damage. For instance, (Vidal et al., 2013) assessed the environmental impacts of pavement material with zeolite-based WMA in a cradle-to-grave LCA analysis and found that WMA can increase damage to human health by 6–7%. The use of vulcanized and devulcanized crumb rubber obtained from processing

ELTs for asphalt material can increase human toxicity in the materials production and construction stage assessed using The Recipe method at midpoint level (Bressi et al., 2019; Puccini et al., 2019). In the material production, construction, and maintenance stages, the incorporation of 0.3% cellulose fibre in HMA increases the burden for agricultural land occupation if compared to standard HMA and ELT fiber HMA. Furthermore, (Landi et al., 2020). Additionally, in a full life cycle LCA scenario, the use of waste plastics and crumb rubber from end-of-life materials on pavement surface layer could reduce Photochemical Oxidation Potential by 68% (T. M. Gulotta et al., 2019). These studies demonstrate that in addition to energy use and GWP and energy demand, other impacts do occur. This is in line with Santero et al. (2010), that inclusion of environmental indicators other than energy, greenhouse gases, and conventional air pollutants is essential. However, although impact categories such as Water depletion, Toxic releases and Land have been used, energy use and greenhouse gas emissions remain the most frequently investigated.

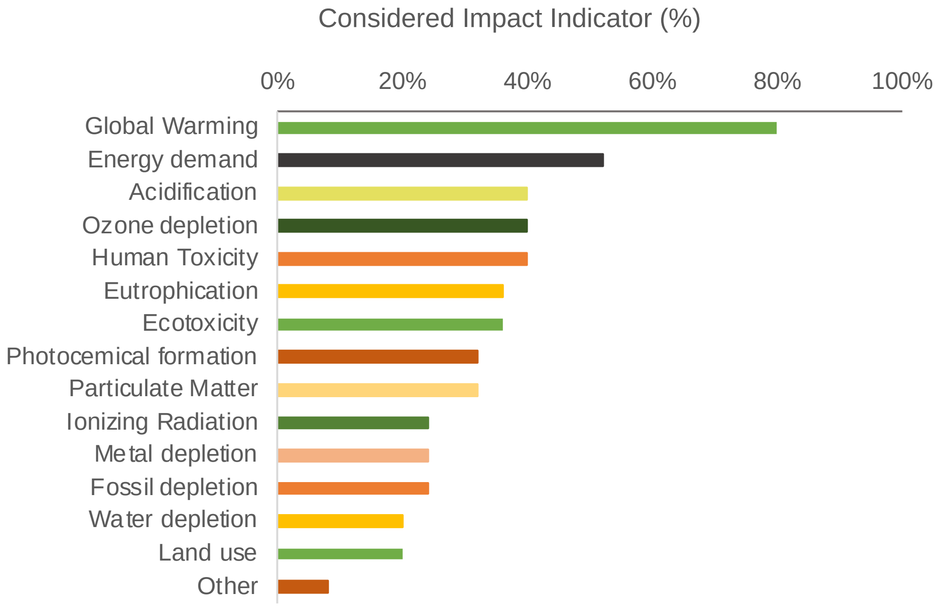

Figure 2.3 Impact indicators used in the reviewed studies

It can also be highlighted that other than different impact categories, various impact methods or models have been used by the LCA practitioner. In their study (Cherubini, 2018) analysed various impact indicators and found differences of up to 44% in the values of the same environmental indicator when calculated using different impact assessment methods. In the synthesis of LCA studies in this review (Figure 2.4), it was found that the predominant method employed are IPCC, Recipe, and CED (19%, 16%, and 14%, respectively). The selection of some of these methods may be based on the consideration of research objectives (Hoxha et al., 2021). For instance, for analysis which is focusing only on GHG impact, the most widely used method was the IPCC model (Araújo et al., 2014, Hasan et al., 2020; Puccini et al., 2019; Tokede et al., 2020), and studies of energy consumption, the CED method is the most widely used method. While some studies expanded the results to include more indicators, several studies opted to utilise the Recipe approach due to its comprehensive capabilities, which are accessible through various LCA software (Blankendaal et al., 2014; Bressi et al., 2019; Farina et al., 2017; Hasan et al., 2020; Vidal et al., 2013).

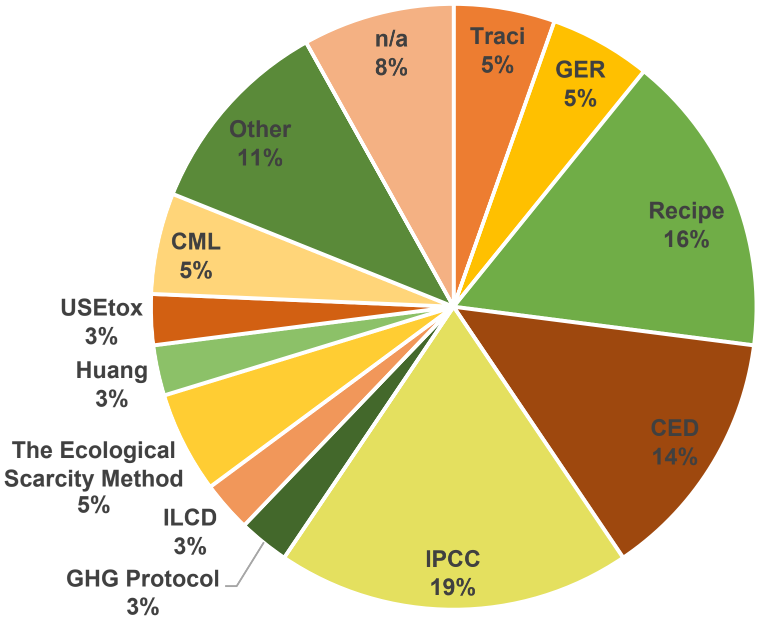

Figure 2.4 Impact assessment model

Another consideration in choosing the impact indicator method is the geographical location of the research being carried out. Although some methods are widely used on a global scale, such as CML and Recipe (Mehmeti & Canaj, 2022), on the other hand, there are also methods developed for specific areas. For example, the TRACI method recommended by EN15804 only represents circumstances for the United States or specific states or regions within the United States (Harvey et al., 2016) hence, it is less suitable for research in other domains. Therefore, the consideration and adaptation of the method used to analyse impact indicators is essential, ensuring that it conforms with the study's specific objectives and geographical context. It is crucial to consistently disclose the chosen methodology, since the selected method may influence the results obtained.

2.7. Data Quality and Uncertainty in LCA

Improving the sustainability of pavements requires a thorough evaluation of environmental impacts within all stages of a pavement's life with the LCA framework. LCA studies are subject to assumptions and simplifications that lead to uncertainties. For example, as stated by Wang et al. (2012), energy emission factors vary between LCI databases. To this end, it is prudent to carry out sensitivity or uncertainty analysis in order to verify the reliability of LCA results. Santero et al. (2010) stated that pavement LCAs routinely fail to adopt any such approach and generally assume a single published value with neither supporting rationale nor a sensitivity analysis. However, since then, more studies have incorporated sensitivity and uncertainty parameters to identify the robustness of results. Table 2.3 shows the synthesis of LCA studies that include uncertainty analysis.

Table 2. 3 LCA Uncertainty analysis

Study	Sources of Uncertainty	Analysis

White et al. (2010)	Climate change	Sensitivity analysis
Yu & Lu (2012)	Traffic growth and fuel economy improvement	Sensitivity analysis
Wang et al. (2012)	Inventory data:	Sensitivity analysis
Vidal et al. (2013)	Inventory Data, composition of asphalt mixes, transportation distances	Uncertainty, Monte Carlo simulation
Butt et al. (2014)	Transport distances and the electricity production mix	Sensitivity analysis
Noshadravan et al. (2013)	Roughness	Uncertainty, Monte Carlo simulation
Yu et al. (2014)	Contents of asphalt modifiers, allocation percentage, mixing process, milling or manufacturing process and transportation distances	Uncertainty, Monte Carlo simulation
Giani et al. (2015)	Inventory data	Uncertainty, Monte Carlo simulation
Trupia et al. (2017)	Traffic growth, IRI and MPD deterioration rate, fuel efficiency	Sensitivity analysis
Cao et al. (2019)	Material energy consumption, equipment energy consumption, mixing temperature reduction, and material transportation distance	Uncertainty, Monte Carlo simulation
Guest et al. (2020)	Climate change	Sensitivity analysis
Tokede et al. (2020)	Material (lignin) replacement	Uncertainty, Monte Carlo simulation
Vega A et al. (2020)	Recycled concrete aggregate moisture content	Sensitivity analysis
Hasan et al. (2020)	Inventory data	Uncertainty, Monte Carlo simulation

It can be seen that a range of sources of uncertainty have been examined. (US EPA, 2016) states that the extensive inventory data leads to high uncertainty in LCA results, primarily due to the uncertainties present in the LCI data. Thus, the pedigree matrix approach introduced by (Weidema & Wesnaes, 1996) was recommended. This approach was introduced to assess the data quality aspect and assign a quality rating based on reliability, completeness, temporal correlation, geographical correlation, and additional technological correlation. In this review, some studies have performed uncertainty analysis of the LCI foreground data inventory by analysing the range of data distribution for given input values. However, only three studies conduct uncertainty analysis of the background data using the pedigree matrix score. (Giani et al., 2015; Hasan et al., 2020; Vidal et al., 2013) estimate data uncertainty through uncertainty distributions for each data input (foreground data) and the pedigree matrix score as a function of data quality (background data) utilizing lognormal distributions in uncertainty analysis. Other research evaluates various sources of uncertainty in the material and production phase, such as transport distances, electricity production, energy use, etc. For example Butt et al. (2014) addressed the sensitivity analysis of transport distances and the electricity production mix, and Yu et al. (2014) considered the uncertainty of material and equipment energy consumption, mixing temperature reduction, and material transportation distance on cradle-to-gate pavement LCA.

Not many studies have emphasized future uncertainties that will likely emerge over the long-term but some have concluded that future volatility will significantly impact analysis results. For instance, Cao et al. (2019) concluded that the use stage accounts for large disparities in energy consumption. Noshadravan et al. (2013) and Trupia et al. (2017) included the sensitivity of CO_2 emissions due to pavement surface deterioration rates. Yu & Lu (2012) concluded that use stage fuel consumption is very sensitive to traffic growth and improvements in fuel economy. Guest et al. (2020) indicated that future climate change will increase pavement roughness and create a significant uncertainty in maintenance schedules. This occurs due to changes in climate that can have an impact on pavement distress levels such as rutting, roughness and cracking, which influences maintenance decisions (Haslett et al., 2021; Qiao, Dawson, Parry, & Flintsch, 2019), which in turn lead to varying LCA results.

From these studies it can be concluded that uncertainty, for instance in deterioration rates and the impacts of climate change can be significant in LCA analyses which include long life cycles. Future LCA studies should incorporate uncertainty analysis, particularly in use and maintenance phases over extended analysis periods. More comprehensive and reliable results can be achieved by focusing on uncertainty in future lifecycle phases by using appropriate probabilistic methods, such as Monte-Carlo simulation.

3. Life Cycle Cost Assessment

3.1. Application of LCCA to Asphalt Mixtures

Life Cycle Cost Assessment (LCCA) is an evaluation method used to assess the economic benefits of investment alternatives. The Federal Highway Administration (FHWA) describes LCCA as an engineering economic appraisal that builds on the well–grounded principles of economic evaluation to analyze different alternative strategies during the designated analysis period (FHWA, 1998). FHWA has provided guidelines that comprehensively describe the use of LCCA in highway design and management, as summarised in Figure 3.1.

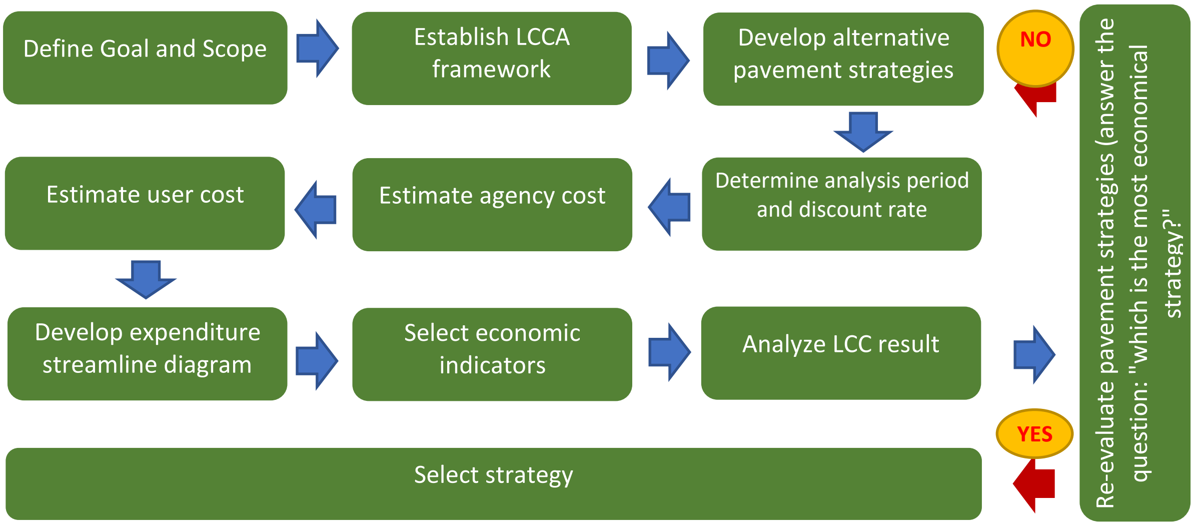

Figure 3. 1 Basic pavement LCCA framework (based on FHWA, 1998)

LCCA has been used to determine pavement construction or maintenance cost-effectiveness (Santos et al., 2015). Table 3.1 presents recent published studies of pavement LCCA that have been reviewed in this paper. This section will summarize these studies while discussing the strengths and limitations of the research as well as potential areas for further study.

Table 3. 1 LCCA studies of Asphalt Pavement

Study	Application	System Boundary	Analysis Period	Declared Unit	Economic Impact	Indicator	Discount rate
Abdelaty et al. (2016)	M&R strategy	M&R	26 years	1 mile	Agency Cost	EUAC	4%
Nazzal et al. (2016)	Material selection	Construction, M&R	10 years	1 mile	Agency Cost	NPV	n/a
Wang & Wang (2017)	M&R strategy	M&R, use	20 years	1 mile	Agency Cost, User Cost	NPV, EUAC	4%
Santos et al., (2017)	M&R strategy	Material production, construction, M&R, use, End of Life	50 years	5.9 km	Agency Cost, User Cost	NPV	2.3%
Qadir et al. (2018)	Material selection	Construction, M&R	NA	Total project	Agency Cost	NPV	n/a
Coleri et al. (2018)	Material selection	Material production	50 years	1.61 km	Agency Cost	NPV	4%
Chen et al. (2019)	M&R strategy	M&R, use	40 years	1 km	Agency Cost, User Cost	NPV	4%
Guo et al. (2019)	Pavement structural design	M&R, use	30 years	mile	Agency Cost, User Cost	NPV	4%
Qiao et al. (2019)	Climate Impact evaluation	M&R, use	40 years	1 km	Agency Cost, User Cost	NPV	4%
Yao et al. (2019)	M&R strategy	M&R	20 years	m^2	Agency Cost	EUAC	4%

Souliman et al. (2020)	Material and pavement structural design	Material production, construction	-	1 km	Agency Cost	n/a	n/a
Salameh & Tsai (2020)	M&R strategy	M&R	30 years	mile	Agency Cost	NPV	3%
Paul et al. (2021)	Material selection	Material production, construction, M&R	20 years	1 km	Agency Cost	NPV	n/a
Habte (2021)	Pavement structural design	Material production, construction, M&R	20 & 40 years	1 km	Agency Cost, User Cost	NPV	10.23%
Ma et al. (2022)	M&R strategy	M&R	48 years	Lane/ mile	Agency Cost	EUAC	4%
Jung et al. (2022)	M&R strategy	M&R	20 years	1 km	Agency Cost, User cost	n/a	n/a

* EUAC: equivalent uniform annual costs; NPV: net present value.

3.2. Life Cycle Stages

The Federal Highway Administration produce some of the most widely accepted guidance and recommendations for conducting LCCA. FHWA's Pavement Policy states that pavement shall be designed to accommodate current and predicted traffic needs in a safe, durable, and cost-effective manner. FHWA conducted a thorough review on LCCA practices through a series of workshop and regional peer exchanges since the FHWA policy regulations do not specify procedures to follow to meet the requirement, and each State highway agency is expected to use a design procedure appropriate for its conditions, (FHWA, 2019).Thus the LCCA stages can include one or more processes and activities that encompass the pavement life cycle, as presented in Figure 3.2. As Table 3.1 shows, most of the studies included maintenance and rehabilitation (M&R) strategies rather than including new materials in the pavement. However, regarding the maintenance and rehabilitation strategy itself, Babashamsi et al. (2016) underlined that pavement LCCA models often suffer from the limitation of excluding preventive maintenance treatments. This has remained largely the case since then. From the synthesis of LCCA studies, only a third addressed preventive maintenance practices such as chip seal and crack seal (Wang & Wang, 2017), diamond grinding and micro-surfacing (Guo et al., 2019), and pothole patching (Habte, 2021).

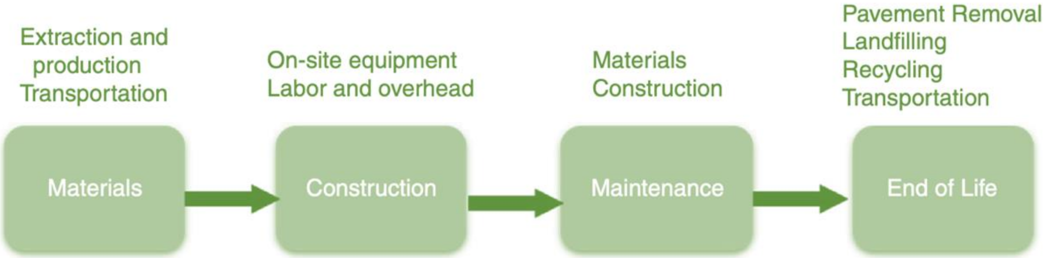

Figure 3. 2 Simplified system boundary of LCCA study (Swei et al. 2015)

In addition, LCCA practices were unable to take into account important factors that would influence future maintenance. In LCCA, the future maintenance cost is estimated from historical records and recent bids (Wilde et al. 1999). In a similar manner, Nazzal et al. (2016) undertook annual field evaluations on pavements that had been in service for ten years. Wang & Wang (2017) used IRI from road survey databases. Chen et al. (2019) developed condition distributions using the Kaplan-Meier survival analysis method from observed field data to predict rehabilitation alternatives. Qadir et al. (2018); Santos, et al. (2017) and Santos et al. (2015) defined M&R activities according to the Highway Officials Standard (VDOT, 2011). However, the use of historical data and standard methods may be unable to predict future deterioration, which is influenced by many uncertain factors. And in addition, this technique is also not applicable for novel materials, which requires several years of field observations to predict future maintenance. This may account for the scarcity of studies on the development of novel materials that is due to the limited available data and the uncertainty in future performance.

Some LCCA research has begun to accommodate mechanistic-empirical methods to determine maintenance schedules. The Mechanistic-Empirical Pavement Design (MEPDG) can be utilized to predict the number and timing of pavement maintenance activities. The pavement performance is defined through the distress output, for example, roughness and cracking. The calculation will consider material type, pavement structure, traffic number, and environmental factors. Praticò et al. (2011); Qiao et al. (2019); Souliman et al. (2020) and Swei et al. (2015) found that the use of the mechanistic-empirical method (rather than the design manual) to define future maintenance has significant implications on the analysis result. Still, very few studies employ an analytical method to investigate the LCCA of novel materials. In addition, if compared with a prescribed maintenance schedule, mechanistic-empirical methods could accommodate future uncertainties for maintenance strategies as well as for new materials. For instance, future uncertainty caused by climate change is one of the factors that can change pavement performance and thus maintenance frequency. With the mechanistic-empirical methods, the effect of climate change can be represented by changes in temperature in the pavement input to calculate performance prediction during service life.

With the MEPDG method, Qiao et al. (2019) integrated climate variability impacts into the analysis of flexible pavement LCCA to derive the additional life cycle costs incurred due to changes in climate. According to this study, during 40 years of analysis period climate change increase life cycle road maintenance expenditures by up to 64%. Similarly, Guest et al. (2020) modelled flexible pavement structure performance under various climate scenario and several analysis period. This research concluded that climate change will increase IRI and create a significant uncertainty in the maintenance schedule.

3.3. Analysis Period

FHWA proposes at least 35 years as the time horizon for pavement LCCA (FHWA, 1998). This allows for a series of routine maintenance activities and at least one subsequent rehabilitation activity. However, the foregoing LCCA studies have variables in their frameworks which makes it difficult to draw any comparative conclusions. The difference includes the analysis period of the given studies, which varies from 20 to 75 years, where 20 years was the most frequently selected analysis time span, which accounted for 31% of the papers. The selection of this time-scale was based on the standard design in each country where the LCCA study was conducted, such as the long-term pavement performance in the US (Paul et al., 2021; Wang & Wang, 2017), pavement design manual in Ethiopia (Habte, 2021), and pavement design life in Korea (Jung et al., 2022). The analysis of a longer time period (typically 40 to 50 years) was usually selected to model a series of repetitive rehabilitations based on the estimated life of the rehabilitation type (Chen et al., 2019; Coleri et al., 2018; Ma et al., 2022; Santos et al., 2017), or to explore the impact of another factor, such as climate change that needs a longer assessment period to see a difference (Qiao et al., 2015).

3.4. Economic Impact Assessment

Life cycle costs can fall upon transportation agencies, highway users, or society. Highway Agency cost refers to all the disbursement by the agency throughout the entire project period, while road user costs include travel time costs (TTC) and vehicle operating costs (VOC). The social cost, for example due to environmental impact, can be difficult to determine and consequently, is rarely incorporated in LCCA, although it is widely acknowledged (Li, Xiao, Zhang, & Amirkhanian, 2019). For instance He et al. (2021) added user life cycle costs due to crashes as a social impact. However, the calculation of crashes was based only on the correlation between crash rate and volume over capacity (v:c) ratios during maintenance activity. Therefore, it may not accurately represent the association between each type of pavement and the actual frequency of collisions. In addition, Santos et al. (2019) considered the assessment of safety, user comfort (UC), noise reduction (NR), and traffic congestion (TC) as social impacts. However, there was no evidence for how safety, UC or NR impacts change over time and therefore these impacts were omitted from the analysis, and TC was used as the sole social impact parameter with hourly delay time as the unit of measurement. In addition, hourly TC can be quantified as a monetary unit to make it more comprehensible, and so falls under the area of economic costs.

Two economic indicators are typically used in LCCA: net present value (NPV) and equivalent uniform annual costs (EUAC). NPV converts all costs that occur in different years to one single base year in order to conduct the comparison, as shown in equation (1). In comparison, EUAC distributes NPV to a yearly cost within the whole life cycle, presented in equation (2).

$$NPV = \sum_0^t \frac{c}{(1+i)^{t'}} \qquad \text{Equation (1)}$$

$$EUAC = NPV \frac{i\,(1+i)^t}{(1+i)^t - 1'} \qquad \text{Equation (2)}$$

where:

c = the cost at year t

i = discount rate;

t = time period

There is clear understanding and agreement on the need to discount future costs but there is no clear consensus on what discount rate would be appropriate. FHWA recommended that the discount rates employed in LCCA should reflect historical trends over long periods of time(FHWA, 1998). From the studies reviewed, the discount rate value varied from 2% to 10.23% as presented in table 3. The value most often agreed to be used in LCCA is a discount rate of 4% (Abdelaty et al., 2016; Coleri et al., 2018; Guo et al., 2019; Ma et al., 2022; Qiao et al., 2019; Z. Wang & Wang, 2017; Yao et al., 2019). FHWA also recommends a sensitivity analysis on the discount rate. Swei et al. (2015) conducted a sensitivity analysis on discount rates by varying the percentage between 1% and 7%. The study shows that the 90th-percentile of LCCA shifted by 14%, while the relative mean shifts by 12%, for two different materials being compared.

3.4.1. *Agency Cost*

The highway Agency costs include the entire cost expended by the highway agency throughout the service life. This consists of the initial cost for pavement construction and future costs associated with maintenance activities to ensure pavement performance. The Agency cost is a large proportion of the total life cycle cost and has a close relationship with the material used in pavement construction. Asphalt quality plays an essential role with respect to the pavement life and changes in the construction financing, thus affecting the amount of Agency cost. Most LCCA studies take into account the Agency cost and some only include Agency cost in their LCCA analysis (Praticò et al., 2011; Swei et al., 2015).

3.4.2. *User Cost*

User cost includes Vehicle Operating Cost (VOC), which includes the cost incurred by the drivers during the use stage as a function of pavement vehicle interaction resulting from pavement deterioration. It is associated with overall pavement condition, pavement roughness, which is often represented by the international roughness index (IRI) value; by far the most widely used index to estimate the VOC (Guo et al., 2019; Habte, 2021; Qiao et al., 2015; Wang & Wang, 2017). The cost categories contributing to total VOC are fuel consumption, tire wear, vehicle maintenance and repair, and mileage-related vehicle depreciation.

Apart from these VOC, the driver also incurs work zone (WZ) costs as a result of maintenance activity, when facing traffic delays as a consequence of the restrictions enforced by a WZ traffic management plan. This includes Additional VOC (referred to as WZ VOC including additional fuel costs during queuing) and Travel Delay Cost (TDC). However, the user cost is frequently neglected, and Babashamsi et al. (2016) reported that during major rehabilitation and construction activities, the majority of LCCA only use TDC as part of user costs. Since then, current research shows that TDC and WZ VOC remain the least explored costs in LCCA studies. WZ cost can be significant in the LCCA analysis since delay and congestion that occur during M&R can be serious. TDC is calculated from the time difference between normal speed and the lower speed when passing through the WZ. Santos et al. (2017) calculated that the WZ VOC and TDC accounts for up to 66% of all total costs during pavement rehabilitation for the project they studied.

3.5. Data Quality and Uncertainty in LCCA

There are limitations to data availability and reliability in LCCA analysis and uncertainty analysis is a key tool to appraise the potential impact of uncertain inputs on the study results. Uncertainties can be addressed using different approaches, including sensitivity analysis or risk analysis (a probabilistic method). Of the LCCA studies of asphalt pavement in Table 3.1, only around 40% considered uncertainty. The factors studied and type of uncertainty analysis in these studies is presented in Table 3.2.

Table 3. 2 LCCA Uncertainty analysis

Study	Sources of Variation in LCCA										Analysis
	Discount rate	Deterioration / Predicted service life	Treatment timing	Material/ Treatment cost	Transport distance	IRI value	Maintenance threshold level	Traffic	Analysis period	Climate	
Abdelaty et al. (2016)	✓		✓								Risk probability, Monte Carlo simulation
Chen et al. (2019)				✓	✓						Risk probability, Monte Carlo simulation

Wang & Wang (2017)	✓		✓		✓		✓			Sensitivity
Santos, Bryce, et al. (2017)	✓		✓	✓						Sensitivity
Guo et al. (2019)		✓	✓							Risk probability, Monte Carlo simulation
Qiao et al. (2019)									✓	Sensitivity
Salameh & Tsai (2020)	✓	✓				✓		✓		Sensitivity

In pavement LCCA practice, sensitivity analysis is primarily used because of its practicality. With this method, parameters are changed one at a time to determine how a change in input value will affect the overall result. This method falls short of determining the effects of simultaneous changes in other inputs on the LCCA result. Therefore, it is recommended to use probabilistic methodologies in uncertainty analysis to consider the uncertainty that is typically hidden in the traditional deterministic approaches. In this light, (FHWA, 1998) also suggests that a probabilistic approach is the preferred method, however a sensitivity analysis should be included as a minimum.

With regard to the parameters considered in the uncertainty analyses, most of the authors examined the discount rate and treatment cost uncertainty in their study. Not many studies have considered long-term performance uncertainty during pavement service life. This has only been done by a few, for example, treatment timing (Abdelaty et al., 2016), IRI value (Wang & Wang, 2017), and deterioration calculation / predicted service life (Guo et al., 2019; Salameh & Tsai, 2020). Therefore, it is recommended that future studies should acknowledge more uncertainty parameters regarding performance levels and pavement deterioration.

4. Integration of LCA and LCCA

LCA and LCCA are often studied separately, which results in an outcome that a product is not optimised in terms of the economy and the environment. However, pavement construction will significantly impact the overall environmental footprint and incurred costs. For example, Abdelaty et al. (2016) compared three pavement rehabilitation options and found that the two most economical alternatives have very similar values to each other and so, the road agency has to consider another factor to select one of those options. Subsequently, Nazzal et al. (2016) stated that ground tire rubber-modified mixtures only had a slightly higher cost compared with polymer-modified mixes. While Gulotta et al. (2018) and Yu et al. (2014) determined that ground tire rubber asphalt has more environmental benefits than polymer modification. Additionally, (Tushar et al., 2022) conclude that CR-modified pavement demonstrates that CR recycling reduces carbon emissions by 71.91% compared to landfills. However, separate LCA and LCCA research cannot be used as a basis for drawing conclusions and deciding which mixture is more efficient since each study has a different scope and framework.

Accordingly, it is critical that the pavement infrastructure is evaluated by a comprehensive assessment which accounts for pavement cost and environmental impact. The integration of LCA and LCCA has been increasing over the past ten years, and examples are given in Table 4.1.

Table 4. 1 Examples of LCA and LCCA integration studies for asphalt pavements

Study	Material/Product	System Boundary	LCA	LCCA
Yu et al. (2013)	Portland cement concrete (PCC) overlay, HMA overlay, and crack, seat, and overlay (CSOL)	Maintenance, use	Energy consumption, GHG	Agency costs, user costs
Santos et al. (2017)	In place recycling pavement	Maintenance, use, end of life	GWP, CED	Agency costs, user costs
Santos, Ferreira, & Flintsch (2017)	Micro-surfacing, thin hot mix overlay, corrective maintenance, restorative maintenance, conventional reconstruction, recycling-based reconstruction	Maintenance, use, end of life	GHG	Agency costs, user costs
Hong & Prozzi (2018)	RAP overlay	Maintenance, use, end of life	Energy consumption, GHG	Agency costs, user costs
Santos et al (2019)	RAP, WMA	Materia production, construction, maintenance, use, end of life	GWP, Energy consumption, SMC	Agency costs, user costs, social costs
Cao et al (2019)	Hot in-place recycling and milling-and- filling	Material production, construction	GPW, ODP, POCP, AP	Agency costs, user costs
Zheng et al. (2019)	Thin HMA, hot mix asphalt with warm mix additive, and hot mix asphalt with RAP	Production, construction, maintenance	Energy consumption,	Agency costs
Heidari et al. (2020)	HMA and plain cement concrete pavement (PCCP)	Material production, construction, maintenance, use	Energy consumption, GHG	Agency costs, user costs
Ruiz & Guevara (2020)	Maintenance options	Maintenance	GHG	Agency costs
Nascimento et al. (2020)	Waste tire rubber	Material production, construction	GHG	Agency costs

Bhat & Mukherjee (2020)	RAP	Material production, construction	GWP	Agency costs
Rodríguez-Fernández et al. (2020)	Porous asphalt mixtures with RAP, EAF slag, WMA, nano-modified binder	Material production, construction, Maintenance, use, end of life	HH, ED, RA	Agency costs
Choudhary et al. (2021)	Asphalt mixes containing brick dust (BD), recycled concrete aggregate dust (CD), limestone slurry dust (LD), rice straw ash (RSA), glass powder (GP), carbide lime (CL), and copper tailing (CT)	Material production, construction,	GWP	Agency costs
Ruffino et al. (2021)	Asphalt Mixture containing paint sludge	Material production	GWP, GER	Agency costs
He et al. (2021)	Warm mix asphalt overlay, cold in-place recycling, full depth reclamation, intelligent compaction, precast concrete pavement systems	Maintenance, use	GWP, Fossil fuel consumption, Energy consumption	Agency costs, user costs, social costs
Al-Humeidawi & Chafat (2021)	HMA flexible pavement, composite Portland Concrete Cement (PCC)	Material production, construction, maintenance, end of life	GWP, AP	Agency costs
Mattinzioli et al. (2021)	RAP and crumb rubber (CR), warm and half-warm-mix asphalts, of bio-based binders	Material production, construction, replacement	GHG	Agency costs
Gupta et al. (2021)	Porous asphalt, hydrated lime filler, aramid fiber, aramid-polyolefin fibers, aramid pulp, and cellulose fibers	Material production	GWP, HT, MECO	Agency costs
Zhao et al. (2021)	Construction and demolition waste	Material production, construction, maintenance, end of life	Energy consumption, GWP, water demand, hazardous waste, CO, PM_{10}, NO_x, SO_2	Agency costs
Riekstins, Haritonovs, & Straupe (2022)	Crumb rubber modified asphalt	Material production, construction, maintenance, end of life	CO_2 equivalent, Energy consumption	Agency costs

GWP: Global Warming Potential; CED: Cumulative energy demand; GER: gross energy requirement, ODP: Ozone Depletion Potential ; POCP: Photochemical Ozone Creation Potential; AP: Acidification Potential; HH: human health, ED: ecosystem diversity; RA :resource availability; SMC: Secondary materials consumption, MRR: Materials to be reused or recycled, WC: Water consumption, AC: Acidification indicator of soil and water, EU: Eutrophication indicator, SOD: Stratospheric ozone depletion indicator, PM: Particulate matter, HT: Human Toxicity MECO: Marine Ecotoxicity

As Table 4.1 shows, past research on integrating pavement LCA and LCCA has been used to assess M&R strategy selection (Cao et al. (2019); He et al. (2021); Hong & Prozzi (2018); Santos, Ferreira, et al. (2017); Yu et al. (2013); Zhang et al. (2008)), although Choudhary et al. (2021); Gupta et al. (2021); and Ruffino et al. (2021) studied the feasibility of asphalt mixture using LCA and LCCA in the production stage.

The application of LCA and LCCA integration to evaluate pavement mixture options as new material considering a wider life cycle has rarely been attempted, which means that the assessment of long-term performance of the mixture has been limited. For example, while quantifying cost and environmental burden from material production and construction phase, Bhat & Mukherjee (2020); and Nascimento et al. (2020) additionally assessed asphalt service live performance but did not quantify the result in the LCA and LCCA. Hence the effect of road performance on long-term costs and environmental impact was not assessed. In this light, the omission of some life cycle stages may be appropriate in certain circumstances, for instance when comparing products or conducting comparative LCA where performance is anticipated to be similar based on reliable data and analysis. However, LCA should ideally include all life- cycle stages to avoid unintended tradeoffs (Schenck & White, 2014).

Only in recent years have some studies started to conduct full life cycle LCA and LCCA of asphalt mixtures. Santos et al. (2019) studied asphalt mixtures containing RAP and WMA by comparing environmental, economic and social dimensions. However, this study, again used prescribed maintenance, which assumed the same timetable for all mixtures. Mattinzioli et al. (2021) investigated the use of novel bio-binder and RAP, and the durability of the surface course was assumed based upon literature. This means that these studies did not predict and include deterioration rates due to material differences and external factors such as the climate change effect, while performing sensitivity analysis on the durability based on information from literature. Only one of the reviewed studies, conducted by Riekstins, Haritonovs, & Straupe (2022), relies on laboratory data to establish an assumption regarding the service life of the investigated mixture. This study evaluated the cradle-to-grave LCA and LCCA of tire rubber modified asphalt, which was presumed to have one additional year of service live than the standard practice based on laboratory performance tests.

Some 60% of the combined LCA-LCCA research reviewed overlooks user cost, which could result in an unbalanced comparison between environmental and economic results. For instance, Rodríguez-Fernández et al. (2020) studied the full life cycle assessment and cost of porous asphalt mixtures with RAP, EAF slag, WMA, and nano-modified binder. However, the user cost during the use stage was excluded from this study while taking into account leaching for the environmental impact. Zhao et al. (2021) analyzed numerous environmental impacts, including Energy consumption, GWP, water demand, hazardous waste, CO, PM10, NOx, and SO_2, but only calculated agency costs for comparison. Such approaches may result in unbalanced decision-making because the LCA and LCCA assessments do not consider the same stages and variables.

To this end, LCA-LCCA integration for novel material development that considers the entire life cycle is suggested as a topic for future study. It is also necessary to estimate pavement performance and maintenance schedule over the length of the pavement's lifetime to evaluate the entire life cycle of asphalt mixtures instead of using prescribed maintenance based on historical data or literature without considering future changes, e.g. in traffic or climate. Differences in the frequency of road maintenance will not only affect treatment agency costs but also WZ user costs and for this reason mechanistic-empirical pavement design can be used to predict maintenance schedules as frequently practiced in the LCCA research. Subsequently, the decision-making process for selecting alternative pavement options can be based on comprehensive and balanced assessment studies.

5. Summary

More than ten years ago Santero, Masanet, & Horvath (2010) published a landmark review of the state-of-the-art in road pavement LCA, and this paper seeks to provide an overview of progress in asphalt pavement LCA since then. While most studies are now careful to define characteristics of the pavement FU, such as dimension and location, there is still no standardized set of FUs. This may seem appropriate because road pavements vary widely in terms of geometry, materials and traffic but this also means that comparison between studies is problematic. This review shows no significant improvement in incorporating all life cycle phases, and materials production is the only phase included in every asphalt road pavement LCA reviewed in this study. Correspondingly, the integration of realistic maintenance schedules remains a limitation of many LCAs. Sensitivity and uncertainty analysis are more frequently included now, but inconsistencies are present in the sources of uncertainty examined, with uncertainty in the foreground inventory data and transport distance being the main parameters examined across the case studies. The inclusion of impact categories such as water depletion, toxic releases and land use has increased, although energy use and greenhouse gas emissions (GWP or carbon footprint) remain the most frequently investigated.

To improve the comparability of asphalt pavement LCA studies, we recommend that a standardized FU (or set of FUs) is defined, for each component of the pavement, to be reported against in addition to any FUs specific to individual studies. In addition, in order to enhance comparability of LCA results, harmonization and adoption of PCR and EPD for asphalt materials and pavements is essential.

As the carbon net-zero agenda continues to gain importance, whole life studies should become the norm, and the use, maintenance and end-of-life lifecycle phases should gain more attention in further research. For best practice, more comprehensive and robust conclusions can be drawn from LCA studies by focusing on uncertainty, including for future lifecycle phases, using appropriate probabilistic methods. Impact assessment should be extended beyond carbon footprint (GWP) to include toxic releases and other environmental impacts, including during development of novel materials where new substances are included.

In their review of asphalt pavement LCCA studies, Babashamsi et al. (2016), found that most studies were limited to assessing maintenance and rehabilitation strategies. This remains the case and suggests that LCCA studies are more limited than LCA studies in terms of the life cycle phases considered, for instance in studying the development of new materials. There appears to be more reluctance to include the uncertainty associated with future performance of new technologies and its impact on future costs than for future environmental impacts. While assessing M&R strategy, the majority of LCCA research still focuses on major maintenance, such as overlay and rehabilitation, without considering preventive maintenance. In addition, many LCCA studies of asphalt pavements continue to neglect user costs, such as work zone vehicle operation cost and travel delay cost. Social costs are generally not considered. This review also shows that many studies still conduct sensitivity analysis without consideration of probabilistic uncertainty methods, which could significantly impact decision making based on LCCA results.

The results of this literature review suggest that more attention should be paid to developing studies that include new materials and technologies and how they impact M&R and end-of-life costs. User costs during maintenance also need to be considered in further research. To accommodate uncertainty, future studies should include probabilistic uncertainty analysis alongside sensitivity analysis, to provide for more robust results.

Like LCCA studies, the integration of pavement LCA and LCCA is mostly limited to only the maintenance phase for the purpose of examining M&R strategy, or else extending LCA in cradle-to-gate analysis to investigate novel mixture development, rather than addressing the wider life cycle. The majority of the combined LCA-LCCA studies reviewed ignore user cost, which could lead to an unbalanced comparison between the outcomes of LCA and LCCA. Failure to assess social costs in LCCA will exacerbate this because some LCA environmental impacts have clear social implications, such as on human health.

We propose that attention needs to be given to LCA-LCCA integration that takes into account the complete life cycle. Additionally, to evaluate the complete life cycle of asphalt mixtures, a prediction of pavement performance and maintenance during the entire lifetime is needed, rather than making assumptions solely based on historical data or literature. For example, some LCCA studies have modelled the entire service life performance, using mechanistic-empirical pavement design to predict the maintenance programme, although few LCA studies have taken this approach. For methodical decision-making about pavement design and M&R alternatives, both short- and long-term costs and environmental impacts should be estimated. This will provide highway authorities with quantitative evidence that supports decision making in the light of both environmental impacts and financial costs.

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