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

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Title

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

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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. discount rate and analysis period, which supports the conclusion of a missing conclusive and robust framework.

Keywords

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

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);

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1. Introduction

With the increasing focus on sustainability, the road industry is confronted with the challenge of considering sustainable practices [1]. Enabling sustainable transition 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 needs to gain attention [4–6]. Considering budgetary constraints, agencies need to use rigorous decision-making methodologies that provide insights about long-term economic viability. One of those methodologies is life cycle cost analysis (LCCA), which evaluates the economic burden while considering 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: e.g. the availability of supporting data, insights in 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 inconsistency in system boundaries and input parameters [5,19]. Some authors suggest a hybridized eco-efficiency analysis, which combines life cycle assessment (LCA) to determine the environmental impact and LCCA to determine the economic impact [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]. Hence, it is important to analyse the parallelism of these models and how they are applied in road projects.

This paper presents a state-of-the-art review of the available literature on the application of LCCA in the road industry. Having a robust framework to calculate the economic impact of new road projects will help the industry with its sustainable transition. It is vital to gain insight into the application and limitations of LCCA in road projects so the modelling of its economic impact can be improved. This review 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 and how are they determined?
    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, valuable information can be accessed 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]).* In 1960, the American Association of State Highway and Transportation Officials (AASHTO) published an informational guide on project procedures. According to AASHTO, cost computations should reflect original investments, anticipated lifespans, maintenance and salvage values [24]. They highlighted the importance of cost comparisons based on service lives of pavement structures because maintenance would seriously affect the cost comparison.

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 includes 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. As 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 requirements to conduct an LCCA for projects on the national highway system with a cost above $25 million [28]. In 1996, they wrote a policy statement where they highlighted the importance of LCCA and encouraged the implementation in all projects [29]. FHWA published a manual for LCCA in pavement design in 1998 that addressed broad fundamental principles as well as detailed procedures. It advocated the use of probabilistic approaches to incorporate risk analysis to consider uncertainty which was typically hidden in the traditional deterministic approaches [30].

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: "*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 future costs: "*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 the life cycle cost 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. Two approaches are differentiated 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 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].

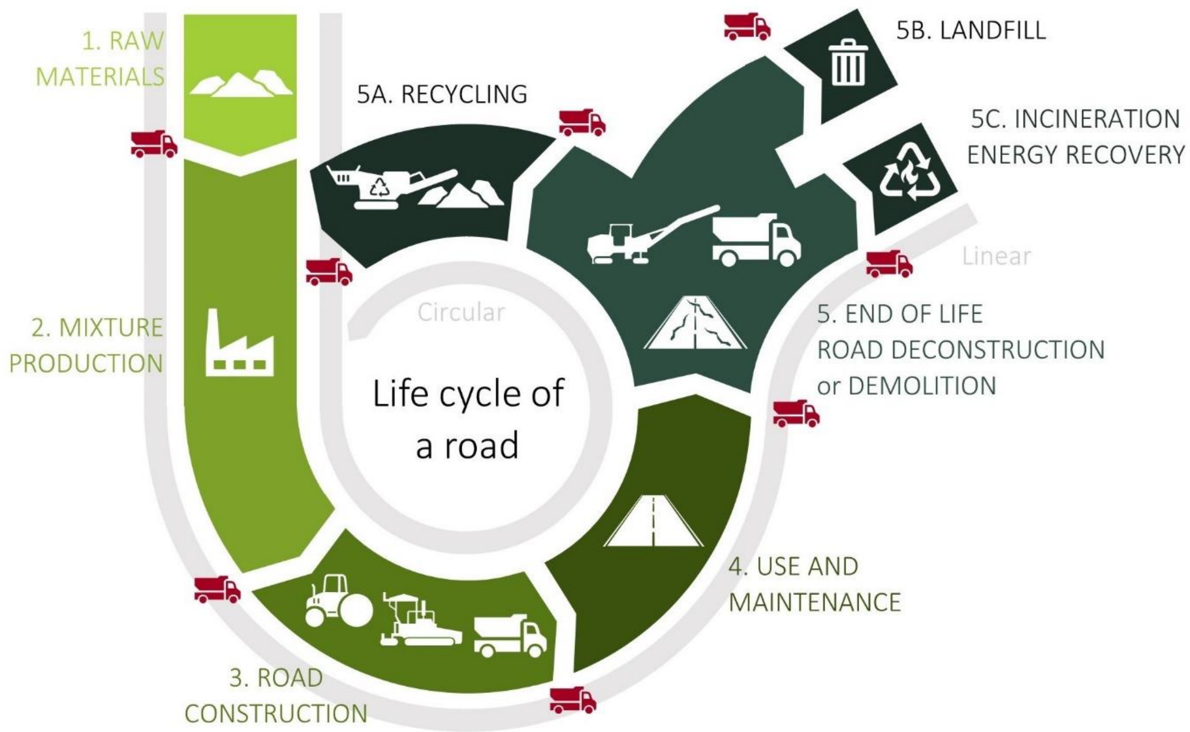

Fig. 1 Representation of the life cycle of a road based on a circular and linear approach. (The trucks in between the life cycle phases are representing possible transportation phases).

Whether recycling is preferred over new materials depends on the impact of multiple factors. For example, the difference in transportation distances, the change in durability of the new product and the impact of the recycling or disposal processes. Hence, including all life cycle phases is important for the sustainability assessment of alternatives [37–39]. Therefore, the following part of the paper will describe all the life cycle phases 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, energy, labour, and transportation of materials to the production plant. The cost components are often 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]. Furthermore, the transportation type can 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 distances or types are considered. Therefore, it is important to settle this cost 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 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 site. Afterwards, construction begins 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 road layers, and integrating the 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 [3].

Furthermore, road users incur extra costs due to construction, which includes: VOC, a higher possibility for AC and work zone delay costs (WZDC) [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]. In this stage, the condition of the surface layer is of great importance as the rolling resistance can highly affect the fuel costs. Road durability and performance are 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 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. Preservation is applied when the road is still in good condition [53,54]. 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 [55]. 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 [55]. 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 [55]. Rehabilitation has the highest cost because it involves the milling or demolishing of the existent road and the reconstruction of a new one [56]. Similar to the construction phase, the associated cost components for M&R activities may include materials, construction machinery or equipment, labour and transportation [3,57].

3.5. End of Life: road deconstruction/demolition 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 [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 and cannot be directly reused, 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

The following part of the paper consists of describing the process and steps of an LCCA and is presented in Fig. 2. To provide additional information about the use of specific modelling parameters, and to show how they are applied in current studies, information from recent cases was collected. An initial selection was made using Web of Science as a database. Afterwards, if the selected literature referred to cases within the scope of this review, those cases were also analysed. This process was repeated until no new cases from the past decade were found that concerned LCCA for road-engineering projects. Detailed information of the individual cases is described in Appendix A and Appendix B and was used to design and discuss Fig. 3 - Fig. 4 and Fig. 6 - Fig. 9.

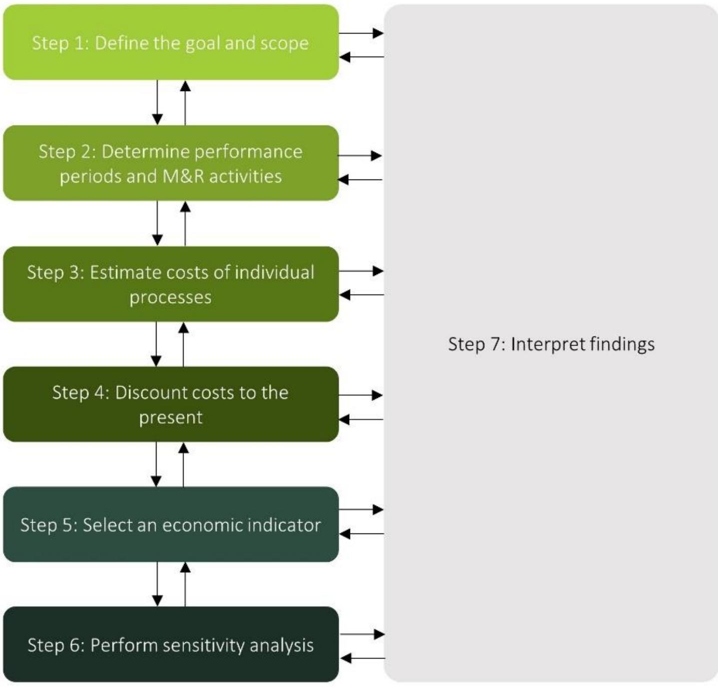

Fig. 2 Flowchart LCCA - process and steps

4.1. Define goal & scope and alternative design strategies

The first step in performing an LCCA is defining the goal & scope and design alternatives. This helps to understand how design choices may impact future costs for the road user, initial construction, M&R and EOL [58,59]. It is important to keep in mind that all alternatives have to meet all necessary standards so that environmental performance, durability and safety 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 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 [59]. 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. Caltrans proposes 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 [62]. 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 [59]. 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. 3, which shows the analysis periods used in the recent case studies from Appendix A and Appendix B per road type. Because different materials have different service lives, the cases were split into pavements, which only included concrete or asphalt layers, and full structures which also included bases and subbases below the pavement. Fig. 3 shows that 27% of the cases did not specify an analysis period as it were cost-benefit analyses (CBA) or simple payback period analyses (SPPA) which did not focus on long-term assessments. Additionally, it shows a wide variety of applied analysis periods. This is an important observation as it has implications for the comparison of results. Studies with different analysis periods should never be compared because the LCC is highly dependent on the analysis period as it defines the timeframe in which costs are considered.

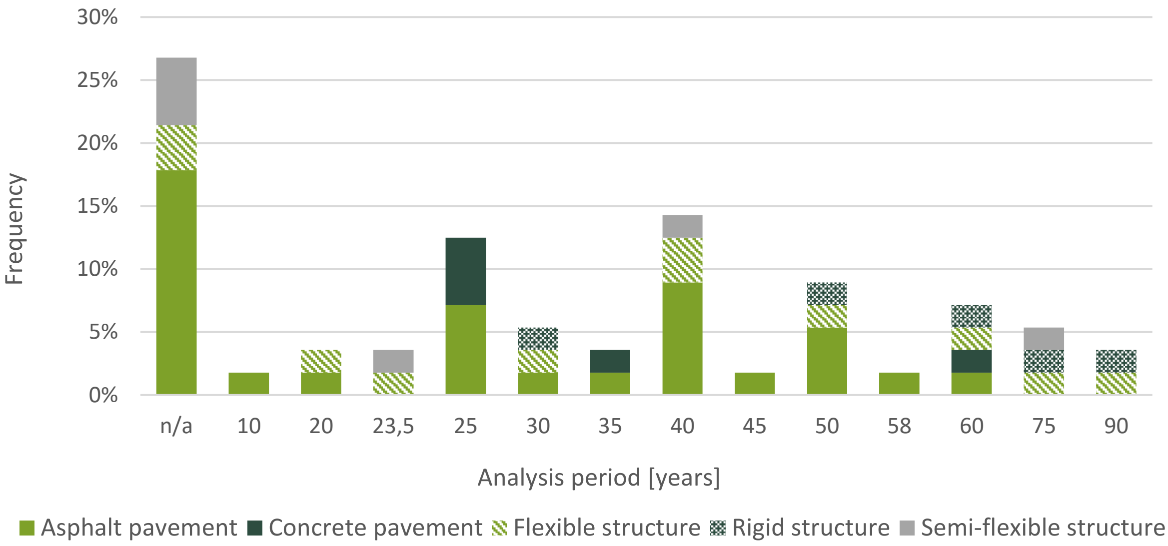

Fig. 3 Frequency of analysis period used in recent case studies per road type (n=56)

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 analysis periods of 50 years or more. 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.

Fig. 4 presents the analysis period used per set of system boundaries. The analysis shows four system boundaries which were used: initial construction (from extraction to construction), M&R, initial construction to M&R and the full life cycle (initial construction to EOL). Only 48% of the cases consider the full life cycle of a road, also, these studies have a wide variety of analysis periods. Additionally, 29% of the case studies did not use or specify an analysis period (n/a). Furthermore, 85% of the studies which are focussing on M&R often use no analysis period or an analysis period of 25 years. Finally, it can be concluded that the most frequently used defined analysis periods are 25, 40 and 50 years.

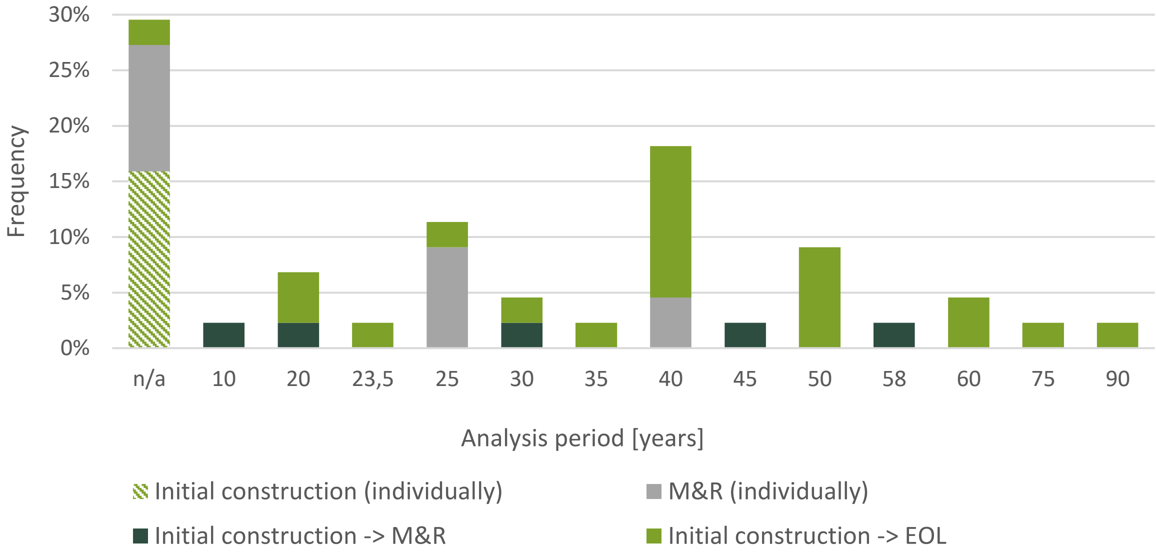

Fig. 4 Frequency of analysis period used in recent case studies per set of system boundaries (n=44)

4.2. Determine performance periods & M&R activities

After the alternatives and analysis period have been determined, it is important to predict the initial service lives and M&R to account for future costs [59,63]. Robbins et al. [63] provided the following definitions: *"The initial period is 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 threshold*" (p.6 [63]). 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 affect the frequency of agency intervention, consequently affecting costs during construction and M&R [63].

Therefore, the use of pavement performance data in a pavement management system (PMS), in combination with a pavement performance prediction model (PPPM), is critical [64,65]. These techniques predict the optimal timing for M&R based on different factors that cause road deterioration, such as ageing, traffic and climatic effects [66]. Hence, a PPPM helps to allocate funds for projects efficiently and decreases the M&R cost [65,67,68]. Fig. 5 demonstrates the operation of a PPPM [9,59,63]. The top part shows two alternatives with a difference in condition deterioration, hence, different performance periods. Once a threshold limit has been reached, an intervention is triggered. This intervention has a cost which is displayed in the lower part of the figure. After M&R has been applied, the pavement condition improves again and the performance period is reset. The magnitude of the cost and the number of repetitions are determined by the threshold limits. By determining the LCCA over the specified period of analysis, thus over several periods of performance, alternatives can be compared. 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 [10,69]. 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.

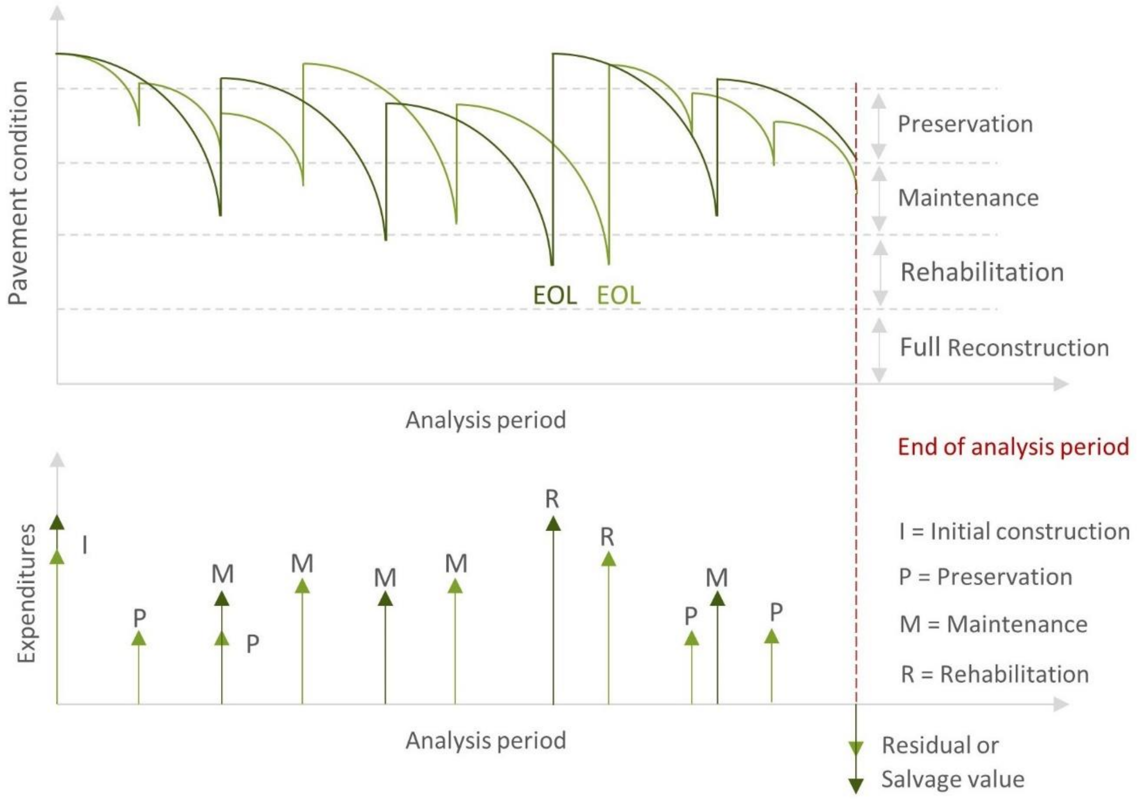

Fig. 5 A typical PPPM curve with corresponding expenditure stream diagram based on [9,59,63]

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 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 [70–73]. 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 [74].

4.3. Estimate costs

According to the ISO 15686-5 standard and Santos et al., costs can be categorized as being either fixed or variable. Fixed costs 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 [3,61]. Materials can be variable because the unit price may vary depending on the purchased quantity. Others, such as Estevan et al. and Wong, 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 [75,76].

A third distinction can be made between tangible or intangible costs [44,69]. According to Ozbay et al., 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 [69]. 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, on the other hand, are the costs encountered as a result of implementing the project but are incurred indirectly and are out-of-pocket [69]. 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 or future [46]. In LCCA, all the aforementioned categories are incurred either by the road agency or by the road user [69]. Therefore, all the cost components of the case studies were categorized under user and agency costs as presented in Fig. 6.

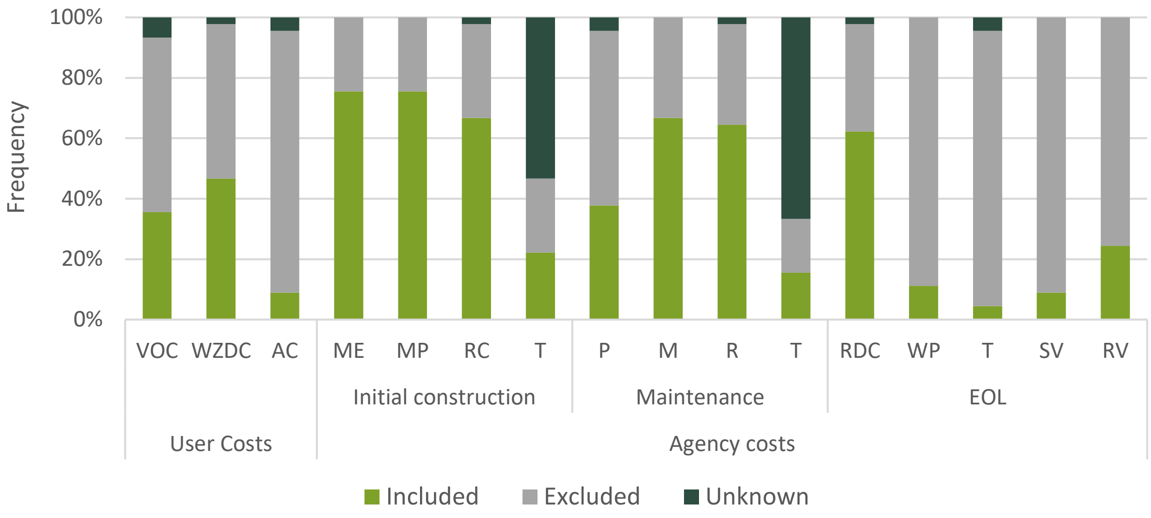

Fig. 6 Frequency of cost components used in recent case studies (n=45) where VOC = Vehicle Operation Costs, WZDC = Work Zone Delay Costs, AC = Accident Costs, ME = Material Extraction, MP = Mixture Production, RC = Road Construction, T = Transport, P = Preservation, M = Maintenance, R = Rehabilitation, RDC = Road Deconstruction/Demolition, WP = Waste Processing, SV = Salvage Value, RV = Residual Value

4.3.1. Agency costs

Agency costs denote 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 [30,32,67]. 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 [77]. 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., strongly recommend considering traffic management costs in comparing alternatives as they may have a significant effect [77]. 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. 6 demonstrates that costs related to materials, production and construction are well represented. What stands out is that transportation is either unknown or excluded in 77% of the cases. 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 [77]. 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. 6 that only 38% of the studies consider preservation and that transportation costs during M&R are excluded or unknown in 84%. 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/demolition of the existing road or pavement, the transportation of waste, waste processing and the salvage or residual value [44,50,63,78]. However, Fig. 6 demonstrates that EOL is excluded in most cases. The only cost component that the cases are considering, is the cost associated with the deconstruction/demolition of the road. Furthermore, 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 in this article 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 [79]. As discussed before, several pavement condition indicators exist.

Therefore, Eq. 3 is presented, based on [79], where the residual value is determined using 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 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 [58,77,80]. Fig. 6 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. According to Lee et al., RUC is often excluded due to its complexity and/or challenges that are associated with quantifying the cost components based on unreliable data [32]. For example, the effect of the surface layer condition on the fuel consumption as it is influenced by the rolling resistance. 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 [81]. However, there are two important reasons why RUCs should be included in LCCAs. 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 [80]. 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 [82], FHWA's HERS-ST model [80], EPA's Moves model [83], World Bank's HDM-4 model [84], Australian Road Research Board's Road Fuel Consumption model [85] and NCHRP's MicroBENCOST model [86]. 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 [53]:

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

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.

The MicroBENCOST [86] 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, 11 default 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 [86]:

$$VOC = \sum_{i=1}^{11} \left(UVOC_{fuel,i} + UVOC_{oil,i} + UVOC_{tire,i} + UVOC_{M\&R,i} + UVOC_{dep,i} \right) \qquad \text{Eq. 5}$$

Where *VOC* is the vehicle operation cost per km for 11 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.

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 method to compute the VOCs of seven vehicle types as a function of fuel, oil, tires, M&R and depreciation as presented in [80]. In addition, the model combines the aforementioned costs and combines them in 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 [80]:

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

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 [56–58,80]. 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. proposed a framework using Eq. 7 - Eq. 10 [58]:

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

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

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

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

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. 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 [80]. Therefore, it is proposed that Eq. 10 transforms in Eq. 11 where *i* stands for the traffic category and *n* stands for the total amount of considered traffic categories.

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

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 [50,56,58,80]. According to the framework proposed by FHWA, the first step is to determine the pre-construction crash rate (CR_{PC}). If no data is available, Eq. 12 can be used to estimate CR_{PC} based on historical data [80]:

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

Where CR_{PC} is the pre-construction crash rate per million vehicle km of travel, *AnP* is the analysis period in years, *A* is the number of crashes (based on historical data) 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 [80]:

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

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, 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.

However, several authors indicate that the crash rate and unit cost of crashes are dependent on the severity of the crash. 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 [50,57,58,80]. Therefore, it is proposed that Eq. 13 should be transformed into Eq. 14, where *i* stands for the crash category:

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

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 [87]. 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 [88].

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. According to Langdon et al, discounting is used when a series of costs over time must be put onto a common basis for decision-making purposes, not where the objective is to project annual costs on a year by year base. Therefore, when different alternatives have different cost profiles over time, it is likely that discounting will be applied in order to determine their LCCs, whereas it is often left out when the LCC of a single option is determined [60].

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% [44,46,89]. 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 [90]. 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 [46,91,92].

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

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

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Fig. 7 presents the discount rates used in the case studies per economic indicator. The most applied specified discount rate is 4%. 21% of the 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, 6% of the cases 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, a range of 2 to 5% would be better as 71% of the applied discount rates fall within this range.

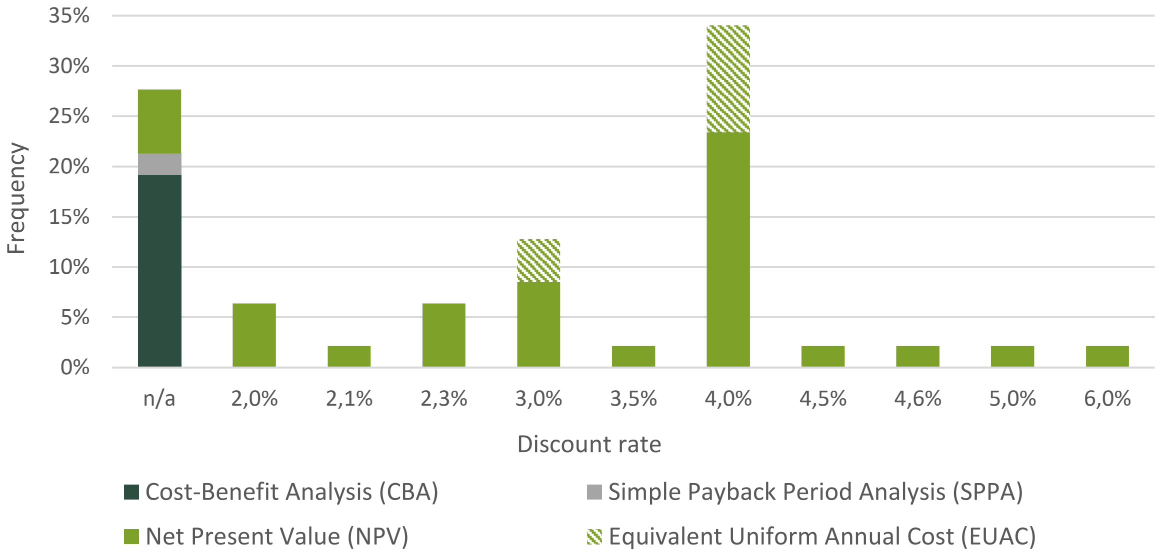

Fig. 7 Frequency discount rates used in recent case studies per economic indicator (n=47)

Once a discount rate has been established, a discount factor can be calculated based on whether nominal costs or real costs are being applied as specified in the ISO standard 15686-5. According to the standard, LCCA uses real costs to ensure accuracy regardless of the point in time at which these are incurred [61]. 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 soon. To convert a real cost to a discounted cost, the factor $q_{d,rc}$ in Eq. 16 should be used as specified in [61].

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

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 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 as presented in [61].

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

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.

4.5. Commonly used economic models

Once all cost categories, associated with each pavement alternative, have been identified and estimated, the computation of LCCA begins. Fig. 8 shows that the recent cases use four commonly applied economic indicators. A regular CBA or NPV is performed in 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. A summary of their advantages and disadvantages is presented in Table 1.

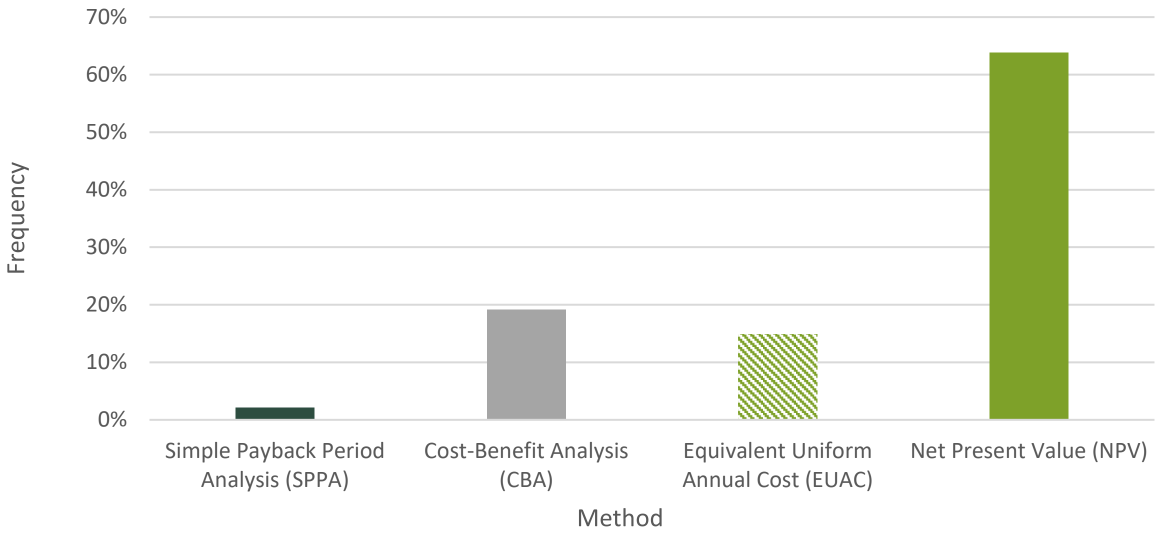

Fig. 8 Frequency of economic indicators used in recent case studies (n=47)

4.5.1. Simple Payback Period Analysis (SPPA)

The ISO standard 15686-5 defines SPPA as: "*the number of years elapsed between the initial investment, operational costs and the time which cumulative savings offset the investment*" (p.35 [61]). 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. The standard defines 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 [61].

Table 1 Summary of advantages and disadvantages of economic indicators

Economic Indicator	Advantages	Disadvantages
1. Simple Payback Period Analysis	Defines the period to recover initial investment costs.	Does not consider the value of time (unless discounted payback period analysis is used). Does not determine the LCC as the result is a period.
2. Cost-Benefit Analysis	Considers other non-economic benefits. User friendly method.	Is often limited to a specific part of the life cycle, e.g. the production cost => does not determine the LCC.
3. Net Present Value	Presents the total LCC in one value => easy to compare different alternatives. Considers the value of time.	Alternatives need to have the same analysis period. In-dept analysis is needed to compare individual life cycle stages.
4. Equivalent Uniform Annual Cost	Alternatives with different analysis periods can be compared. Considers the value of time.	Actual LCC is not presented as this is recalculated into an average yearly number.

4.5.2. 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 simplified version of a sustainability assessment as it combines multiple pillars of sustainability but limits the focus to a specific part of a road's life cycle. Because it is limited to a part of the life cycle, 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.

4.5.3. 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 [4,13,30,93]. 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, the authors propose a robust framework using 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.

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

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

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

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

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

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

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/demolition, waste processing and transportation) in year n, SV_n is the salvage value in year n, RV_{AnP} is the residual value at the end of the analysis period.

4.5.4. 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 [46,56,61,94]. The EAUC of a road alternative can be determined by implementing Eq. 22 or Eq. 23 into Eq. 24:

$$EAUC_T = NPV_T * \frac{d(1+d)^{AnP}}{(1+d)^{AnP} - 1} \qquad \text{Eq. 24}$$

Where $EUAC_T$ is the total EAUC based on NPV_T, NPV_T is the NPV calculated according to Eq. 22 or Eq. 23, *d* is the discount rate and *AnP* is the analysis period.

4.6. Sensitivity analysis

Results of LCCA are influenced by different uncertainties because cost allocations are often based on quotations, estimations and literature sources [19,33,95]. Thus, there is a need to perform a sensitivity analysis to examine how variations in parameters and assumptions may affect the robustness of the analysis [58,75,87,96]. 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;
- 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. 9 demonstrates how sensitivity analysis was performed in the case studies. Generally, LCCA and sensitivity analysis are categorized in two ways, deterministic and probabilistic [5,97–100]. Most case studies used deterministic models to perform their calculations. However, in some cases authors combined both models to compare their results.

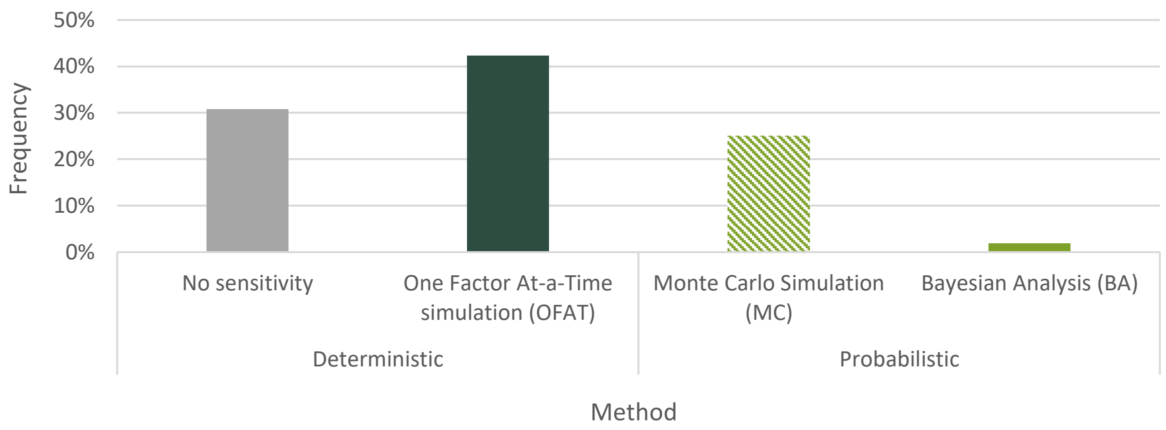

Fig. 9 Frequency of sensitivity analysis used in recent case studies (n=52)

Fig. 9 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.

4.6.1. 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 [69,81,98–101]. 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 [69]. 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 [99].

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 [81].

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.

4.6.2. 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 [21,81]. The first step in performing a probabilistic LCCA is to identify uncertain input parameters and to develop probability density functions for these parameters [102]. Afterwards, a simulation is performed using an iterative process to sample LCCs based on these distributions. As presented in Fig. 10, the iterative process 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.

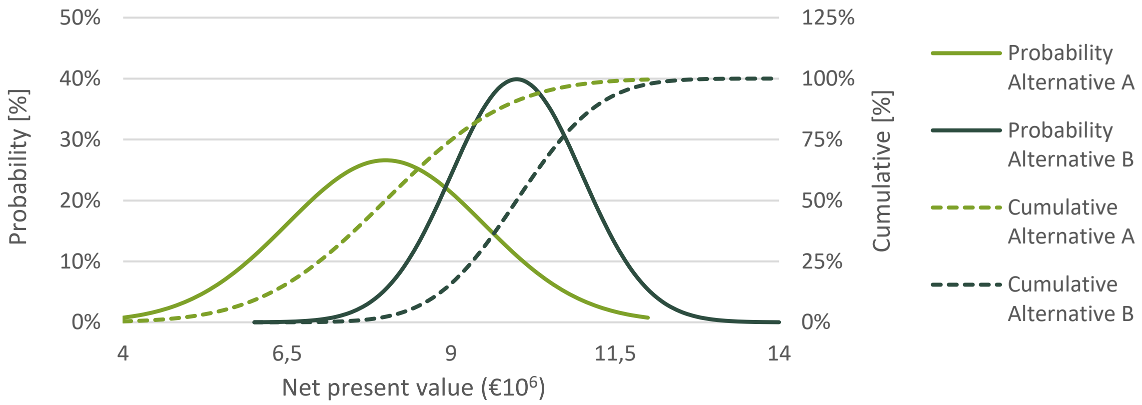

Fig. 10 Example of probabilistic modelling of the NPV of two alternatives

Fig. 9 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 [99,103–106]. 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. [107] 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. 11 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. 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.

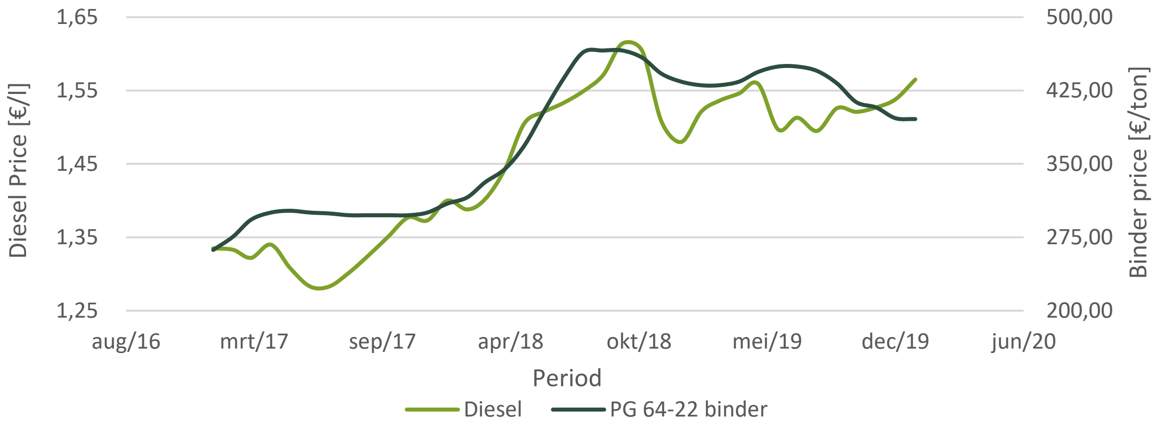

Fig. 11 Comparison price diesel & PG 64-22 binder for the period jan/17 - jan/20 [108,109]

To overcome this shortcoming, Wang et al [107] 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.

5. Discussion and conclusion

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 3-5% because discount rates are often location and time specific. However, the review showed that expanding this range to 2-5% would be more suitable as the frequency of cases that fall within this range increases from 55% to 71%. The two most commonly applied economic indicators are the NPV 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.

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Appendix A. Recent case studies (2010-2016)

General information				**Analysis information**				**User costs**			**Agency costs**												
											Initial Constr.				**Maintenance**				**EOL**				
Author	**Year**	**Country**	**Focus**	**Method**	**AnP [years]**	**DR [%]**	**SA**	**VOC**	**WZDC**	**AC**	**ME**	**MP**	**RC**	**T**	**P**	**M**	**R**	**T**	**RDC**	**WP**	**T**	**SV**	**RV**
Robinette et al. [110]	2010	USA	FS, SFS	CBA	-	-	-	-	-	-	x	x	x	?	x	x	x	?	x	-	-	-	-
Leng et al. [111]	2011	USA	AP	CBA	-	-	-	-	x	-	x	x	x	?	-	-	-	-	-	-	-	-	-
Lee et al. [112]	2011	USA	FS, RS	NPV	60	4%	-	-	x	-	x	x	x	?	-	x	x	?	x	-	-	-	-
Amini et al. [91]	2012	Iran	FS	NPV	40	2,3%	OFAT	x	x	-	x	x	x	x	x	x	x	?	x	-	-	-	-
Cheng et al. [94]	2012	USA	AP	NPV, EUAC	20	4%	MC	x	x	-	x	x	x	?	x	x	x	?	x	-	-	x	-
Santos et al. [79]	2012	Portugal	FS	NPV	40	3%	-	?	?	?	x	x	x	?	x	x	x	?	x	-	-	-	x
Gschösser et al. [47]	2013	Switzerland	FS, SFS, RS	NPV	75	2%	-	-	-	-	x	x	x	x	-	x	x	x	x	x	x	-	-
Li et al. [45]	2013	USA	FS, SFS	NPV	23,5	3%	-	-	-	-	x	x	x	x	-	-	x	x	x	-	-	x	x
Aurangzeb et al. [113]	2014	USA	AP	NPV	45	4%	OFAT	?	x	?	x	x	x	?	x	x	x	?	-	-	-	-	x
Mirzadeh et al. [46]	2014	Sweden	AP	EUAC	25	4%	OFAT	-	x	-	x	x	x	x	-	-	x	x	x	-	-	-	-
Son et al. [114]	2014	USA	AP	CBA	-	-	MC	?	x	-	-	-	-	-	-	x	-	?	-	-	-	-	-
Zaumanis et al. [115]	2014	?	AP	SPPA	-	-	OFAT	-	-	-	x	x	-	?	-	-	-	-	-	x	-	-	-
Santos et al. [3]	2015	USA	AP	NPV	50	2,3%	OFAT	x	x	-	x	x	x	x	-	x	x	x	x	-	-	-	x
Yang et al. [116]	2015	USA	AP	CBA	-	-	-	-	-	-	x	x	x	x	-	-	-	-	-	-	-	-	-
Yu et al. [53]	2015	?	AP	NPV	40	4%	-	x	-	-	-	-	-	-	x	x	x	?	x	-	-	-	x
Abdelaty et al. [33]	2016	USA	AP	EUAC	25	4%	MC, OFAT	-	-	-	-	-	-	-	x	x	x	?	x	-	-	-	-
Nazzal et al. [117]	2016	USA	AP	NPV	10	?	-	-	-	-	x	x	x	?	?	x	?	?	?	-	-	-	-
Souliman et al. [118]	2016	Sweden	AP	CBA	-	-	OFAT	-	-	-	x	x	x	?	-	-	-	-	-	-	-	-	-
Sultan et al. [68]	2016	China	FS, SFS	CBA	-	-	-	-	x	-	x	x	?	?	-	-	-	-	-	-	-	-	-
Sultan et al. [119]	2016	China	SFS	NPV	40	?	-	-	x	-	x	x	x	?	-	x	x	?	x	x	?	x	-
Wennström et al. [56]	2016	Sweden	AP	NPV, EUAC	40	4%	OFAT	x	x	x	x	x	x	?	-	-	x	?	x	-	-	-	x
Yepes et al. [120]	2016	Chile	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/Demolition, 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

Appendix B. Recent case studies (2017-2020)

General information				Analysis information				User costs			Agency costs Initial Constr.				Maintenance				EOL				
Author	Year	Country	Focus	Method	AnP [years]	DR [%]	SA	VOC	WZDC	AC	ME	MP	RC	T	P	M	R	T	RDC	WP	T	SV	RV
Akbarian et al. [21]	2017	USA	AP, CP	NPV	35	2%	MC	x	x	-	x	x	x	?	x	x	x	?	X	-	-	-	X
Wu et al. [92]	2017	China	CP	NPV	25	3,5%	MC, OFAT	x	x	-	-	-	-	-	x	x	x	?	X	-	-	-	-
Liu et al. [121]	2017	UK	AP	CBA	-	-	-	-	-	-	-	x	-	-	-	-	-	-	-	-	-	-	-
Underwood et al. [51]	2017	USA	AP	NPV	30	4%	-	-	-	-	x	x	x	?	-	-	x	?	X	-	-	-	X
Santos et al. [87]	2017	USA	AP	NPV	50	2,3%	OFAT	x	x	-	x	x	x	x	x	x	x	x	X	-	-	-	X
Ozer et al. [122]	2017	USA	SFS	CBA	-	-	-	-	-	-	x	x	x	x	-	-	-	-	-	-	-	-	-
Batouli et al. [58]	2017	USA	FS, RS	NPV	50	5%	MC, OFAT	x	x	x	x	x	x	?	?	x	x	?	X	-	-	-	-
Torres-Machi et al. [55]	2017	Chile	AP, CP	NPV	25	6%	OFAT	-	-	-	-	-	-	-	x	x	x	?	X	-	-	-	-
Coleri et al. [78]	2018	USA	AP	NPV	50	?	OFAT	-	-	-	x	-	x	?	-	-	x	?	X	-	-	-	X
Lee et al. [32]	2018	USA	AP, CP	NPV	60	4%	-	-	x	-	x	x	x	?	-	x	x	?	X	-	-	-	-
Diependaele [89]	2018	USA	FS, RS	NPV	90	3%	OFAT	-	-	-	x	x	x	?	x	x	x	?	X	-	-	-	-
Diependaele [89]	2018	Belgium	AP, CP	NPV	inf.	4%	OFAT	-	-	-	x	x	x	?	x	x	x	?	X	-	-	-	-
Qiao et al. [123]	2019	USA	FS	NPV	20	4,6%	OFAT	x	x	-	x	x	-	?	-	x	-	?	-	-	-	-	-
Qiao et al. [52]	2019	USA	FS	NPV	20	2%	OFAT	x	-	-	x	x	x	x	x	x	-	x	X	X	X	X	-
Wang et al. [98]	2019	USA	AP	EUAC	-	4%	BA, OFAT	-	-	-	-	-	-	-	-	x	x	?	-	-	-	-	-
Chen et al. [124]	2019	Taiwan	AP	NPV	40	4%	MC, OFAT	x	x	-	x	x	x	x	-	x	x	x	X	-		-	-
Guo et al. [5]	2019	USA	FS, RS	NPV	30	4%	MC, OFAT	x	-	-	x	x	x	?	-	x	-	?	-	-	-	-	-
Okte et al. [57]	2019	USA	AP	NPV	58	3%	OFAT	x	x	x	x	x	x	?	-	x	-	?	-	-	-	-	-
Nahvi et al. [100]	2019	USA	AP	EUAC	-	3%	MC	-	-	-	-	-	-	-	x	-	-	?	-	-	-	-	-
Choi [50]	2019	Korea	AP	NPV	40	4,5%	-	x	x	x	-	-	-	-	-	x	x	?	X	-	-	-	-
Nahvi et al. [12]	2019	USA	AP	EUAC	-	3%	MC	-	-	-	-	-	-	-	x	-	-	?	-	-	-	-	-
Gu et al. [17]	2019	USA	AP	NPV	40	2,1%	MC, OFAT	x	x	-	x	x	x	?	-	x	x	?	X	-	-	-	X
Jahanbakhsh et al. [48]	2020	Iran	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/Demolition, 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

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