Implementing life cycle cost analysis in road engineering: A critical review on methodological framework choices

Preprint *in* Renewable and Sustainable Energy Reviews · November 2020

DOI: 10.1016/j.rser.2020.110284

4 authors:

Ben Moins
University of Antwerp

Cyril France
University of Antwerp

Wim Van den bergh
University of Antwerp

Amaryllis Audenaert
University of Antwerp

Renewable and Sustainable Energy Reviews, 133, 2020
doi: 10.1016/j.rser.2020.110284

Title

Implementing life cycle cost analysis in road engineering: A critical review on methodological framework choices

Authors

MOINS, B. [a]*; FRANCE, C. [a]; VAN DEN BERGH, W. [a]; AUDENAERT, A. [a]

[a]Energy and Materials in Infrastructure and Buildings (EMIB), University of Antwerp, Campus Groenenborger, Groenenborgerlaan 171, 2020 Antwerp, Belgium

***Corresponding author**

E-mail address: ben.moins@uantwerpen.be (Ben MOINS)

Publication reference

Moins B, France C, Van den bergh W, Audenaert A. Implementing life cycle cost analysis in road engineering: A critical review on methodological framework choices. Renewable & Sustainable Energy Reviews. 2020;133. doi:10.1016/j.rser.2020.110284

Abstract

Life cycle cost analysis (LCCA) has received notable attention and application within the road industry. As one of the three pillars in sustainability assessment, LCCA offers an empirical framework to assess costs over the entire lifespan of road projects. To incorporate the agency and user cost for all different life cycle phases, a robust framework is needed. Thus, it is vital to gain insight into the application and limitations of LCCA in road projects. Reviewing the existing economic models and frameworks, with a particular focus on road projects, will be the first step in providing a robust and uniform model. The goal of this paper is to provide a state-of-the-art review of existing methodologies in the wider field of LCCA for road projects. Hence, it can highlight critical processes and identify hotspots so the robustness of LCCA frameworks can be increased. It is concluded that agency costs related to the end of life (EOL) phase, transport and road user costs are often excluded, despite having a substantial impact. However, with sustainability in mind, these aspects are important and should always be incorporated. Modelling the EOL enables the user to include the effect of recycling, hence lowering the economic impact of raw material extraction. Additionally, road user costs are closely related to the social aspect of sustainability assessment. Finally, this paper presents the inconsistent use of modelling parameters, e.g. applied discount rate and analysis period, which supports the conclusion of a missing conclusive and robust framework.

Highlights

- If an LCCA wants to transform into a sustainability assessment, it should always incorporate road user costs.
- If pavements are compared, an analysis period of 40 years will probably be sufficient. However, when full structures are compared, an analysis period of 40 years will not be long enough.
- It is concluded that transport between extraction, production, construction and waste processing sites are often excluded or unknown.

Keywords

Life cycle cost analysis; LCCA; Life cycle cost; LCC; Road engineering; Life cycle thinking; Net present value; Equivalent uniform annual cost

Renewable and Sustainable Energy Reviews, 133, 2020
doi: 10.1016/j.rser.2020.110284

Word count

9592 words

Abbreviations

Life Cycle Cost Analysis (LCCA); Life Cycle Assessment (LCA); Life Cycle Cost (LCC); American Association of state Highway and Transportation Officials (AASHTO); Net Present Value (NPV); Equivalent Uniform Annual Cost (EUAC); Vehicle Operation Cost (VOC); Accident Cost (AC); Federal Highway Administration (FHWA); National Cooperative Highway Research Program (NCHRP); Monte Carlo Simulation (MC); Reclaimed Asphalt Pavement (RAP);Work Zone Delay Cost (WZDC); Maintenance and Rehabilitation (M&R); Pavement Management System (PMS); Pavement Performance Prediction Model (PPPM); Cost-Benefit Analysis (CBA); Simple Payback Period Analysis (SPPA); Road User Cost (RUC); Crash Modification Factor (CMF); Value of Time (VOT); One Factor At-a-Time simulation (OFAT); Monte Carlo Simulation (MC)

Funding sources

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Renewable and Sustainable Energy Reviews, 133, 2020
doi: 10.1016/j.rser.2020.110284

1. Introduction

With the increasing focus on sustainability, the road industry is confronted with the challenge of considering sustainable practices [1]. However, enabling sustainable transition, in combination with ensuring durability, requires high levels of investments [2,3]. Because agencies are often constrained by inadequate funds for investments, the assessment of future costs over longer periods has gained attention [4–6]. Considering budgetary constraints for projects, agencies need to use rigorous decision-making methodologies that provide insights about long-term economic viability of investments. One of those methodologies is life cycle cost analysis (LCCA), which evaluates the economic burden of an asset's life cycle while still focussing on its durability [7–12].

LCCA requires thorough identification of all materials and processes used at every phase. However, the practical application of LCCA depends on several factors. Examples include the availability of credible supporting data, insights in structural characteristics and material properties, modelling deterioration to predict the pavement condition [13–15], and the availability of guidelines to estimate user costs [16–18]. Additionally, it is indicated that different LCCA models are used interchangeably while they cannot be linked due to the lack of consistency in system boundaries and input parameters [5,19]. Some authors suggest a hybridized eco-efficiency analysis, which combines life cycle assessment (LCA) and LCCA [19,20]. Others propose an LCCA based on optimizing performance and available funds [14]. Another type of analysis that is proposed, is a new probabilistic simulation-optimization LCCA that takes into account the uncertainty of the input parameters [5,21,22].

Therefore, the difference in technique and their parallelism should be analysed, and in addition, how they are applied in roads projects. Hence, this study contains two primary aims that are achieved by answering five sub-questions:

1. To provide a state-of-the-art review and analysis of the existing methodologies in the wider field of LCCA for road projects.
    a. How is LCCA for road projects defined and how was it developed?
    b. What are the life cycle phases and related cost components of a road?
2. To highlight the critical processes and differences between the models, and to identify the shortcomings so the robustness of an LCCA framework for road projects can be increased.
    a. Which cost components are currently (not) considered?
    b. What are the most commonly applied economic models and corresponding analysis parameters?
    c. How is sensitivity analysis being performed?

In order to answer these, 44 case studies from the past decade were analysed. In this way, practitioners can access valuable information to gain insights into LCCA in practical terms. A full discussion of price ranges and the impact of individual materials on the life cycle cost (LCC) lies beyond the scope of this study as it would distract attention from the aforementioned gaps.

2. LCCA development and definitions

The concept of cost comparison in road engineering was first introduced by William Mitchell Gillespie in 1847. He stated: "*The road which is truly cheapest is not the one which has cost the least money, but the one which makes the most profitable returns in proportion to the amount which has been expended upon it" (p.65 [23]).* This concept was not widely used until the 1950s and 1960s. In 1960, the American Association of State Highway and Transportation Officials (AASHTO) published an informational guide on project procedures [24]. According to AASHTO, cost computations should reflect original investments, anticipated lifespans, maintenance and salvage values. They highlighted the importance of cost comparisons based on service life of a pavement structure because maintenance would seriously affect the cost comparison. However, it should only be implemented when based on accurately kept long-term records.

Initially developed by the US Department of Defence to enhance its cost-effectiveness in awarding competitive bids, LCCA have gained relevance in other sectors that seek to make decisions for sustainable development. AASHTO introduced LCC in their road design guide in 1972 and reused it in their 1983 and 1993 guides. According to AASHTO, LCC consists of all costs and benefits involved in the provision of pavements throughout their complete life cycle. This should include costs related to construction, maintenance, rehabilitation and recycling for the highway agency and costs related to travel time, vehicle operation (VOC), accidents (AC) and time delay during initial construction, maintenance or rehabilitation for the road user. Since these costs do not occur at the same time, an interest rate or time value of money became important. Hence, the terms net present value (NPV) and equivalent uniform annual cost (EUAC) were introduced [25]. The National Cooperative Highway Research Program (NCHRP) adopted these definitions and published in 1985 one of the first manuals to perform an LCCA of pavements [26]. In 1988, they revised this work, which resulted in recommendations regarding methods of cost-effectiveness analysis for highway projects [27].

Later in 1995, the Federal Highway Administration (FHWA) published a designation act with requirements to conduct an LCCA for all project segments on the national highway system with a cost of $25 million or more [28]. In 1996, they wrote a policy statement where they highlighted the importance of LCCA and encouraged the implementation in projects with a cost lower than $25 million [29]. FHWA published a manual for LCCA in pavement design in 1998 that addressed broad fundamental principles as well as detailed procedures. This document advocated the use of probabilistic approaches to incorporate risk analysis to consider uncertainty, which was typically hidden in the traditional deterministic approaches [30]. Therefore, it became the foundation for later FHWA LCCA guidance and tools.

LCCA for European road projects was introduced in 1997 during the Forum of European Highway Research Laboratories [4]. This led to the establishment of the PAV-ECO (economic evaluation of pavement maintenance) project in 1999 with European agencies from Finland, Denmark, Germany, France, Switzerland and United Kingdom [31]. Recently, efforts have been made by several researchers to define the term LCCA. Santos et al. [3] stressed the importance of long-term effects: "*LCCA is an analytical methodology that uses economic principles to evaluate long-term alternative investment options in infrastructure management processes in order to select optimal strategies*" *(p.1 [3]).* Also, Lee et al. focussed on long-term effects: *"LCCA is an analytical technique that uses economic principles to evaluate long-term alternative investment options for highway construction" (p.2* [32]*).* Abdelaty et al. focussed on the fact that LCCA should be performed during the design stage of projects. According to them, LCCA is "*a set of procedures used to evaluate the economic value of different design alternatives at the design stage of the project development process" (p.724* [33]*).*

Guo et al. combined both aspects in the following definition: *"LCCA is a way to evaluate the long-term cost-effectiveness of different pavement designs or treatment actions" (p.389 [5]).* Hasan et al. did not focus on the timeframe or period when an LCCA should be performed, but on a clear difference between initial costs and costs that incur in the future: "*LCCA is the conventional procedure for the* *evaluation of the financial benefits and returns from any investment by analysing its future expenditures along with the initial costs" (p.542* [34]*).*

All the previous definitions are somewhat different. However, there are some keywords that are recurring: analytical technique, economic principles, long-term, a period of analysis, design alternatives, initial costs and future costs. The lack of a clear and conclusive definition for LCCA in road engineering makes it is imperative to have a working definition. In the context of road engineering, this paper defines LCCA as a systematic or analytical methodology that uses economic techniques to evaluate long-term life cycle costs of alternatives by calculating the initial costs and discounting all future costs incurred, throughout the road's lifespan, over a predefined period of analysis.

3. The life cycle of a road

The general life cycle of a road is presented in Fig. 1. This diagram differentiates two approaches for material flows. The first approach is linear, represented by phase 1 raw materials extraction until phase 5B landfill or 5C energy recovery after incineration, which considers material flows where new virgin materials are required after the end of life (EOL) of the previous system. The second approach is circular, represented by phase 1 raw materials extraction until phase 5A recycling, which has the goal to utilize products at the highest value of all time and takes into account material flows where primary materials are saved due to recycling and reuse of waste products after the EOL of the previous system [7,35,36].

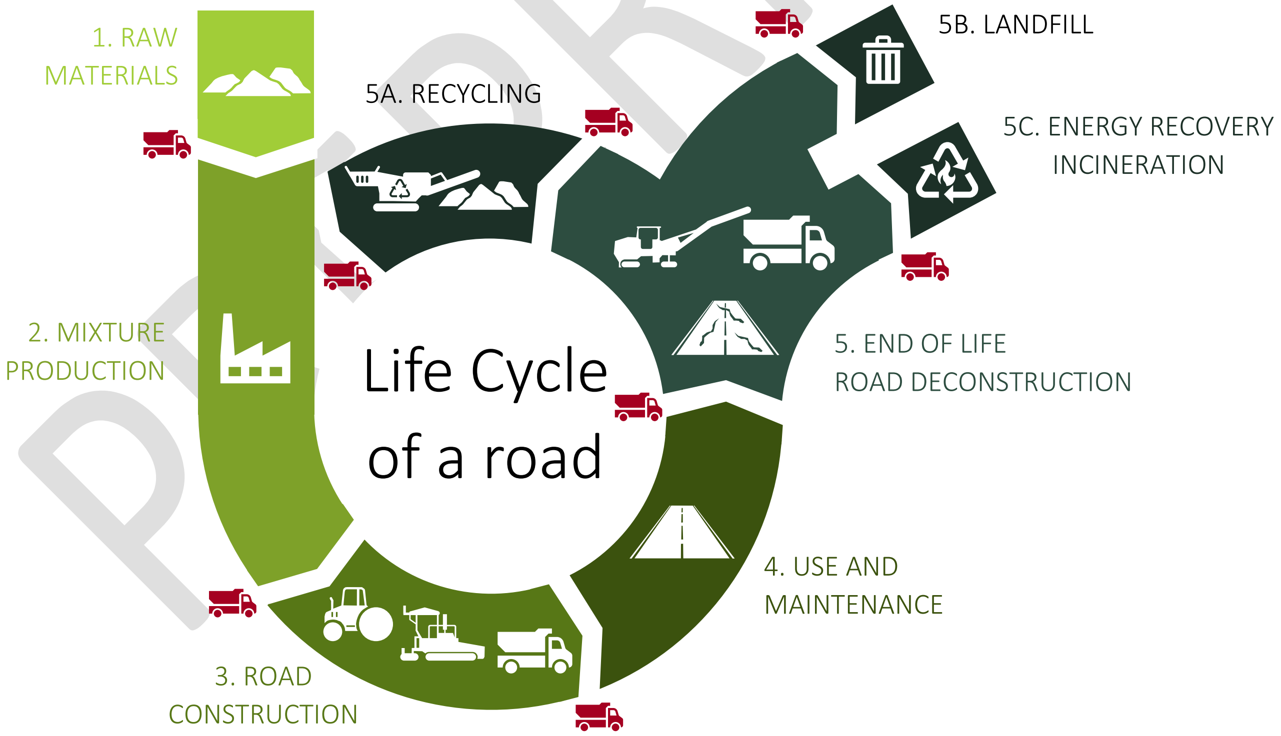

Fig. 1 Representation of the life cycle of a road based on a circular and linear approach. (The trucks in between the life cycle phases are representing possible transportation phases).

Whether recycling or reuse is preferred over the use of new materials depends on the impact of multiple factors. For example, the difference in transportation distances, the impact of the recycled or reused materials on the durability of the new product and the impact of the recycling or disposal processes. Hence, including all the different life cycle phases is important for the sustainability assessment of alternatives [37–39]. Therefore, the following part of the paper will describe all the different life cycle phases of a road and important cost components which should be considered.

3.1. Raw materials extraction

A holistic consideration of the LCCA of a road's life cycle commences with the cost of raw materials extraction, acquisition and/or production of primary materials such as aggregates, fillers, sand, bitumen, cement, water and additives [40,41]. This should include all the processes involved in acquiring (e.g. extracting and mining), processing (e.g. refining and crushing) and transporting road materials [1]. The costs associated with this phase arise from the use of equipment, materials, energy, labour, and transportation of materials to the production plant. In most cases, all the cost components are grouped into a material unit price. However, distances between materials sources and production plants can significantly affect the cost of materials, especially when secondary waste materials are being recycled and compared with primary materials [42–44]. In addition, the transportation type can also have a substantial effect on the cost of the materials [44]. This makes it difficult to differentiate costs if a unit price is used when other transport distances or types are considered for other alternatives. Therefore, for a detailed LCCA, the cost of transportation should be settled separately from the material cost.

3.2. Mixture production

The production of bitumen or cement-bound mixtures is according to several authors one of the main contributors to the total LCC due to the high amount of energy that is needed for drying, heating and mixing the different materials [45–49]. The energy consumption during production also has a strong link with the impact of the material extraction phase. For example, when primary aggregates for asphalt production are being saved due to the use of reclaimed asphalt pavement (RAP), a second burner often needs to be installed for drying RAP. Consequently, the energy cost during the production will increase, while the material cost decreases. Vice versa, when the energy consumption is lowered, for example, when the temperature is decreased to produce warm mix asphalt instead of hot mix asphalt, an additive is used. This additive is an extra material which increases the material cost but decreases the energy cost during production. Other cost components that are associated with this phase are the costs for handling the materials at the production plant, equipment, emission permits, labour, taxes, licensing and operation permits [3,50].

3.3. Road construction

Road construction comprises diverse processes and associated equipment requirements for initial construction works [40,41]. First, the unbound materials, bitumen or cement-bound mixtures and equipment must be transported to the construction site. Afterwards, construction can begin, which can include (but is not limited to) the following aspects: clearing of the site, excavating, treating the base or foundation with cement or lime and compacting it, constructing and compacting the different road layers, and integrating the different ancillary road facilities (e.g. lighting and signs) [40]. The associated costs include transportation, safety measurements, construction machinery or equipment (i.e. fuel consumption, mobilization, demobilization, insurance, taxes, interest depreciation and licenses), storage on site and labour (i.e. wages, contractual benefits) [3]. Additionally, road users incur extra costs due to construction. These costs can be significant and should be included in the analysis. They include VOC, a higher possibility for AC due to more narrow lanes and work zone delay costs (WZDC) due to time loss [1].

3.4. Use phase and maintenance

The use phase accounts for the interactions between vehicles, the pavement surface condition and the pavement performance over its service life [40]. The road user costs associated with this stage consist of fuel consumption, tire wear, vehicle maintenance and vehicle depreciation due to mileage [1,3,40]. Road durability and performance is affected by climatic factors [51,52] (e.g. temperature) and human-induced activities (e.g. traffic load and initial design), consequently causing deterioration. Therefore, maintenance is needed to lower the road's deterioration speed. Maintenance and rehabilitation (M&R) are a set of preventive and reactive works that are performed at different periods throughout the service life of the road to enhance the overall performance and maintain its serviceability [41]. If there is excessive deterioration, rehabilitation is required to restore the pavement to its former condition.

In general, three types of M&R can be identified [53–57]. Preservation is applied when the road is still in good condition. This treatment extends the road's service life without increasing its structural capacity, which makes this treatment relatively simple and inexpensive. However, preservation treatments must be applied before deterioration starts which results in a more frequent application. Examples of preservation treatments are crack filling, patching, slurry seals, chip seals, micro-surfacing and diamond grinding. Maintenance delays future deterioration and improves the road's condition without substantially increasing its structural capacity. Examples of maintenance treatments are ultra-thin and thin asphalt overlays, stress absorbing membrane interlayers for concrete pavements, hot in-place recycling and cold in-place recycling. Finally, when the pavement condition and structural capacity is too poor, with a high risk of structural failure, service life must be extended by applying rehabilitation treatments. Rehabilitation has the highest cost because it involves the milling or demolishing of the existent road and the reconstruction of a new one. Similar to the construction phase, the associated cost components for M&R activities may include materials, construction machinery or equipment, labour and transportation [3].

3.5. End of Life: road deconstruction and waste processing

The EOL phase includes the final disposal, processing or recycling of the road at the end of its service life [1,41]. Generally, three waste streams are generated when a road is milled or demolished and transported to a processing site [3,40]. Firstly, see 5A in Fig. 1, waste can be processed (crushed and sieved) into secondary materials for production, e.g. RAP or reclaimed concrete aggregate. Secondly, it can be disposed at a landfill site, as presented by 5B in Fig. 1, when the material is contaminated with and cannot be reused directly as construction material, e.g. asphalt with steel fibres. However, this is not preferred because it is a linear stream that results in the extraction of new virgin materials. Additionally, waste should only be landfilled when it is not harmful to the surrounding environment. Finally, if the materials are harmful to the surrounding environment, such as RAP containing tar, they are incinerated so that energy can be recovered, see 5C in Fig. 1. The associated cost components are fees for waste generation and disposal, transportation, milling/demolishing and sweeping during deconstructing, waste processing and labour.

4. LCCA in road engineering – Process & Steps

4.1. Define goal & scope and alternative design strategies

The first step in performing an LCCA is to define the goal & scope and design alternatives. This helps to understand how design choices may impact the future cost of the road user, initial construction, M&R and EOL [58,59]. It is important to keep in mind that all alternatives have to follow all necessary standards so that mechanical performance and durability are ensured during the specified period of analysis [60]. The analysis period is regarded as the time horizon over which future costs are evaluated. However, the BS ISO 15686-5 standard [61], which describes the methodology for performing LCCA for buildings and constructed assets, does not specify an analysis period. According to the standard, it is the researcher who determines the analysis period.

Walls and Smith [59] advocate for an analysis period longer than the road's lifespan, except for instances in which there is an extremely long-lived road, e.g. roads with perpetual pavements. In that case, the analysis period should be equal to the road's lifespan. Other authors, such as Caltrans [62] and Li et al. [44], recommend an adequately long analysis period to reflect long-term costs associated with practical design strategies, including M&R and EOL. They propose analysis periods of 35 and 55 years. The analysis period of 35 years is suggested if a preventive maintenance program for 20-year design alternatives is compared. The analysis period of 55 years should be used when 20-year and 40-year design alternatives are compared. Analysis periods shorter than 10 years should only be used when the road or pavement is a temporary solution which needs significant reconstruction within this analysis period. Generally, when alternatives with different design lives are compared, the analysis period should be based on the alternative with the longest design life. Additionally, as a rule of thumb, the selected analysis period should be the same for all alternatives under consideration so that the long-term costs for these alternatives can be determined and compared with each other.

The absence of a clear guideline for a predefined analysis period is demonstrated in Fig. 2, which shows the analysis periods used in the recent case studies from **Fout! Verwijzingsbron niet gevonden.** and **Fout! Verwijzingsbron niet gevonden.**. The graph shows a wide variety of applied analysis periods. This is an important observation as it has implications for the comparison of results from different authors. Studies with different analysis periods should never be compared because the LCC is highly dependent on the analysis period used. The large spread of the results suggests that only a few studies can be compared with each other and that results should never be compared one-to-one without considering the analysis periods.

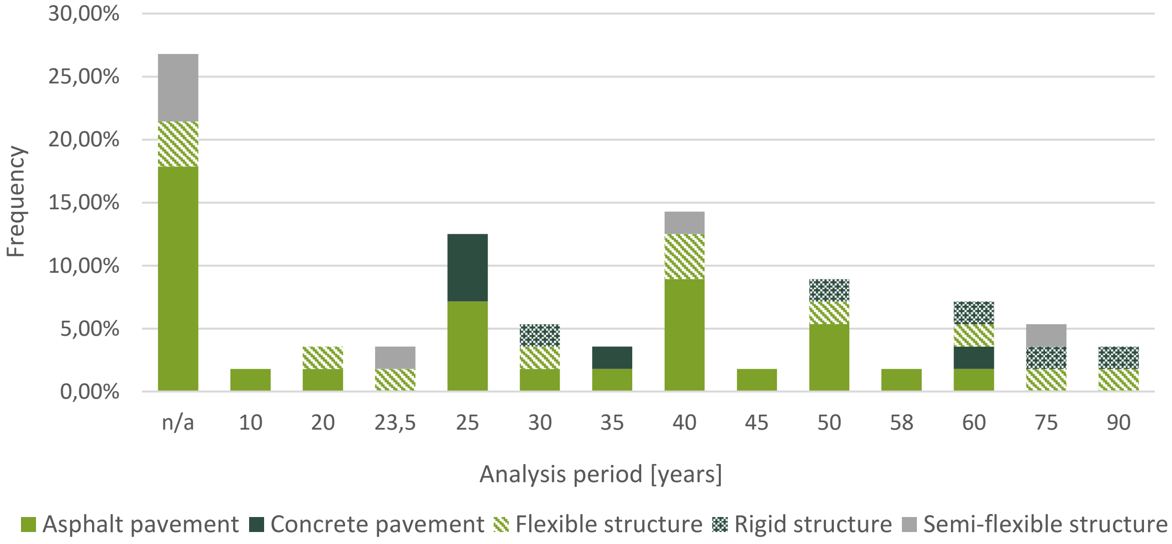

Fig. 2 Frequency of analysis period used in recent case studies per road type (n=56)

However, some observations can be made despite the variance in analysis period. Generally, it can be concluded that studies which are focusing on the life cycle of rigid structures use longer analysis periods. In addition, case studies that are only focusing on flexible and/or semi-flexible structures use shorter analysis periods. As mentioned before, it is important to use the same analysis period for all alternatives. Therefore, when studies combine rigid structures with other types, the analysis period also tends to be higher. This is likely to be related with the higher lifespan of concrete compared to asphalt.

Renewable and Sustainable Energy Reviews, 133, 2020
doi: 10.1016/j.rser.2020.110284

Table 1 Recent case studies (2010-2016)

General information					**Analysis information**				**User costs**			**Agency costs**												
												Initial Constr.				**Maintenance**				**EOL**				
Author	**Year**	**Country**	**Variants**	**Focus**	**Method**	**AnP**	**DR**	**SA**	**VOC**	**WZDC**	**AC**	**ME**	**MP**	**RC**	**T**	**P**	**M**	**R**	**T**	**RDC**	**WP**	**T**	**SV**	**RV**
Robinette et al. [63]	2010	USA	12	FS, SFS	CBA	-	-	-	-	-	-	x	x	x	?	x	x	x	?	x	-	-	-	-
Leng et al. [64]	2011	USA	3	AP	CBA	-	-	-	-	x	-	x	x	x	?	-	-	-	-	-	-	-	-	-
Lee et al. [65]	2011	USA	3	FS, RS	NPV	60	4%	-	-	x	-	x	x	x	?	-	x	x	?	x	-	-	-	-
Amini et al. [66]	2012	Iran	2	FS	NPV	40	2,3%	OFAT	x	x	-	x	x	x	x	x	x	x	?	x	-	-	-	-
Cheng et al. [67]	2012	USA	2	AP	NPV, EUAC	20	4%	MC	x	x	-	x	x	x	?	x	x	x	?	x	-	-	x	-
Santos et al. [68]	2012	Portugal	16	FS	NPV	40	3%	-	?	?	?	x	x	x	?	x	x	x	?	x	-	-	-	x
Gschösser et al. [47]	2013	Switzerland	3	FS, SFS, RS	NPV	75	2%	-	-	-	-	x	x	x	x	-	x	x	x	x	x	x	-	-
Li et al. [45]	2013	USA	3	FS, SFS	NPV	23,5	3%	-	-	-	-	x	x	x	x	-	-	x	x	x	-	-	x	x
Aurangzeb et al. [69]	2014	USA	4	AP	NPV	45	4%	OFAT	?	x	?	x	x	x	?	x	x	x	?	-	-	-	-	x
Mirzadeh et al. [46]	2014	Sweden	1	AP	EUAC	25	4%	OFAT	-	x	-	x	x	x	x	-	-	x	x	x	-	-	-	-
Son et al. [70]	2014	USA	6	AP	CBA	-	-	MC	?	x	-	-	-	-	-	-	x	-	?	-	-	-	-	-
Zaumanis et al. [71]	2014	?	1	AP	SPPA	-	-	OFAT	-	-	-	x	x	-	?	-	-	-	-	-	x	-	-	-
Santos et al. [3]	2015	USA	3	AP	NPV	50	2,3%	OFAT	x	x	-	x	x	x	x	-	x	x	x	x	-	-	-	x
Yang et al. [72]	2015	USA	11	AP	CBA	-	-	-	-	-	-	x	x	x	x	-	-	-	-	-	-	-	-	-
Yu et al. [53]	2015	?	1	AP	NPV	40	4%	-	x	-	-	-	-	-	-	x	x	x	?	x	-	-	-	x
Abdelaty et al. [33]	2016	USA	3	AP	EUAC	25	4%	MC, OFAT	-	-	-	-	-	-	-	x	x	x	?	x	-	-	-	-
Nazzal et al. [73]	2016	USA	2	AP	NPV	10	?	-	-	-	-	x	x	x	?	?	x	?	?	?	-	-	-	-
Souliman et al. [74]	2016	Sweden	3	AP	CBA	-	-	OFAT	-	-	-	x	x	x	?	-	-	-	-	-	-	-	-	-
Sultan et al. [75]	2016	China	7	FS, SFS	CBA	-	-	-	-	x	-	x	x	?	?	-	-	-	-	-	-	-	-	-
Sultan et al. [76]	2016	China	3	SFS	NPV	40	?	-	-	x	-	x	x	x	?	-	x	x	?	x	x	?	x	-
Wennström et al. [56]	2016	Sweden	12	AP	NPV, EUAC	40	4%	OFAT	x	x	x	x	x	x	?	-	-	x	?	x	-	-	-	x
Yepes et al. [77]	2016	Chile	4	AP, CP	NPV	25	4%	-	-	-	-	-	-	-	-	x	x	x	?	x	-	-	-	-

AnP = Analysis Period, DR = Discount Rate, SA = Sensitivity Analysis, VOC = Vehicle Operation Costs, WZDC = Work Zone Delay Costs, AC = Accident Costs, ME = Material Extraction, MP = Mixture Production, RC = Road Construction, T = Transport, P = Preservation, M = Maintenance, R = Rehabilitation, RDC = Road Deconstruction, WP = Waste Processing, SV = Salvage Value, RV = Residual Value, AP = Asphalt Pavement, CP = Concrete Pavement, FS = Flexible Structure, SFS = Semi-Flexible Structure, RS = Rigid Structure, CBA = Cost-Benefit Analysis, NPV = Net Present Value, EAUC = Equivalent Annual Uniform Cost, SPPA = Simple Payback Period Analysis, OFAT = One Factor At-a-Time, MC = Monte Carlo simulation, BA = Bayesian Analysis, - = Excluded, x = Included, ? = Unknown

Table 2 Recent case studies (2017-2020)

General information					**Analysis information**				**User costs**			**Agency costs**												
												Initial Constr.				**Maintenance**				**EOL**				
Author	**Year**	**Country**	**Variants**	**Focus**	**Method**	**AnP**	**DR**	**SA**	**VOC**	**WZDC**	**AC**	**ME**	**MP**	**RC**	**T**	**P**	**M**	**R**	**T**	**RDC**	**WP**	**T**	**SV**	**RV**
Akbarian et al. [21]	2017	USA	6	AP, CP	NPV	35	2%	MC	x	x	-	x	x	x	?	x	x	x	?	X	-	-	-	X
Wu et al. [78]	2017	China	3	CP	NPV	25	3,5%	MC, OFAT	x	x	-	-	-	-	-	x	x	x	?	X	-	-	-	-
Liu et al. [79]	2017	UK	10	AP	CBA	-	-	-	-	-	-	-	x	-	-	-	-	-	-	-	-	-	-	-
Underwood et al. [51]	2017	USA	3	AP	NPV	30	4%	-	-	-	-	x	x	x	?	-	-	x	?	X	-	-	-	X
Santos et al. [80]	2017	USA	14	AP	NPV	50	2,3%	OFAT	x	x	-	x	x	x	x	x	x	x	x	X	-	-	-	X
Ozer et al. [81]	2017	USA	8	SFS	CBA	-	-	-	-	-	-	x	x	x	x	-	-	-	-	-	-	-	-	-
Batouli et al. [58]	2017	USA	3	FS, RS	NPV	50	5%	MC, OFAT	x	x	x	x	x	x	?	?	x	x	?	X	-	-	-	-
Torres-Machi et al. [54]	2017	Chile	20	AP, CP	NPV	25	6%	OFAT	-	-	-	-	-	-	-	x	x	x	?	X	-	-	-	-
Coleri et al. [82]	2018	USA	3	AP	NPV	50	?	OFAT	-	-	-	x	-	x	?	-	-	x	?	X	-	-	-	X
Lee et al. [32]	2018	USA	2	AP, CP	NPV	60	4%	-	-	x	-	x	x	x	?	-	x	x	?	X	-	-	-	-
Diependaele [83]	2018	USA	2	FS, RS	NPV	90	3%	OFAT	-	-	-	x	x	x	?	x	x	x	?	X	-	-	-	-
Diependaele [83]	2018	Belgium	2	AP, CP	NPV	inf.	4%	OFAT	-	-	-	x	x	x	?	x	x	x	?	X	-	-	-	-
Qiao et al. [84]	2019	USA	3	FS	NPV	20	4,6%	OFAT	x	x	-	x	x	-	?	-	x	-	?	-	-	-	-	-
Qiao et al. [52]	2019	USA	2	FS	NPV	20	2%	OFAT	x	-	-	x	x	x	x	x	x	-	x	X	X	X	X	-
Wang et al. [85]	2019	USA	2	AP	EUAC	-	4%	BA, OFAT	-	-	-	-	-	-	-	-	x	x	?	-	-	-	-	-
Chen et al. [86]	2019	Taiwan	3	AP	NPV	40	4%	MC, OFAT	x	x	-	x	x	x	x	-	x	x	x	X	-		-	-
Guo et al. [5]	2019	USA	2	FS, RS	NPV	30	4%	MC, OFAT	x	-	-	x	x	x	?	-	x	-	?	-	-	-	-	-
Okte et al. [55]	2019	USA	1	AP	NPV	58	3%	OFAT	x	x	x	x	x	x	?	-	x	-	?	-	-	-	-	-
Nahvi et al. [87]	2019	USA	4	AP	EUAC	-	3%	MC	-	-	-	-	-	-	-	x	-	-	?	-	-	-	-	-
Choi [50]	2019	Korea	3	AP	NPV	40	4,5%	-	x	x	x	-	-	-	-	-	x	x	?	X	-	-	-	-
Nahvi et al. [12]	2019	USA	2	AP	EUAC	-	3%	MC	-	-	-	-	-	-	-	x	-	-	?	-	-	-	-	-
Gu et al. [17]	2019	USA	1	AP	NPV	40	2,1%	MC, OFAT	x	x	-	x	x	x	?	-	x	x	?	X	-	-	-	X
Jahanbakhsh et al. [48]	2020	Iran	9	AP	CBA	-	-	-	-	-	-	x	x	-	?	-	-	-	-	-	X	-	-	-

AnP = Analysis Period, DR = Discount Rate, SA = Sensitivity Analysis, VOC = Vehicle Operation Costs, WZDC = Work Zone Delay Costs, AC = Accident Costs, ME = Material Extraction, MP = Mixture Production, RC = Road Construction, T = Transport, P = Preservation, M = Maintenance, R = Rehabilitation, RDC = Road Deconstruction, WP = Waste Processing, SV = Salvage Value, RV = Residual Value, AP = Asphalt Pavement, CP = Concrete Pavement, FS = Flexible Structure, SFS = Semi-Flexible Structure, RS = Rigid Structure, CBA = Cost-Benefit Analysis, NPV = Net Present Value, EAUC = Equivalent Annual Uniform Cost, SPPA = Simple Payback Period Analysis, OFAT = One Factor At-a-Time, MC = Monte Carlo simulation, BA = Bayesian Analysis, - = Excluded, x = Included, ? = Unknown

Fig. 3 presents the analysis period used per set of system boundaries. The analysis shows that 29,5% of the case studies did not use or specify an analysis period (n/a). This includes nine cases that performed a cost-benefit analysis (CBA), one case that performed a simple payback period analysis (SPPA) and three cases that calculated the EUAC of maintenance activities for asphalt pavements with service lives under 15 years. In total, five cases used an analysis period of 25 years. Four of these are only focussing on M&R and do not consider initial construction and EOL. Additionally, there are two CBAs that only focus on M&R and do not consider other costs. Hence, it can be concluded that studies which are focussing on M&R often use no analysis period or analysis periods shorter than 25 years. Finally, it can be concluded that CBAs don't use an analysis period because all activities are done in the base year.

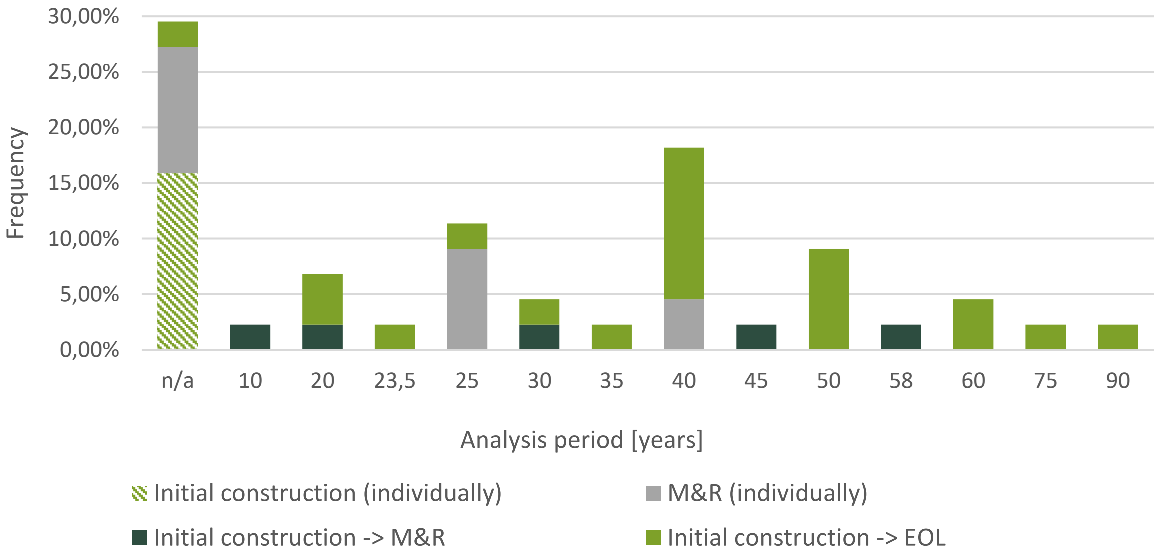

Fig. 3 Frequency of analysis period used in recent case studies per set of system boundaries (n=44)

4.2. Determine performance periods & M&R activities

After the design alternatives and analysis period have been determined, it is important to predict the initial service lives and M&R to account for future costs [59,88]. Yang et al. [89] describe the initial period as the average time in years for a newly constructed road to reach an agency's threshold for the first rehabilitation, while the rehabilitation period is the length of time after this first threshold to reach another rehabilitation threshold. Because M&R may be postponed due to budgetary restrictions, the actual rehabilitation does not necessarily occur at the same time which a pavement has reached the performance threshold. Hence, inaccurate estimations of the performance periods directly affects the frequency of agency intervention, consequently affecting agency costs and user costs during construction and M&R [88].

Therefore, the use of pavement performance data in a pavement management system (PMS), in combination with a pavement performance prediction model (PPPM), is critical [90,91]. These are vital techniques as they predict the optimal timing for M&R based on different factors that cause road deterioration, such as material ageing, traffic characteristics and climatic effects [92]. Hence, a PPPM helps to allocate funds for road projects efficiently and decreases the cost of M&R [75,91,93]. Fig. 4 demonstrates the operation of a typical PPPM [9,59,88]. To significantly increase the pavement condition, when excessive distress has accumulated, high maintenance budgets are often needed for rehabilitation. Therefore, in some cases, it is better to use preventive maintenance strategies, which have lower costs than rehabilitation, but need to be applied more frequently. To select the optimal strategy, it is important to determine the impact on the overall LCC using available budgets and the level of acceptance of distress.

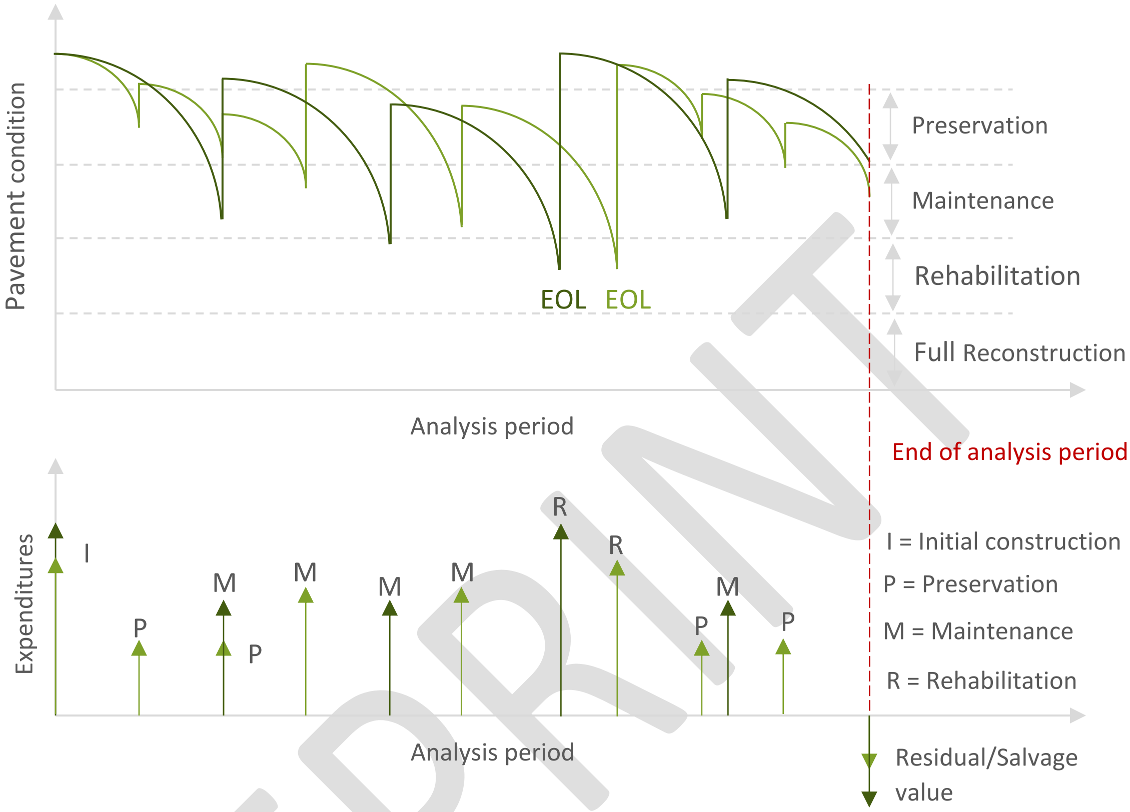

Fig. 4 A typical PPPM curve with corresponding expenditure stream diagram

The PPPM uses a condition indicator, often based on measurements of surface characteristics, to predict the pavement condition. Over the years, different pavement condition indicators have been designed for PPPMs and used to characterize the physical condition of roads and to allow accurate M&R decision-making. Some of the most commonly used indicators include the Pavement Serviceability Index, Pavement Condition Index, International Roughness Index, Pavement Condition, Present Serviceability Rating and Pavement Surface Condition Index [94–97]. The choice and application of a PPPM is location specific because the type and accumulation of distress over time often depends on the climate and traffic characteristics [98]. Once all activities have been determined for the analysis period, a corresponding expenditure stream diagram can be prepared, see Fig. 4. The graphical representation of an expenditure diagram in LCCA is important because it presents a visual overview of all cash flows for all alternatives with regards to its initial construction, M&R and EOL considerations throughout its life cycle [10,99].

4.3. Estimate costs

The costs presented in section 3 are often categorized in several groups. According to the ISO standard [61] and Santos et al. [3], costs can be categorized as being either fixed or variable. Costs that are fixed remain the same regardless of the amount of material production, e.g. costs of insurances, depreciation, licensing and permits. Costs that are influenced by the amount of produced mixture are variable costs. Materials can be, for example, variable because the unit price may vary depending on the purchased quantity. Others, such as Estevan et al. [100] and Wong [101], categorize costs under direct or indirect. According to them costs that are directly associated with road construction e.g. acquisition, production, construction, M&R and EOL are direct costs and external costs like environmental costs are indirect costs.

A third and related distinction can be made between tangible or intangible costs [44,99]. Tangible costs are "measurable" out-of-pocket costs that are considered as the project's expenditures and are estimated based on their available market values. Hence, these are all costs related to the construction, M&R and EOL phase of a road incurred by contractors and road agencies. Intangible costs are the costs encountered as a result of implementing the project but are incurred indirectly and are out-of-pocket. Intangible costs are, for example, incurred by road users because of the time delay due to road construction. Finally, costs can be categorized as either present costs or future costs [46]. In LCCA, all the aforementioned categories are incurred either by the road agency or by the road user [99]. Therefore, all the cost components of the case studies were categorized under user and agency costs as presented in Fig. 5.

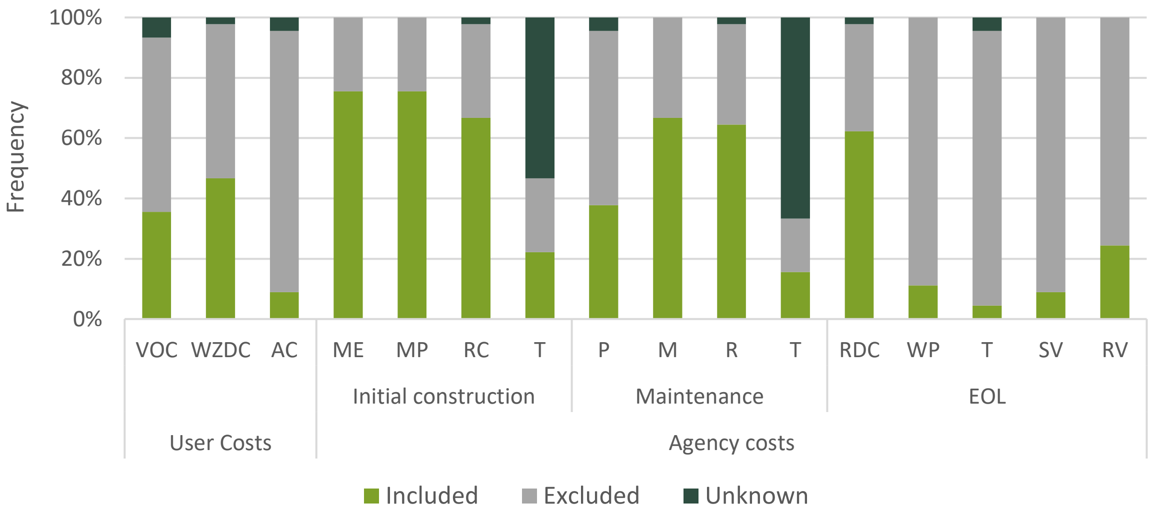

Fig. 5 Frequency of cost components used in recent case studies (n=44) where VOC = Vehicle Operation Costs, WZDC = Work Zone Delay Costs, AC = Accident Costs, ME = Material Extraction, MP = Mixture Production, RC = Road Construction, T = Transport, P = Preservation, M = Maintenance, R = Rehabilitation, RDC = Road Deconstruction, WP = Waste Processing, SV = Salvage Value, RV = Residual Value

4.3.1. Agency costs

Agency costs denotes all costs incurred directly by the road agency throughout the road's lifespan [58]. These costs should include preliminary engineering, contract administration, production, construction, M&R, transportation of materials and equipment and EOL [30,32,93]. Furthermore, agency costs are estimated for the entire length and lifespan of the design alternatives under consideration. Therefore, these costs are often subdivided into three categories: costs associated with initial construction in the beginning of the road project, M&R during the use phase and EOL at the end of the project.

In LCCA, comparisons are only made between competing alternatives that are mutually exclusive, reflecting differential costs between alternatives. Therefore, costs that are equal for all alternatives are often excluded in the analysis. In the past, traffic control costs were not included by many agencies because authors assumed that construction durations for all alternatives would be the same. However, it is possible that alternatives have different construction periods. Hence, the alternative with the longest construction period will have the highest traffic control cost. Therefore, Jackson et al. [102], strongly recommend considering traffic management costs in comparing alternative design costs as they may have a significant effect. Another example of a cost component that is often excluded, is the planning of a road project, e.g. costs related to structural and/or mixture design and preliminary testing. Fig. 5 demonstrates that most of the other cost components, related to initial construction, are included in LCCA. What stands out in Fig. 5 is that transportation is either unknown or excluded in 77% of the cases. When CBA or SPPA is performed, it is highly likely that the analysis will focus on the initial construction as it takes place in the base year. However, in some LCCAs initial construction is left out of the analysis because the project is focussing on M&R.

Although preservation costs are generally low, thus negligible compared to other costs, preservation has to be performed on a regular basis and thus should not be underestimated [102]. It is observed that these especially have a significant effect on the LCCA when rapid fluctuations are observed in future M&R and material prices [53]. However, it is apparent from Fig. 5 that very few studies consider preservation and that transportation costs during M&R are often excluded or unknown. The percentage of studies that include M&R is lower compared to initial construction as CBAs and SPPAs often exclude this phase.

The final subcategory of the agency cost is the EOL cost related to the deconstruction of the existing road or pavement, the transportation of waste, waste processing and the salvage or residual value [44,50,82,88]. However, Fig. 5 demonstrates that EOL in most cases is excluded. The only cost component that the cases are considering is the cost associated with the deconstruction of the road, hence milling. In addition, it was found that salvage and residual value are being used interchangeably despite the difference in modelling. Therefore, clear and conclusive definitions are introduced for the use in road design. This paper defines residual value as the value of a road when its service life reaches beyond the end of the analysis period and salvage value as the value after the recycling of materials when a road has reached the end of its service life, so primary materials are saved.

According to Gu et al. [17], the salvage value of a material is calculated based on the price of the primary materials minus the processing cost of the recycled material. RAP, for example, has two possibilities. Firstly, it can be recycled as an unbound or cement-bound material when the bitumen is not recycled. Therefore, the salvage value is equal to the material and transport cost of primary aggregates minus the cost of transport and processing RAP. Secondly, it can be recycled into new bitumen-bound layers. Hence, the salvage value is equal to the binder percentage of RAP multiplied by the price (transport included) of virgin bitumen plus the aggregate percentage of the RAP multiplied by the price (transport included) of primary aggregates minus the cost of transport and processing RAP. Hence, Eq. 1 is proposed to determine the salvage value:

$$SV = \left(\sum_{i=1}^{n} x_i \left(UME_i + UT_i * L_i \right) \right) - UWP_{rec.} - UT_{rec.} * L_{rec.} \qquad \text{Eq. 1}$$

Where *SV* is the salvage value after recycling in €/ton, *n* is the number of materials that are being saved, x_i is the mass percentage of material i in the recycled content, UME_i is the unit price of material i in €/ton, UT_i is the unit price for transporting material i in €/(ton.km), L_i is the transport distance of material i in km, $UWP_{rec.}$ is the unit cost for processing the recycled material in €/ton, $UT_{rec.}$ is the unit price for transporting the recycled material in €/(ton.km) and $L_{rec.}$ is the transport distance of the recycled material i in km.

The residual value on the other hand can be determined in a simple fashion using Eq. 2 [17,51,53,56]:

$$RV = CC\left(1 - \frac{S}{T}\right) \qquad \text{Eq. 2}$$

Where *RV* is the residual value after the end of the analysis period, *CC* is the construction cost of the latest activity (initial construction or M&R), *S* is the expected service life until the end of analysis and *T* is the total expected service life.

However, according to Santos et al., it is better to link the residual value of a pavement with its remaining surface condition [68]. As discussed before, several pavement condition indicators exist. Therefore, Eq. 3 presents the residual value in terms of a general indicator that can be replaced by any specific indicator.

$$RV = CC * \frac{PCI - PCI_{threshold}}{PCI_{initial} - PCI_{threshold}} \qquad \text{Eq. 3}$$

Where *RV* is the residual value after the end of the analysis period, *CC* is the construction cost of the latest activity (initial construction or M&R), *PCI* is the measured value of the applied pavement condition indicator after the analysis period is finished, $PCI_{threshold}$ is the threshold limit for M&R for the pavement condition indicator and $PCI_{initial}$ is the initial value of the pavement condition indicator of a new pavement or after M&R activities.

4.3.2. User costs

User costs are mainly incurred by the public through the use and operation of vehicles as well as their travel time. The road user cost (RUC) is often grouped as an aggregation of WZDCs, VOCs and ACs [58,102,103]. Fig. 5 indicates that RUC is often excluded in LCCAs for road projects. A possible explanation for this might be that CBAs or SPPAs are focussing on the initial construction and are often only interested in the agency cost. There are, however, other possible explanations. Firstly, RUC is often excluded due to its complexity and challenges that are associated with quantifying the cost components based on unreliable data. Secondly, LCCAs often only include significant differences between alternatives. When projects assume no difference in construction time, there will be no difference in RUC, hence RUC is left out of the analysis. However, there are two important reasons why RUCs should be included in LCCAs for road projects. Firstly, the RUC has a strong connection with the social aspect of sustainability assessments of road projects as the RUC is paid by society. Secondly, although the construction period for several alternatives might not differ, the planning of M&R can differ. Hence, due to discounting, there will be a difference in RUC. Therefore, the following part of this section will describe how the components of the RUC can be determined.

4.3.2.1. Vehicle operation cost (VOC)

VOC models are used to quantify the cost related to vehicle operation and changes in traffic flow conditions. These models can be very complex as they consider several parameters including vehicle category, pavement condition, fuel consumption, oil consumption, tire wear, vehicle M&R, depreciation and time related adjustment factors. Some of the most applied VOC models in road engineering are: NCHRP's report 133 method [104], FHWA's HERS-ST model [103], EPA's Moves model [105], World Bank's HDM-4 model [106], Australian Road Research Board's Road Fuel Consumption model [107] and NCHRP's MicroBENCOST model [108]. Three of these models will be discussed to present the difference in complexity and show which parameters can be included in VOC models.

The model applied by Yu et al. [53] is a simplified version of the aforementioned models. Yu et al. are focussing on the VOC by only considering the fuel consumption of five different vehicle categories and the road condition using Eq. 4:

$$VOC = UC_f \sum_{i=1}^{5} \left(FC_{base,i} * AF_{PC,i} \right) \qquad \text{Eq. 4}$$

Where *VOC* is the vehicle operation cost per km for five different vehicles, UC_f is the unit cost of fuel in €/l, $FC_{base,i}$ is the fuel consumption for vehicle type i in ml/km and $AF_{PC,i}$ is an adjusting factor based on the pavement condition as presented in Table 3.

Table 3 Effects of roughness on fuel consumption for a speed of 112 km/h applied by Yu et al. [53]

Vehicle class	**Fuel consumption**	**Adjusting factors**				
		International Roughness Index (m/km)				
	1	**2**	**3**	**4**	**5**	**6**
Medium Car	107.85 ml/km	1.02	1.05	1.07	1.09	1.12
Van	128.96 ml/km	1.01	1.02	1.03	1.03	1.04
SUV	140.49 ml/km	1.02	1.04	1.06	1.08	1.10
Light truck	251.41 ml/km	1.01	1.02	1.02	1.03	1.04
Articulated truck	656.11 ml/km	1.01	1.02	1.04	1.05	1.06

The MicroBENCOST model includes, in addition to the fuel consumption, the following parameters: oil consumption, tire consumption, vehicle M&R and vehicle depreciation. The model calculates the VOC by applying equations that include facility length, traffic volume, three vehicle categories and the relevant cost components. Afterwards individual VOCs are calculated and multiplied with their unit costs and a pavement condition factor. Finally, the total VOC is calculated by taking the sum of the several components as presented by Eq. 5.

$$VOC = \sum_{i=1}^{3} \left(UVOC_{fuel,i} + UVOC_{oil,i} + UVOC_{tire,i} + UVOC_{M\&R,i} + UVOC_{dep,i} \right) \qquad \text{Eq. 5}$$

Where *VOC* is the vehicle operation cost per km for 3 different vehicles, $UVOC_{fuel,i}$ is the fuel-related unit VOC per km for vehicle category i, $UVOC_{oil,i}$ is the oil-related unit VOC per km for vehicle category i, $UVOC_{tire,i}$ is the tire-related unit VOC per km for vehicle category i, $UVOC_{M\&R,i}$ is the M&R-related unit VOC per km for vehicle category i and $UVOC_{dep,i}$ is the depreciation-related unit VOC per km for vehicle category i.

Table 4 HERS-ST unit costs for VOC resource components in 2004 dollars [103]

Cost Component	**Small auto's**	**Medium/large auto**	**4-tire truck**	**6-tire truck**	**3+ axle single**	**3-4 axle combo**	**5+ axle combo**
Fuel ($/gal)	1.93	1.93	1.93	1.93	1.84	1.84	1.84
Oil ($/quart)	4.48	4.48	4.48	1.79	1.79	1.79	1.79
Tires ($/tire)	45.89	72.55	79.96	193	477.90	477.90	477.90
M&R ($/1000 miles)	103.50	125.60	159.60	298.70	422.50	437.60	437.60
Depreciation ($/vehicle)	19717	23255	25061	37448	82386	95432	103767

However, the previous models are both using constant speeds and do not consider speed change cycles due to work zones or curvatures of the road. FHWA has developed the HERS model to analyse these aspects and uses a fairly complicated method to compute the VOCs of seven vehicle types as a function of fuel, oil, tires, M&R and depreciation as presented in Table 4. In addition, the model calculates individual VOC components for:

1. Constant speed operating based on the vehicle category, average speed, average consumption and pavement condition;
2. Extra operating due to speed change cycles;
3. Extra operating due to road curvature;

Afterwards the total VOC is given using Eq. 6:

$$VOC = \sum_{i=1}^{7} \left(UVOC_{CS,i} + UVOC_{SC,i} + UVOC_{RC,i} \right) \quad \text{Eq. 6}$$

Where *VOC* is the vehicle operation cost per km for seven different vehicles, $UVOC_{CS,i}$ is the constant speed-related unit VOC per km for vehicle category i, $UVOC_{SC,i}$ is the speed change-related unit VOC per km for vehicle category i and $UVOC_{RC,i}$ is the road curvature-related unit VOC per km for vehicle category i.

Hence, it can be concluded that the computation of VOCs has several levels of complexity. Although it is often neglected, it is an important parameter which should be considered during the computation of the road user cost. Especially, because the impact of vehicle operation has such a strong connection with the social and environmental aspects of sustainability assessment.

4.3.2.2. Work zone delay cost (WZDC)

WZDCs are calculated using the delay time due to work zones, the value of time (VOT) and the number of vehicles that are affected by the construction zone [55,56,58,103]. Several models exist, however almost all of them are based on the same parameters: speed flow, traffic demand, capacity analysis, queue length and queue speed. Batouli et al. [58] proposed a framework using Eq. 7 - Eq. 10:

$$t_{SR} = \frac{L_{WZ}}{v_{WZ}} - \frac{L_{WZ}}{v_0} \quad \text{Eq. 7}$$

$$t_Q = \frac{L_Q}{v_Q} \quad \text{Eq. 8}$$

$$t_{WZD} = t_{SR} + t_Q \qquad \text{Eq. 9}$$

$$WZDC = t_{WZD} * AADT * t_{WZ} * VOT \qquad \text{Eq. 10}$$

Where *WZDC* is the total work zone delay cost, t_{sr} is the speed reduction delay in hours, L_{WZ} is the work zone length in km, v_{WZ} is the maximum speed in the construction zone in km/h, v_0 is the upstream speed in km/h, t_Q is the queue delay in h, L_Q is the average queue length in km, v_Q is the queue speed in km/h, t_{WZD} is the work zone delay time in h, *AADT* is the annual average daily traffic, t_{WZ} is the work zone duration in days and *VOT* is the value of time in €/h.

The abovementioned framework is in line with the framework proposed by FHWA [103]. However, FHWA highlights that the VOT differs for alternative traffic categories. There should be, for example, a difference between the VOT of passenger cars for personal travel, business travel or trucks. Therefore, Eq. 10 should be transformed in Eq. 11 where *i* stands for the traffic category and *n* stands for the total amount of considered traffic categories.

$$WZDC = t_{WZD} * t_{WZ} * \sum_{i=1}^{n} (VOT_i * AADT_i) \qquad \text{Eq. 11}$$

4.3.2.3. Accident cost (AC)

ACs are all costs incurred by road users resulting from an increase in accidents in work zones due to lane closure and more narrow lanes [50,56,58,103]. According to the framework proposed by FHWA [103], the first step is to determine the pre-construction crash rate (CR_{PC}). In case no data is available, Eq. 12 can be used to estimate CR_{PC}:

$$CR_{PC} = \frac{A * 10^6}{L_{WZ} * 365 * \sum_{i=1}^{AnP} AADT_i} \qquad \text{Eq. 12}$$

Where CR_{PC} is the pre-construction crash rate per million vehicle km of travel, *AnP* in the analysis period in years, *A* is the number of crashes along the project for the analysis period, L_{WZ} is the length of the work zone in km and $AADT_i$ is the annual average daily traffic in year i of the analysis period.

Afterwards, the accident cost can be determined using Eq. 13:

$$AC = CR_{PC} * CMF_{LC} * CMF_{SM} * t_{WZ} * AADT * L_{WZ} * UAC \qquad \text{Eq. 13}$$

Where *AC* is the accident cost related to road construction, CR_{PC} is the pre-construction crash rate per km, CMF_{LC} is a crash modification factor (CMF) due to an increase in crashes after lane closure (as presented, for example, in Table 5), CMF_{SM} is a CMF due to a decrease in crashes after safety measures, t_{wz} is the work zone duration in days, *AADT* is the annual average daily traffic, L_{WZ} is the length of the work zone in km and *UAC* is the unit cost of accidents.

Table 5 Average crash rates and crash modification factors for Interstate work zones in Indiana [103]

Sites	Crash rate per 10 million vehicle miles travelled Normal	Work zone	CMF_{LC}
Sites using cross-over (2 lanes each direction)	6.0329	8.0431	1.33
Sites using Partial lane closure (2 lanes each direction)	5.5916	7.4528	1.33
Sites using cross-over (3 lanes each direction)	5.8278	9.3544	1.61
Sites using Partial lane closure (3 lanes each direction)	7.5166	10.1006	1.34

However, several authors [50,55,58,103] indicate that the crash rate and unit cost of crashes are dependent on the severity of the crash. Therefore, crash categories should be implemented based on their severity, see Table 6. The number of categories depends on the used injury scale, but in most cases, there are three main categories: fatal accidents, accidents with injury and accidents with property damage only. Therefore Eq. 13 should be transformed into Eq. 14, where *i* stands for the crash category:

$$AC = CMF_{LC} * CMF_{SM} * t_{WZ} * AADT * L_{WZ} * \sum_{i=1}^{3} \left(CR_{PC,i} * UAC_i\right) \qquad \text{Eq. 14}$$

Table 6 Typical work zone crash modification factors, related to crash severity, for lane closure on freeways [103]

Crash Types	Crash Severity	CMF_{LC}
All	All	1.77
All	Property damage only	1.90
All	Injury	1.60
Night-time	All	1.57
Night-time	Property damage only	1.63
Night-time	All	1.34

4.4. Discount future costs

Discounting is a commonly used technique for comparing costs and revenues occurring at different stages in time or to emphasize the importance of present costs rather than future costs. Hence, discounting accounts for the time value of money [80]. Similarly, discounting is based on the principle that a sum of money at present is worth more than the same amount of money at a future date due to the purchasing power of that sum today. Discounting to present values adjusts the future costs of an asset, considering inflation and the real earning power of money. This allows alternatives which are incurring costs at different stages in time to be compared and assessed on the same basis as costs incurred at the present [109].

The need to discount usually depends on factors such as the chosen economic analysis, the purpose of the LCCA and the nature of the project. Generally, discounting is used when a series of costs over time has to be put onto a common basis for decision-making purposes, not where the objective is to project annual costs on year by year base [60]. Therefore, when carrying out an LCCA of two or more options with different cost profiles over time, it is likely that discounting will be applied, whereas it may not be necessary if the aim is to prepare a cost profile for one option alone.

Choosing the most appropriate discount rate is a critical step. Key considerations will be the cost of required investments, the anticipated level of risk and the opportunity cost of the investment. In the public sector, these usually fall within the range of 3 to 5% [44,46,83]. The rate may also vary from country to country. For instance, the European Commission recommends using a discount rate of 3% as a benchmark in the Member States and 5% in the other Cohesion Member States [110]. However, in case no discount rate is specified, this can be calculated based on the mathematical relationship between the inflation rate and the interest rate using Eq. 15 [46,66,78].

$$d = \frac{1 + i_{int}}{1 + i_{inf}} - 1 \qquad \text{Eq. 15}$$

Where d is the real discount rate, i_{int} is the interest rate and i_{inf} is the inflation rate.

Fig. 6 presents the discount rates used in the case studies per economic indicator. The most applied specified discount rate is 4%. Ten case studies did not apply a discount rate as they performed CBAs or SPPAs and did not consider costs that were incurred in the future. However, it is important to note that these studies can apply discount rates, for example, when prices from the past are used. In addition, three case studies used an NPV but did not specify their used discount rate. 55% of the case studies are using a discount rate that lies in between the specified range of 3 to 5%. However, the graph shows that the results are more distributed to the lower side of the range. Hence, if the same range width should be used, a range of 2 to 4% would be better as 63% of the applied discount rates fall in this range.

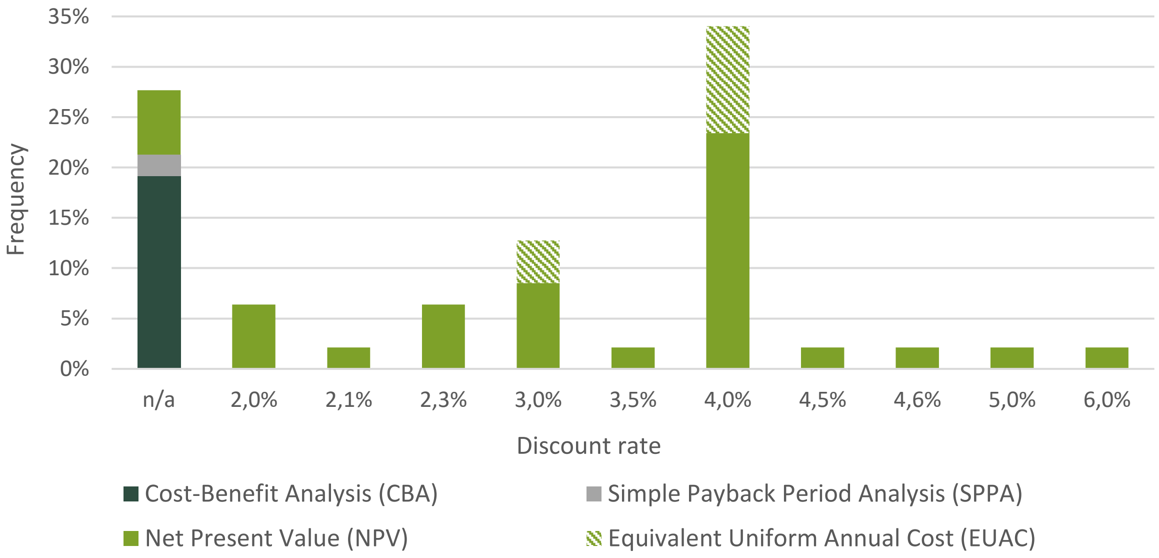

Fig. 6 Frequency discount rates used in recent case studies per economic indicator (n=46)

Once a discount rate has been established, a discount factor can be calculated based on whether nominal costs or real costs are being applied [61]. Real costs are used in LCCA to ensure accuracy regardless of the point in time at which costs are incurred. Hence, using real costs allows the use of current known information and is based on costs that were incurred in the recent past or will incur in the near future. To convert a real cost to a discounted cost, the factor $q_{d,rc}$ in Eq. 16 should be used.

$$q_{d,rc} = \frac{1}{(1+d)^n} \qquad \text{Eq. 16}$$

Where $q_{d,rc}$ is the discount factor for real costs, d is the proposed discount rate and n is the number of years between the base date and the incurrence of the cost.

In some cases, changes in price can be estimated due to, for example, forecast changes in efficiency, inflation or deflation and technological improvements. Hence, a nominal value is more appropriate to consider the variety in costs in the future. However, it is important that these predicted values for future LCCs are as accurate as possible using robust benchmark data sets. The factor $q_{d,nc}$ in Eq. 17 should be used to convert a nominal cost to a discounted cost.

$$q_{d,nc} = \frac{1}{(1+d)^n(1+a)^n} \qquad \text{Eq. 17}$$

Where $q_{d,nc}$ is the discount factor for nominal costs, d is the proposed discount rate, a is the expected change in general prices per annum and n is the number of years between the base date and the incurrence of the cost.

5. LCCA in road engineering – Commonly used economic models

Once all cost categories, associated with each pavement alternative, have been identified and estimated, the computation of LCCA begins. Fig. 7 shows that the resent cases use four commonly applied economic indicators. A regular CBA or NPV is performed is 85% of the cases. However, in some cases a combination of multiple techniques is used. Given the range of economic indicators, a discussion of these models will be presented in the following part of this section.

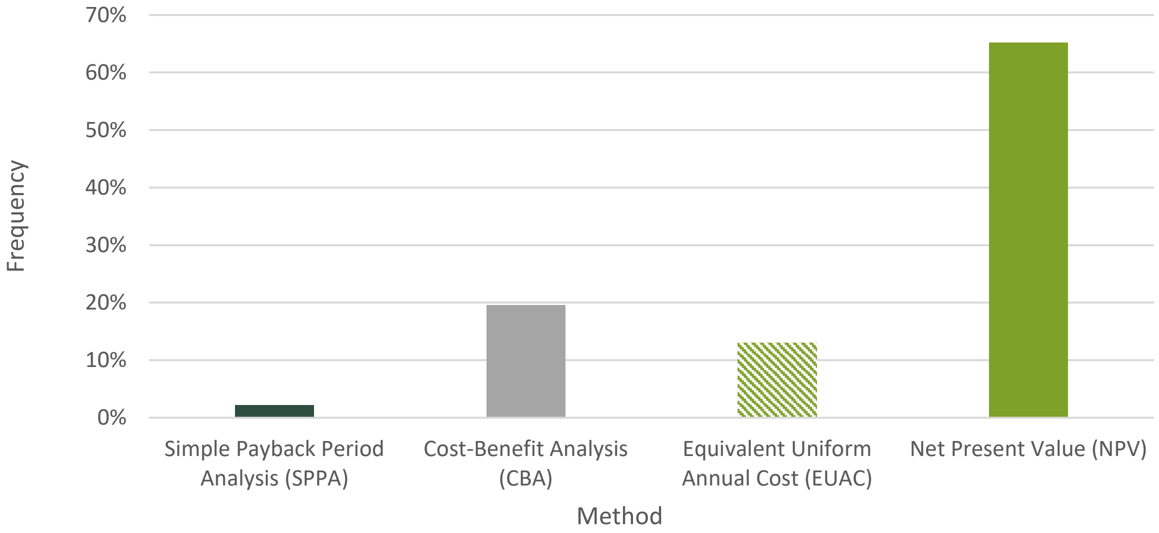

Fig. 7 Frequency of economic indicators used in recent case studies (n=46)

5.1. Simple Payback Period Analysis (SPPA)

An SPPA computes the number of years elapsed between the initial investment, operational costs and the time which cumulative savings offset the investment. Although it is an interesting method for investors, it should never be used as a stand-alone model for LCCA as it does not express costs over a longer period. It can be of interest, for example, when new investments are made in a production plant, in order to improve the durability of their mixtures, and SPPA is coupled with another LCCA model to analyse the long-term effects. In total, there are two options for computing the payback period. It can either be simple, when no value of time is considered, or discounted when it does consider the value of time.

5.2. Cost-Benefit Analysis (CBA)

A CBA compares the costs and benefits of several alternatives in order to decide which alternative is best. In road engineering CBA often combines the production cost of mixtures with their mechanical performance in the laboratory or with the environmental impact during production. Hence, it is a simple version of a sustainability assessment. However, it often only focusses on one phase of a pavement's life cycle, therefore, it does not fall within the framework of LCCA. Although it is a simple and user-friendly method, it should not take precedence over complex LCCA computations. If a CBA is using fixed prices from the past, or it wants to compute costs in the future, these should be discounted to the base year of calculation.

5.3. Net Present Value (NPV)

According to several authors, NPV is considered as the economic indicator of choice to perform LCCA because it can quantify costs and benefits of road alternatives into a single value, while discounting future cash flows into the present [4,13,30,111]. Hence, the main advantages of this model are that it considers the value of time and presents the costs and benefits of alternatives in a single value. However, it should only be used when all alternatives have the same analysis period. Otherwise, alternative NPVs cannot be compared with each other. This review paper demonstrated the lack of consistency in a robust framework, which was also the case for NPV models. Therefore, a robust framework is presented in Eq. 18 - Eq. 23. These equations take into consideration all the phases of a road's life cycle, as discussed in the previous sections, and the option to calculate an NPV for the road agency and/or road user based on nominal costs and/or real costs.

$$NPV_{RU,rc} = AC_0 + VOC_0 + WZDC_0 + \sum_{n=1}^{AnP} \frac{AC_n + VOC_n + WZDC_n}{(1+d)^n} \qquad \text{Eq. 18}$$

$$NPV_{RU,nc} = AC_0 + VOC_0 + WZDC_0 + \sum_{n=1}^{AnP} \frac{AC_n + VOC_n + WZDC_n}{(1+d)^n(1+a)^n} \qquad \text{Eq. 19}$$

$$NPV_{A,rc} = CC_0 + \sum_{n=1}^{AnP} \frac{M\&R_n + EOL_n - SV_n}{(1+d)^n} - \frac{RV_{AP}}{(1+d)^{AP}} \qquad \text{Eq. 20}$$

$$NPV_{A,nc} = CC_0 + \sum_{n=1}^{AnP} \frac{M\&R_n + EOL_n - SV_n}{(1+d)^n(1+a)^n} - \frac{RV_{AP}}{(1+d)^{AP}(1+a)^{AP}} \qquad \text{Eq. 21}$$

$$NPV_{T,rc} = NPV_{RU,rc} + NPV_{A,rc} \qquad \text{Eq. 22}$$

$$NPV_{T,nc} = NPV_{RU,nc} + NPV_{A,nc} \qquad \text{Eq. 23}$$

Where $NPV_{T,rc}$ is the real total NPV, $NPV_{T,nc}$ is the nominal total NPV, $NPV_{RU,rc}$ is the real NPV for the road user, $NPV_{RU,nc}$ is the nominal NPV for the road user, $NPV_{A,rc}$ is the real NPV for the road agency, $NPV_{A,nc}$ is the nominal NPV for the road agency, d is the discount rate, n is the number of years between the base year and the occurrence of the cost, a is the expected change in general prices per annum, AnP is the period of analysis, AC_0 is the AC during initial construction, VOC_0 is the VOC during initial construction, $WZDC_0$ is the WZDC during initial construction, AC_n is the AC during M&R in year n, VOC_n is the VOC during M&R in year n, $WZDC_n$ is the WZDC during M&R in year n, CC_0 is the cost related to the initial construction phase (materials extraction, mixture production, road construction and transport), $M\&R_n$ is the cost related to the M&R phase (preservation, maintenance, rehabilitation and transportation) in year n, EOL_n is the cost related to the EOL phase (deconstruction, waste processing and transportation) in year n, SV_n is the salvage value in year n, RV_{AP} is the residual value at the end of the analysis period.

5.4. Equivalent Uniform Annual Cost (EUAC)

As mentioned before, the main disadvantage of a regular NPV is that it requires alternatives with the same analysis period. Therefore, if an LCCA is performed for alternatives with different analysis periods, e.g. when the lifespan of an asphalt pavement is compared with the lifespan of a concrete pavement, an EUAC can be used because it recalculates the NPV into a yearly cost for possessing and maintaining these alternatives [46,56,61,67]. The EAUC of a road alternative can be determined by implementing Eq. 18 - Eq. 23 into Eq. 24:

$$EAUC_{b,c} = NPV_{b,c} * \frac{d(1+d)^{AP}}{(1+d)^{AP}-1} \qquad \text{Eq. 24}$$

Where $EUAC_{b,c}$ is the EAUC based on $NPV_{b,c}$, $NPV_{b,c}$ is the NPV calculated according to Eq. 18 - Eq. 23, d is the discount rate and AP is the analysis period.

6. Sensitivity analysis

Results of LCCA are influenced by different uncertainties because cost allocations are often based on quotations, estimations and literature sources [19,33,112]. Thus there is a need to conduct a sensitivity analysis to examine how variations across a set of parameters and assumptions may affect the robustness of the analysis [58,80,100,113]. Other examples of factors that contribute to the level of uncertainty are:

- Measured or observed values that have a different frequency of occurrence and variation. For example, M&R is not always performed as scheduled but can be postponed;
- The difference in construction procedures and regional requirements;
- Inaccurate modelling due to human error;
- Lack of reliable data;
- Price fluctuations of materials.

Sensitivity analysis often depends on the type of LCCA as the complexity of a sensitivity analysis is related to the complexity of the model and input variables. Fig. 8 demonstrates how sensitivity analysis was performed in the case studies. Generally, LCCA and sensitivity analysis are categorized in two ways, deterministic and probabilistic [5,85,87,114,115]. Most case studies used deterministic models to perform their calculations. However, in some cases authors combined both models to compare their results.

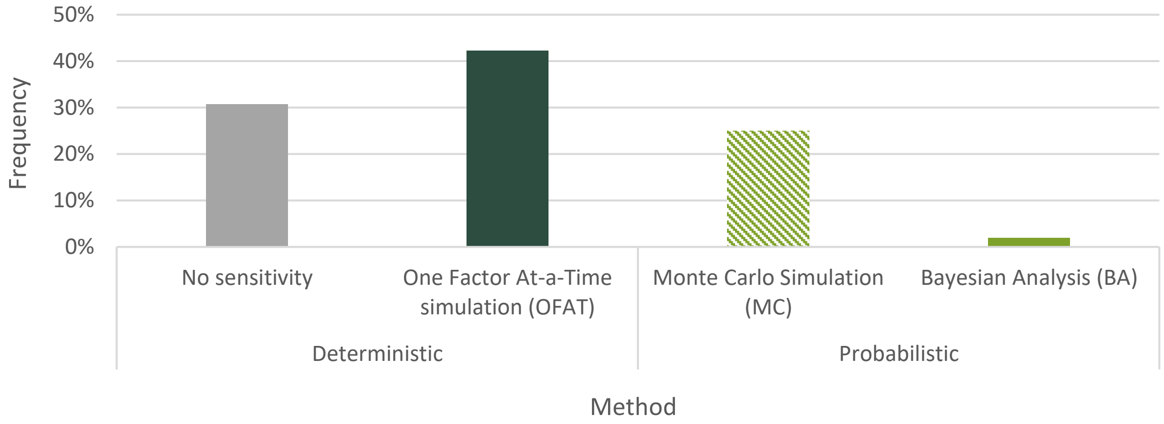

Fig. 8 Frequency of sensitivity analysis used in recent case studies (n=52)

Fig. 8 also demonstrates that 31% of the case studies did not perform sensitivity analysis. As presented in the previous parts of this paper, there is a high level of uncertainty due to the lack of a consistent framework and input data, hence conducting a sensitivity analysis is essential for making conclusive conclusions.

6.1. Deterministic models

The deterministic approach is regarded as easy-to-apply because it involves the use of discrete variables which results in a single output value [85,87,99,115–117]. Particularly, in this type of LCCA, all input variables are assigned a fixed discrete unit value that is mostly based on historical evidence or professional judgment [99]. Deterministic models are used because they can easily identify the main cost contributors of a road's life cycle. Hence, they help road agencies with identifying economic parameters that require special attention in terms of their estimation procedures. However, the deterministic approach is not suited for measuring uncertainty within an input variable as only one discrete value is used for this variable [115].

Therefore, if a sensitivity analysis is performed, it is done using a One Factor At-a-Time simulation (OFAT). The OFAT recalculates the LCC of the road alternatives based on a range of values for one input variable. Afterwards, the results can be evaluated and compared with the initial calculation to identify whether a change in input will affect the overall conclusion and ranking of the road alternatives. Because only one factor is changed per time, this method also fails to estimate the impact on the LCC of a simultaneous change of other inputs [116].

It can be concluded that a deterministic OFAT is user friendly but not capable of assessing projects that contain high uncertainty about several variables. Hence, it should only be applied in projects where low uncertainty is expected because the initial input variables were monitored carefully, and where sensitivity analysis is performed to be certain that a change in input parameter, e.g. discount rate, will not affect the overall result.

6.2. Probabilistic models

In contrast with deterministic models, probabilistic LCCA does account for the uncertainty of individual input variables through random sampling and on the basis of a frequency probability distribution [21,116]. The first step in performing a probabilistic LCCA is to identify uncertain input parameters and to develop probability density functions for these parameters [118]. Afterwards, a simulation is performed using an iterative process to sample LCCs based on these distributions. As presented in Fig. 9, the iterative process thus produces a new probability distribution for the LCC of different road alternatives based on the uncertainty of the input parameters. In a final step, the probability and cumulative density curves of the different alternatives can be compared with each other to validate findings and estimate the likelihood of the LCCA forecast.

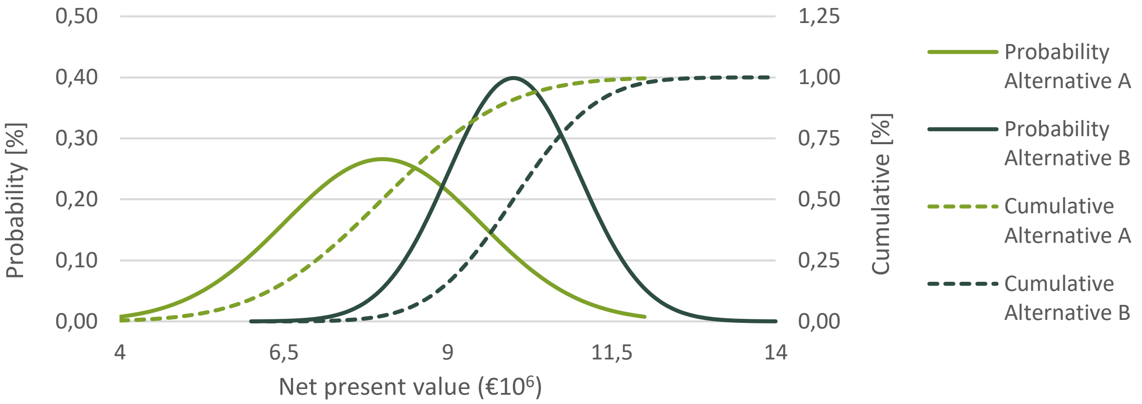

Fig. 9 Example of probabilistic modelling of the NPV of two alternatives

Fig. 8 demonstrates that probabilistic models are not commonly used in road engineering. Although it is a powerful tool to cope with uncertainty, several authors indicate that it is a complex method which is data intensive. Because large datasets are often not available, researchers prefer to use deterministic models. Within the probabilistic models, Monte Carlo simulation (MC) is the most applied method for the iterative process of performing an LCCA in road engineering as it can generate complex and aggregated uncertainty information based on simple process input distributions.

However, Wang et al. [119] highlight an important shortcoming of MC. MC randomly generates input data for the computation of the LCCA without taking into consideration a possible interaction between individual input parameters. Fig. 10 demonstrates the relationship between unit prices of bitumen (PG 64-22) and fuel (diesel). As both products are derived from crude oil, their unit price is also related to each other, as presented in the graph. Therefore, the difference in price evolution, e.g. the binder price is lower than average while the fuel price is higher than average, should be avoided when performing an LCCA.

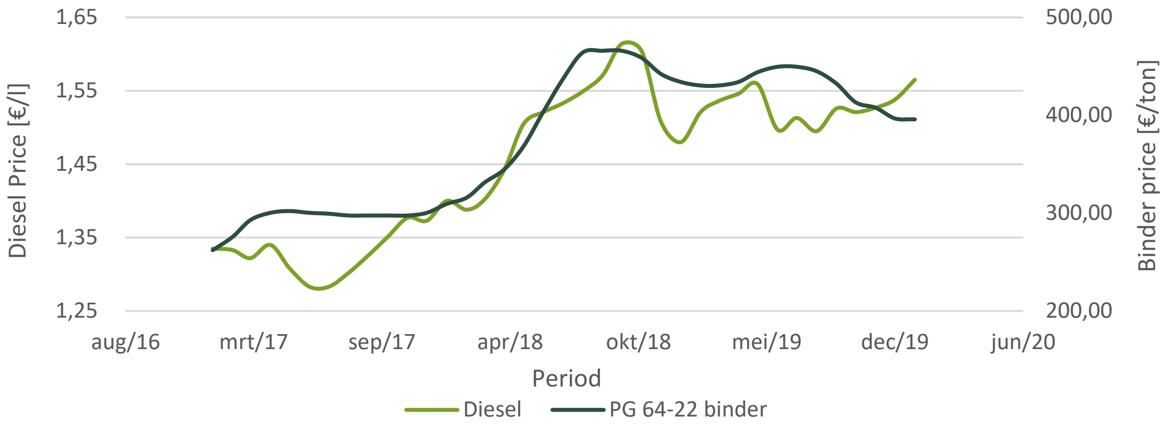

Fig. 10 Comparison price diesel & PG 64-22 binder for the period jan/17 - jan/20 [120,121]

To overcome this shortcoming, Wang et al [119] propose to compute probabilistic models with MC combined with Bayesian inference as it is capable of combining prior knowledge with observed data to produce adjusted distributions. However, it is important to note that although it is a powerful tool, it adds another layer of complexity to the calculations. Therefore, this method is not frequently used for performing LCCA in road engineering, but it could be of great interest.

7. Conclusion and research opportunities

Although LCCA can be a great tool to analyse the economic impact of several alternatives, an assessment of case-based studies has revealed that there is a lack of consistency in the applied frameworks. Firstly, it was demonstrated that there is a large variation in framework boundaries. The EOL phase is often excluded in LCCA. As recycling becomes of greater importance, this is a phase which should gain more attention in further research. It was also identified, that during this phase, salvage value and residual value were used interchangeably despite their difference in modelling. Therefore, this research states that residual value should be linked to a road's service life that exceeds the end of analysis period and that salvage value should be related to recycling and saving new virgin materials.

Additionally, this review showed that road user costs are often excluded in LCCA because authors expect no variation in construction time, hence no variation in road user costs related to work zones. Although this can be correct, this decision should never be based only on whether a difference in construction time is expected. As LCCA discounts future costs, the moment of expenditure is also of great importance. Therefore, when two alternatives have the same initial road user cost, but one alternative performs M&R two years later, this will influence the LCCA. Additionally, the road user cost has a strong connection with the social aspect of sustainability assessment because it is paid by society. Therefore, if an LCCA wants to transform into a sustainability assessment, it should always incorporate user costs.

Although the initial construction and M&R phase are well represented in the LCCAs of the case studies, it is concluded that transport between extraction, production and construction sites are often excluded or unknown. Material unit prices can contain transportation costs. However, if it is not stated clearly whether this price contains transport or not, there is a possibility of double counting or excluding this cost without knowing. Additionally, several researchers have identified the importance of transport in sustainability assessment because it is one of the main contributors to the environmental and economic impact of road projects. Therefore, further research should incorporate transport and clearly state whether material unit prices contain transport or if transportation cost are separately accounted for.

In addition to a lack of consistency in system boundaries, this review also indicated inconsistency in the use of system parameters, such as analysis period, discount rate and economic indicator. The applied analysis periods had a range of 10-90 years and 40 years was the most applied analysis period. It is mentioned that the analysis period should be at least equal to the longest lifespan of the considered alternatives. However, this often depends on the road structure that is analysed. If pavements are compared, an analysis period of 40 years will probably be sufficient. But, when full structures are compared, an analysis period of 40 years will not be long enough.

Although a discount rate of 4% is most commonly used, most researchers specify a range of 3-6% because discount rates are often location and time specific. However, the review showed that a range of 2-5% would be more suitable as more cases fall within this range. The two most commonly applied economic indicators are the NPV, EUAC and CBA. NPV is chosen over EUAC because it gives a single value for the discounted costs and benefits for the entire analysis period, hence it is simple to rank alternatives. However, in case of different analyse periods, the NPV should not be used. This disadvantage is eliminated when using the EUAC as it recalculates the total NPV into a yearly cost. CBA is a simple method, however, it should not be preferred over NPV or EUAC as it often only considers one life cycle phase.

Sensitivity analysis is of great importance as there are several uncertainties within LCCA. It is seen that most LCCAs are deterministic, hence fixed values are being used as input parameters. Because no frequency probability distributions are used as input, sensitivity analysis is done based on varying one factor per time. Prices are not fixed values, therefore probabilistic models should be preferred over deterministic models. The most commonly applied probabilistic model is Monte Carlo simulation. This incorporates the frequency probability distributions and simulates the LCCA multiple times to determine a frequency probability distribution for the LCC of the alternatives. Hence, more statistical and comprehensive conclusions can be made. However, Monte Carlo does not consider correlation between input parameters. Therefore, Bayesian analysis can be of interest.

8. References

1. Van Dam, T.; Harvey, J.; Muench, S.; Smith, K.; Snyder, M.; Al-Qadi, I.; Ozer, H.; Meijer, J.; Ram, P.; Roesler, J.; et al. *Towards Sustainable Pavement Systems: A Reference Document*; 2015;
2. European Union Road Federation *Road asset management: An ERF position paper for maintaining and improving a sustainable and efficient road network*; The European Union Road Federation: Brussels, 2013;
3. Santos, J.; Bryce, J.; Flintsch, G.; Ferreira, A. A comprehensive life cycle costs analysis of in-place recycling and conventional pavement construction and maintenance practices. *Int. J. Pavement Eng.* **2015**, *18*, 727–743.
4. Babashamsi, P.; Md Yusoff, N.I.; Ceylan, H.; Md Nor, N.G.; Salarzadeh, J.H.; Salarzadeh Jenatabadi, H. Evaluation of pavement life cycle cost analysis: Review and analysis. *Int. J. Pavement Res. Technol.* **2016**, *9*, 241–254.
5. Guo, F.; Gregory, J.; Kirchain, R. Probabilistic Life-Cycle Cost Analysis of Pavements Based on Simulation Optimization. *Transp. Res. Rec. J. Transp. Res. Board* **2019**, *2673*, 389–396.
6. Lamptey, G.; Singh, L.; Labi, S.; Sinha, K.C. Systematic framework for incorporating safety in network-level transportation planning and programming. *J. Transp. Eng.* **2010**, *136*, 436–447.
7. Anastasiades, K.; Blom, J.; Buyle, M.; Audenaert, A. Translating the circular economy to bridge construction: Lessons learnt from a critical literature review. *Renew. Sustain. Energy Rev.* **2020**, *117*, 109522.
8. Stephan, A.; Stephan, L. Life cycle energy and cost analysis of embodied, operational and user-transport energy reduction measures for residential buildings. *Appl. Energy* **2016**, *161*, 445–464.
9. Mah, C.M.; Fujiwara, T.; Ho, C.S. Life cycle assessment and life cycle costing toward eco-efficiency concrete waste management in Malaysia. *J. Clean. Prod.* **2018**, *172*, 3415–3427.
10. Lamptey, G.; Ahmad, M.; Labi, S.; Sinha, K. *Life cycle cost analysis for INDOT pavement design procedures*; West Lafayette, 2005;
11. Zuo, J.; Pullen, S.; Rameezdeen, R.; Bennetts, H.; Wang, Y.; Mao, G.; Zhou, Z.; Du, H.; Duan, H. Green building evaluation from a life-cycle perspective in Australia: A critical review. *Renew. Sustain. Energy Rev.* **2017**, *70*, 358–368.
12. Nahvi, A.; Zhang, Y.; Arabzadeh, A.; Gushgari, S.Y.; Ceylan, H.; Jahren, C.T.; Gransberg, D.D.; Kim, S. Economics of upgrading gravel roads to Otta seal surface. *Appl. Econ.* **2019**, *51*, 4820–4832.
13. Rangaraju, P.R.; Amirkhanian, S.N.; Guven, Z. *Life Cycle Cost Analysis for pavement type selection*; 2008;
14. Santos, J.; Ferreira, A. Life-cycle cost analysis system for pavement management at project level. *Int. J. Pavement Eng.* **2013**, *14*, 71–84.
15. Gaurav; Wojtkiewicz, S.F.; Khazanovich, L. Optimal design of flexible pavements using a framework of DAKOTA and MEPDG. *Int. J. Pavement Eng.* **2011**, *12*, 137–148.
16. Salem, O.M.; Deshpande, A.S.; Genaidy, A.; Geara, T.G. User costs in pavement construction and rehabilitation alternative evaluation. *Struct. Infrastruct. Eng.* **2013**, *9*, 285–294.
17. Gu, F.; Tran, N. *Best Practices for Determining Life Cycle Costs of Asphalt Pavements*; 2019;
18. Flannery, A.; Manns, J.; Venner, M. *Life-Cycle Cost Analysis for Management of Highway Assets*; 2016;
19. Miah, J.H.; Koh, S.C.L.; Stone, D. A hybridised framework combining integrated methods for environmental Life Cycle Assessment and Life Cycle Costing. *J. Clean. Prod.* **2017**, *168*, 846–866.
20. Cao, R.; Leng, Z.; Hsu, S.C. Comparative eco-efficiency analysis on asphalt pavement rehabilitation alternatives: Hot in-place recycling and milling-and-filling. *J. Clean. Prod.* **2019**, *210*, 1385–1395.

21. Akbarian, M.; Swei, O.; Kirchain, R.; Gregory, J. Probabilistic Characterization of Life-Cycle Agency and User Costs: Case Study of Minnesota. *Transp. Res. Rec. J. Transp. Res. Board* **2017**, *2639*, 93–101.
22. Li, Z.; Madanu, S. Highway project level life-cycle benefit/cost analysis under certainty, risk, and uncertainty: Methodology with case study. *J. Transp. Eng.* **2009**, *135*, 516–526.
23. Gillespie, W.M. *A manual of the principles and practice of road-making: comprising the location, construction, and improvement of roads and rail-roads.*; A.S. Barnes & CO, 1847;
24. American Association of State Highway Officials (AASHO) *An informational guide on project procedures: A guide for the reviewing of certain administrative, inspection, and documentation practices in use by state highway departments.*; 1960;
25. American Association of State Highway and Transportation Officials (AASHTO) *Guide for design of pavement structures*; 1993;
26. Peterson, D.E. *Synthesis of Highway Practice 122: Life-cycle cost analysis of pavements*; 1985;
27. Campbell, B.; Humphrey, T.F. *Synthesis of Highway Practice 142: Methods of cost-effectiveness analysis for highway projects*; 1988;
28. Federal Highway Administration NHS Designation Act of 1995 Available online: https://www.fhwa.dot.gov/legsregs/nhs_sec.html#sec_303 (accessed on Mar 30, 2020).
29. FHWA FHWA Policy Memos: Life-Cycle Cost Analysis Requirements Available online: https://www.fhwa.dot.gov/legsregs/directives/policy/lcca.htm (accessed on Mar 30, 2020).
30. Walls, J.I.; Smith, M.R. *Life-Cycle Cost Analysis in Pavement Design: In search of Better Investment Desisions*; 1998;
31. Nyvig, A. *Pavement and Structure Management System - Economic Evaluation of Pavement Maintenance*; 1999;
32. Lee, E.B.; Thomas, D.K.; Alleman, D. Incorporating road user costs into integrated Life-Cycle Cost Analyses for infrastructure sustainability: A case study on Sr-91 corridor improvement project (Ca). *Sustainability* **2018**, *10*.
33. Abdelaty, A.; Jeong, H.D.; Dannen, B.; Todey, F. Enhancing life cycle cost analysis with a novel cost classification framework for pavement rehabilitation projects. *Constr. Manag. Econ.* **2016**, *34*, 724–736.
34. Hasan, U.; Whyte, A.; Al Jassmi, H. Critical review and methodological issues in integrated life-cycle analysis on road networks. *J. Clean. Prod.* **2018**, *206*, 541–558.
35. Tomić, T.; Schneider, D.R. The role of energy from waste in circular economy and closing the loop concept – Energy analysis approach. *Renew. Sustain. Energy Rev.* **2018**, *98*, 268–287.
36. Liu, Z.; Adams, M.; Cote, R.P.; Chen, Q.; Wu, R.; Wen, Z.; Liu, W.; Dong, L. How does circular economy respond to greenhouse gas emissions reduction: An analysis of Chinese plastic recycling industries. *Renew. Sustain. Energy Rev.* 2018, *91*, 1162–1169.
37. Wang, J.J.; Wang, Y.F.; Sun, Y.W.; Tingley, D.D.; Zhang, Y.R. Life cycle sustainability assessment of fly ash concrete structures. *Renew. Sustain. Energy Rev.* **2017**, *80*, 1162–1174.
38. Thives, L.P.; Ghisi, E. Asphalt mixtures emission and energy consumption: A review. *Renew. Sustain. Energy Rev.* **2017**, *72*, 473–484.
39. Walmsley, T.G.; Ong, B.H.Y.; Klemeš, J.J.; Tan, R.R.; Varbanov, P.S. Circular Integration of processes, industries, and economies. *Renew. Sustain. Energy Rev.* **2019**, *107*, 507–515.
40. Vidal, R.; Moliner, E.; Martínez, G.; Rubio, M.C. Life cycle assessment of hot mix asphalt and zeolite-based warm mix asphalt with reclaimed asphalt pavement. *Resour. Conserv. Recycl.* **2013**, *74*, 101–114.
41. Harvey, J.T.; Meijer, J.; Ozer, H.; Al-Qadi, I.; Saboori, A.; Kendall, A. *Pavement Life Cycle Assessment Framework*; 2016;
42. Anthonissen et al. Cradle-to-Gate Life Cycle Assessment of Recycling and Impact of Reduced Production Temperature for the Asphalt sector in Belgium. *Int. Symp. Pavement LCA 2014* **2014**, 61–74.

43. Mukherjee, A. *Life cycle assessment of asphalt mixtures in support of an environmental product declaration*; Lanham, MD, 2016;
44. Li, J.; Xiao, F.; Zhang, L.; Amirkhanian, S.N. Life cycle assessment and life cycle cost analysis of recycled solid waste materials in highway pavement: A review. *J. Clean. Prod.* **2019**, *233*, 1182–1206.
45. Li, X.; Wen, H.; Edil, T.B.; Sun, R.; VanReken, T.M. Cost, energy, and greenhouse gas analysis of fly ash stabilised cold in-place recycled asphalt pavement. *Road Mater. Pavement Des.* **2013**, *14*, 537–550.
46. Mirzadeh, I.; Butt, A.A.; Toller, S.; Birgisson, B. Life cycle cost analysis based on the fundamental cost contributors for asphalt pavements. *Struct. Infrastruct. Eng.* **2014**, *10*, 1638–1647.
47. Gschösser, F.; Wallbaum, H. Life cycle assessment of representative swiss road pavements for national roads with an accompanying life cycle cost analysis. *Environ. Sci. Technol.* **2013**, *47*, 8453–8461.
48. Jahanbakhsh, H.; Karimi, M.M.; Naseri, H.; Nejad, F.M. Sustainable asphalt concrete containing high reclaimed asphalt pavements and recycling agents: Performance assessment, cost analysis, and environmental impact. *J. Clean. Prod.* **2020**, *244*.
49. Mirzadeh, I.; Birgisson, B. Accommodating energy price volatility in life cycle cost analysis of asphalt pavements. *J. Civ. Eng. Manag.* **2016**, *22*, 1001–1008.
50. Choi, J. ho Strategy for reducing carbon dioxide emissions from maintenance and rehabilitation of highway pavement. *J. Clean. Prod.* **2019**, *209*, 88–100.
51. Underwood, B.S.; Guido, Z.; Gudipudi, P.; Feinberg, Y. Increased costs to US pavement infrastructure from future temperature rise. *Nat. Clim. Chang.* **2017**, *7*, 704–707.
52. Qiao, Y.; Dave, E.; Parry, T.; Valle, O.; Mi, L.; Ni, G.; Yuan, Z.; Zhu, Y. Life cycle costs analysis of reclaimed asphalt pavement (RAP) under future climate. *Sustainability* **2019**, *11*, 1–16.
53. Yu, B.; Gu, X.; Ni, F.; Guo, R. Multi-objective optimization for asphalt pavement maintenance plans at project level: Integrating performance, cost and environment. *Transp. Res. Part D Transp. Environ.* **2015**, *41*, 64–74.
54. Torres-Machi, C.; Pellicer, E.; Yepes, V.; Chamorro, A. Towards a sustainable optimization of pavement maintenance programs under budgetary restrictions. *J. Clean. Prod.* **2017**, *148*, 90–102.
55. Okte, E.; Al-Qadi, I.L.; Ozer, H. Effects of Pavement Condition on LCCA User Costs. *Transp. Res. Rec. J. Transp. Res. Board* **2019**, *2673*, 339–350.
56. Wennström, J.; Karlsson, R. Possibilities to reduce pavement rehabilitation cost of a collision-free road investment using an LCCA design procedure. *Int. J. Pavement Eng.* **2016**, *17*, 331–342.
57. Directorate, R. Economic Evaluation of Pavement Maintenance - PAV-ECO Project Final Report. **1999**.
58. Batouli, M.; Bienvenu, M.; Mostafavi, A. Putting sustainability theory into roadway design practice: Implementation of LCA and LCCA analysis for pavement type selection in real world decision making. *Transp. Res. Part D Transp. Environ.* **2017**, *52*, 289–302.
59. Walls, J.; Smith, M. *Life-cycle cost analysis in pavement design: in search of better investment decisions*; Washington, DC, 1998;
60. Langdon, D.; Davis Langdon *Life Cycle Costing (LCC) as a contribution to sustainable construction: a common methodology*; London, 2007;
61. International Organization for Standardization *BS ISO 15686-5 Buildings and constructed assets - Service-life planning - Part 5: Life-cycle costing*; BS ISO 156.; BSI Standards Limited: Vernier, Geneva, 2017;
62. Caltrans *Life-Cycle Cost Analysis Procedure Manual*; State of California Department of Transportation Division of Maintenance Pavement Program: California, 2013;

63. Robinette, C.; Epps, J. Energy, emissions, material conservation, and prices associated with construction, rehabilitation, and material alternatives for flexible pavement. *Transp. Res. Rec.* **2010**, 10–22.
64. Leng, Z.; Al-Qadi, I. *Comparative Life Cycle Assessment between Warm SMA and Conventional SMA*; 2011;
65. Lee, E.B.; Kim, C.; Harvey, J. Selection of pavement for highway rehabilitation based on life-cycle cost analysis. *Transp. Res. Rec.* **2011**, 23–32.
66. Amini, A.A.; Mashayekhi, M.; Ziari, H.; Nobakht, S. Life cycle cost comparison of highways with perpetual and conventional pavements. *Int. J. Pavement Eng.* **2012**, *13*, 553–568.
67. Cheng, D.; Hicks, R.G.; Rodriguez, M. Life Cycle Cost Comparison of Rubberized and Conventional HMA in California. **2012**.
68. Santos, J.; Ferreira, A. Pavement Design Optimization Considering Costs and Preventive Interventions. *J. Transp. Eng.* **2012**, *138*, 911–923.
69. Aurangzeb, Q.; Al-Qadi, I.L. Asphalt pavements with high reclaimed asphalt pavement content: Economic and environmental perspectives. *Transp. Res. Rec.* **2014**, *2456*, 161–169.
70. Son, S.; Al-Qadi, I.L. Engineering cost-benefit analysis of thin, durable asphalt overlays. *Transp. Res. Rec.* **2014**, *2456*, 135–145.
71. Zaumanis, M.; Mallick, R.B.; Frank, R. 100% recycled hot mix asphalt: A review and analysis. *Resour. Conserv. Recycl.* **2014**, *92*, 230–245.
72. Yang, R.; Kang, S.; Ozer, H.; Al-Qadi, I.L. Environmental and economic analyses of recycled asphalt concrete mixtures based on material production and potential performance. *Resour. Conserv. Recycl.* **2015**, *104*, 141–151.
73. Nazzal, M.D.; Iqbal, M.T.; Kim, S.S.; Abbas, A.R.; Akentuna, M.; Quasem, T. Evaluation of the long-term performance and life cycle costs of GTR asphalt pavements. *Constr. Build. Mater.* **2016**, *114*, 261–268.
74. Souliman, M.I.; Mamlouk, M.; Eifert, A. Cost-effectiveness of Rubber and Polymer Modified Asphalt Mixtures as Related to Sustainable Fatigue Performance. *Procedia Eng.* **2016**, *145*, 404–411.
75. Sultan, S.A.; Guo, Z. Evaluating life cycle costs of perpetual pavements in China using operational pavement management system. *Int. J. Transp. Sci. Technol.* **2016**, *5*, 103–109.
76. Sultan, S.A.; Guo, Z. Evaluating the performance of sustainable perpetual pavements using recycled asphalt pavement in China. *Int. J. Transp. Sci. Technol.* **2016**, *5*, 200–209.
77. Yepes, V.; Torres-Machi, C.; Chamorro, A.; Pellicer, E. Optimal pavement maintenance programs based on a hybrid Greedy Randomized Adaptive Search Procedure Algorithm. *J. Civ. Eng. Manag.* **2016**, *22*, 540–550.
78. Wu, D.; Yuan, C.; Liu, H. A risk-based optimisation for pavement preventative maintenance with probabilistic LCCA: a Chinese case. *Int. J. Pavement Eng.* **2017**, *18*, 11–25.
79. Liu, S.; Shukla, A.; Nandra, T. Technological, environmental and economic aspects of Asphalt recycling for road construction. *Renew. Sustain. Energy Rev.* **2017**, *75*, 879–893.
80. Santos, J.; Flintsch, G.; Ferreira, A. Environmental and economic assessment of pavement construction and management practices for enhancing pavement sustainability. *Resour. Conserv. Recycl.* **2017**, *116*, 15–31.
81. Ozer, H.; Yang, R.; Al-Qadi, I.L. Quantifying sustainable strategies for the construction of highway pavements in Illinois. *Transp. Res. Part D Transp. Environ.* **2017**, *51*, 1–13.
82. Coleri, E.; Zhang, Y.; Wruck, B.M. Mechanistic-Empirical Simulations and Life-Cycle Cost Analysis to Determine the Cost and Performance Effectiveness of Asphalt Mixtures Containing Recycled Materials. *Transp. Res. Rec.* **2018**, *2672*, 143–154.
83. Diependaele, M. A guide on the basic principles of life-cycle cost analysis (LCCA) of pavements. **2018**.
84. Qiao, Y.; Santos, J.; Stoner, A.M.K.; Flinstch, G. Climate change impacts on asphalt road

pavement construction and maintenance: An economic life cycle assessment of adaptation measures in the State of Virginia, United States. *J. Ind. Ecol.* **2019**, *2005*, 1–14.
85. Wang, H.; Wang, Z. Deterministic and probabilistic life-cycle cost analysis of pavement overlays with different pre-overlay conditions. *Road Mater. Pavement Des.* **2019**, *20*, 58–73.
86. Chen, J.S.; Yang, C.H.; Lee, C. Te Field evaluation of porous asphalt course for life-cycle cost analysis. *Constr. Build. Mater.* **2019**, *221*, 20–26.
87. Nahvi, A.; Zhang, Y.; Arabzadeh, A.; Ceylan, H.; Kim, S.; Gransberg, D.D.; Jahren, C.T.; Gushgari, S.Y. Deterministic and stochastic life-cycle cost analysis for Otta seal surface treatment on low volume roads. *Int. J. Pavement Res. Technol.* **2019**, *12*, 101–109.
88. Robbins, M.; Tran, N. *Review of initial service life determination in LCCA procedures and in practice*; Auburn, 2018;
89. Yang, Y.; Huang, L.; Wang, J.; Xia, Y. Research on reference indicators for sustainable pavement maintenance cost control through data mining. *Sustainability* **2019**, *11*, 1–14.
90. Yao, L.; Dong, Q.; Jiang, J.; Ni, F. Establishment of Prediction Models of Asphalt Pavement Performance based on a Novel Data Calibration Method and Neural Network. *Transp. Res. Rec. J. Transp. Res. Board* **2019**, *2673*, 66–82.
91. Pérez-Acebo, H.; Mindra, N.; Railean, A.; Rojí, E. Rigid pavement performance models by means of Markov Chains with half-year step time. *Int. J. Pavement Eng.* **2019**, *20*, 830–843.
92. Kargah-Ostadi, N.; Zhou, Y. (Mina); Rahman, T. Developing Performance Prediction Models for Pavement Management Systems in Local Governments in Absence of Age Data. *Transp. Res. Rec. J. Transp. Res. Board* **2019**, *2673*, 334–341.
93. Choi, S.; Do, M. Development of the Road Pavement Deterioration Model Based on the Deep Learning Method. *Electronics* **2020**.
94. Rahman, M.M.; Uddin, M.M.; Gassman, S.L. Pavement performance evaluation models for South Carolina. *KSCE J. Civ. Eng.* **2017**, *21*, 2695–2706.
95. Marcelino, P.; Lurdes Antunes, M. de; Fortunato, E. Comprehensive performance indicators for road pavement condition assessment. *Struct. Infrastruct. Eng.* **2018**, *14*, 1433–1445.
96. Pantuso, A.; Loprencipe, G.; Bonin, G.; Teltayev, B.B. Analysis of pavement condition survey data for effective implementation of a network level pavement management program for Kazakhstan. *Sustainability* **2019**, *11*.
97. Marcelino, P.; Antunes, M.L.; Fortunato, E. Current international practices on pavement condition assessment. In *Pavement and Asset Management: Proceedings of the World Conference on Pavement and Asset Management, WCPAM 2017*; 2019; pp. 359–363 ISBN 9780367209896.
98. FHWA Pavement performance measures and forecasting and the effects of maintenance and rehabilitation strategy on treatment effectiveness (revised). **2017**, 1–329.
99. Ozbay, K.; Parker, N.A.; Jawas, D.; Hussain, S. *Guidelines for life cycle cost analysis*; 2003;
100. Estevan, H.; Schaefer, B. *Life Cycle Costing - state of the art report*; 2017;
101. Wong, I.L. Whole life costing: Towards a sustainable built environment. *IET Conf. Publ.* **2010**, *2010*, 248–256.
102. Jackson, N.; Puccinelli, J.; Mahoney, J. *Guide to Using Existing Pavement in Place and Achieving Long Life*; The National Academies Press: Washington, DC, 2014; ISBN 9780309433075.
103. Mallela, J.; Sadasivam, S. *Work Zone Road User Costs Concepts and Applications*; 2011;
104. Curry, D.A.; Anderson, D.G. *Report 133: Procedures for estimating highway user costs, air pollution and noise effects*; 1972;
105. United States Environmental Protection Agency MOter Vehicle Amission Simulator (MOVES) nad other mobile source emissions models Available online: https://www.epa.gov/moves (accessed on Apr 7, 2020).
106. TRL Software World bank: The Highway Design and Maintenance Standards Model Available

online: https://trlsoftware.com/products/economic-appraisal/hdm-4/ (accessed on Apr 7, 2020).
107. Fisk, C.S. The Australian road research board instantaneous model of fuel consumption. *Transp. Res. Part B* **1989**, *23*, 373–375.
108. Transportation economics MicroBENCOST - Transportation Benefit-Cost Analysis Available online: http://bca.transportationeconomics.org/models/microbencost (accessed on Apr 7, 2020).
109. van den Boomen, M.; Schoenmaker, R.; Wolfert, A.R.M.R.M. A life cycle costing approach for discounting in age and interval replacement optimisation models for civil infrastructure assets. *Struct. Infrastruct. Eng.* **2018**, *14*, 1–13.
110. European Commission *Buying green handbook!*; 2016; ISBN 9789279568480.
111. Roberts, F.L.; Kandhal, P.S.; Brown, E.R.; Lee, D.-Y.; Kennedy, T.W. Hot mix asphalt materials, mixture design and construction. **1996**, *2*.
112. Butt, A.A.; Mirzadeh, I.; Toller, S.; Birgisson, B. Life cycle assessment framework for asphalt pavements: methods to calculate and allocate energy of binder and additives. *Int. J. Pavement Eng.* **2014**, *15*, 290–302.
113. Giunta, M.; Bressi, S.; D'Angelo, G. Life cycle cost assessment of bitumen stabilised ballast: A novel maintenance strategy for railway track-bed. *Constr. Build. Mater.* **2018**, *172*, 751–759.
114. Hallin, J.; Sadasivam, S.; Mallela, J.; Hein, D.K.; Darter, M.I.; Von Quintus, H.L. *Guide for pavement-type selection*; Transportation Research Board: Champaign, Illinois, 2011; ISBN 9780309213486.
115. Ilg, P.; Scope, C.; Muench, S.; Guenther, E. Uncertainty in life cycle costing for long-range infrastructure. Part I: leveling the playing field to address uncertainties. *Int. J. Life Cycle Assess.* **2017**, *22*, 277–292.
116. U.S. Department of Transportation *Life-Cycle Cost Analysis Primer*; 2002;
117. Tighe, S. Guidelines for probabilistic pavement life cycle cost analysis. *Transp. Res. Rec.* **2001**, 28–38.
118. Wang, N.; Chang, Y.C.; El-Sheikh, A.A. Monte Carlo simulation approach to life cycle cost management. *Struct. Infrastruct. Eng.* **2012**, *8*, 739–746.
119. Wang, Z.; Wang, H. Probabilistic Modeling of Performance-Related Pay Adjustment for In-Place Air-Void Contents of Asphalt Pavements. *J. Infrastruct. Syst.* **2017**, *23*, 04016033.
120. Indiana Department of Transportation *PG 64-22 Average Monthly Price*;
121. STATBEL Aardolieprijzen - België in Cijfers Available online: https://statbel.fgov.be/nl/themas/energie/aardolieprijzen (accessed on Apr 9, 2020).