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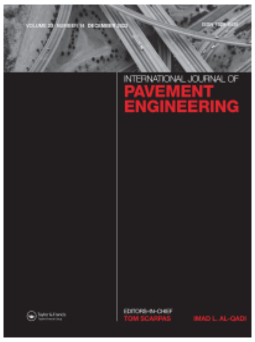

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ABSTRACT
The objective of this research was to evaluate the lifecycle costs associated with emerging pavement maintenance technologies, namely, in-situ rejuvenation and very open emulsion asphalt concrete (ZOEAB+), and scrutinise their suitability over corrective resurfacing maintenance using a stochastic approach. A rational lifecycle inventory was developed by conducting interviews and questionnaire surveys with experts and referring to standard guidelines and international databases. The net present value (NPV) was found sensitive to 12 different inputs with traffic growth rate and discount rate causing the highest uncertainty followed by gasoline and diesel prices. Monte Carlo simulations suggested that the median uncertainty in NPV by using in-situ rejuvenation and ZOEAB+ was 13% and 4% lower than resurfacing. It is envisioned that the research outcomes will assist decision-makers in understanding the uncertainties and costs associated with different maintenance alternatives in the early stages of the project to foster procurement of sustainable and circular pavement maintenance strategies.

KEYWORDS
Lifecycle cost analysis; porous asphalt; net present value; in-situ rejuvenation; ZOEAB+; uncertainty index

1. Introduction

The use of porous asphalt (PA) surface courses is recognised as a sustainable strategy for the construction of highways in the Netherlands (NL) attributed to its multiple benefits such as sound absorption, enhanced skid resistance and mitigation of surface runoff (Zwan, 1990). Almost 90% of the Dutch highway network is designed with PA having a typical void content of 20% (Bendtsen et al., 2012). Most of the highway surfaces are paved with single-layered PA, while others have been designed with two-layered PA, provided it assists in saving the cost of installing additional noise barriers. Past investigations have shown that the porous structure of PA acts as a dampening media and results in tyre-pavement noise reduction by about 4 dB(A) in single-layered PA and 6 dB (A) in double-layered PA compared to dense-graded asphalt concrete (De Bondt *et al.* 2016).

Historically, road administrations have focussed on either the construction of new PA roadway networks (along with several other types) or the upgradation of the existing pavement structures. Since the majority of the pavement network in developed nations such as the NL is already built and functional, the road agencies have shifted their focus from construction to maintenance and preservation. Furthermore, current legislations to meet the sustainable and circular infrastructure development require a higher rate of recycling and reuse of materials, adoption of innovative technologies that result in lower energy requirements and identification of strategies to keep the pavement asset in place for a prolonged duration. Therefore, the adoption of appropriate pavement preservation and maintenance methods can lead to significant material, environmental and economic savings (Reigle and Zaniewski, 2002; Harvey et al., 2012; Chen et al., 2019; Rodríguez-Fernández, 2020).

To ascertain the economic feasibility between competing pavement investment alternatives, lifecycle cost analysis (LCCA) is a scientific framework used by decision-makers that takes into consideration the present and future economic trends (Walls and Smith, 1998). Although there are multiple ways to represent the lifecycle costs (Moins, 2020), net present value (NPV) is the most commonly utilised key performance indicator, which takes into account the future and/or preservation cash flows (discounted to base year) and results in a single economic output that allows easy comparison between distinct alternatives (Chen et al., 2019). While the implementation of LCCA has increased in recent years, decision-makers generally exclude the user costs and treat the inputs as static values to conduct a deterministic analysis (Reigle and Zaniewski, 2002; Chan et al., 2008). Though deterministic LCCA allows for simplified assessment, it does not consider the inherent uncertainties associated with the inputs and is likely to give results that deviate from actual lifecycle costs (Swei et al., 2013).

One of the approaches that has been recommended by the Federal Highway Administration (FHWA) (Federal Highway Administration (FHWA) 2002) and other researchers (Harvey et al., 2012; Swei et al., 2013; Akbarian et al., 2017) to account for the uncertainties is to conduct a probabilistic LCCA. Pittenger *et al.* demonstrated that for 1-inch asphalt mill-and-inlay, the probability of exceedance of deterministic equivalent uniform annual cost (EUAC) was 63%, highlighting the ability of stochastic LCCA to expose the uncertainties (Pittenger, 2012).

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Another study reported that the application of preventive maintenance methods (thin overlays followed by chip seals at set trigger levels) in the early phases of alligator cracking leads to annual savings between $13 and $33 million (Harvey et al., 2012). Researchers suggested that for an analysis period of 5 years, the EUAC for chip sealing was lower than 1-inch asphalt mill-and-inlay and open-graded friction course (OGFC) by about 40 and 37%, respectively (Pittenger, 2011). Furthermore, the effective life of chip seal, microsurfacing and thin asphalt overlays is about 8 years with chip seal being two times cost-effective than microsurfacing and six times cheaper compared to thin asphalt overlays (Zuniga-Garcia, 2018).

Other studies have demonstrated that user costs that comprise expenses related to pavement–vehicle interaction, accidents and delays are one of the major contributors to the total lifecycle costs (Akbarian et al., 2017; Santos, 2017). For instance, Santos *et al.* reported that the road user costs were about four times higher than lifecycle agency costs attributed to the high fuel consumption during the operation phase and work zone delays (Santos, 2017). At the mixture level, a recent study indicated that a PA-wearing course designed with steel slag aggregates had a 78% and 92% higher chance of being cost-effective than a PA surface layer and OGFC designed with natural aggregates (Chen et al., 2019). Others have suggested the use of a nano-modified binder, warm mix asphalt technology and recycled aggregates to produce cost-effective PA mixtures (Rodríguez-Fernández, 2020).

In recent years, in-situ rejuvenation of PA has been recognised as a promising pavement preservation technology attributed to its life-extension benefits (The et al., 2016). This technology involves spraying a rejuvenator agent over the existing PA layer to extend its service life. The application of a rejuvenating agent results in increased resistance to fatigue and ravelling due to alteration in the chemical and rheological parameters without significantly affecting the porosity and skid resistance of PA (Zhang, 2016). The PA sections undergoing in-situ rejuvenation maintenance have shown an average increase in the service life between 2 and 6 years per rejuvenation cycle and also resulted in lower environmental impacts (considering only the construction and demolition phases) and higher cost–benefit ratio compared to untreated sections (The et al., 2016). Note that the cost–benefit ratio was determined by translating the environmental impacts into an economic value by using an environmental cost indicator (Bouwkwaliteit, 2022).

Another PA life-extending maintenance method is the application of a very open-graded asphalt emulsion (also known as ZOEAB + in the NL) mix. ZOEAB + involves application of a fray correction layer having a typical void content of 25% (Koster, 2013). The '+' sign indicates that prior to the application of ZOEAB, a modified adhesive emulsion is sprayed on the existing PAC layer. Extending the lifetime increases the overall sustainability of the road network by keeping the materials in use for longer periods, minimising energy consumption and decreasing traffic disruptions due to maintenance operations.

2. Problem statement, research objective and significance

Roadway agencies across the world are constantly looking for procurement of circular pavement maintenance solutions. Therefore, innovative pavement preservation methods that extend the service life of in-place assets are gaining attention as they fall under the umbrella of higher levels of circularity. Multiple investigations in the past have evaluated the economic feasibility of conventional pavement preservation techniques such as chip seals, microsurfacing and asphalt overlays. In addition, the economic viability of corrective maintenance using virgin and recycled materials has also been investigated. Efforts have also been made to examine the durability of PA pavements subjected to life-extension treatments, namely in-situ rejuvenation and ZOEAB + . However, there is no known research that has attempted to quantify the economic feasibility of these two emerging treatments having little historical information, while covering the use phase. Therefore, the research objectives include

- Evaluating the economic impacts of in-situ rejuvenation and ZOEAB + technologies using a stochastic approach and comparing with traditional resurfacing maintenance, while considering the managerial uncertainties;
- Developing a rational lifecycle inventory that can be integrated into futuristic LCCA studies to refine the existing input PDFs as more data emerge in the future and
- Proposing an uncertainty index that will assist policy-makers to evaluate the reduction in lifecycle costs due to a change in the service life of pavements and assess these maintenance options from a risk-based perspective, while also contributing to scientific decision-making.

The proposed research considers flexibilities in maintenance timelines, unlike traditional studies where the maintenance schedules are fixed. Despite the limitations of using a triangular distribution, it can provide a conservative estimate of the lifecycle costs and also assist in formulating tentative budgets during the pre-tendering phase based on expert opinion. Furthermore, the methodology outlined in this study may be extended by incorporating novel pavement preservation schemes having limited historical information or considering additional lifecycle stages. Overall, this research will enable pavement construction and maintenance stakeholders to identify opportunities to optimise the lifecycle costs and make informed choices to support the transition to a sustainable and circular economy.

3. Methodology

In this case study, resurfacing involved milling the existing surface layer and inlaying with virgin raw materials. Monte Carlo simulations (MCS) were employed to characterise the uncertainties associated with different input parameters and generate stochastic LCCA outputs. The consideration of economic aspects along with other dimensions of sustainability and durability is essential to transition to a circular built environment.

3.1. Goal and scope

The goal of this case study was to utilise a stochastic LCCA to assess the economic performance of three pavement

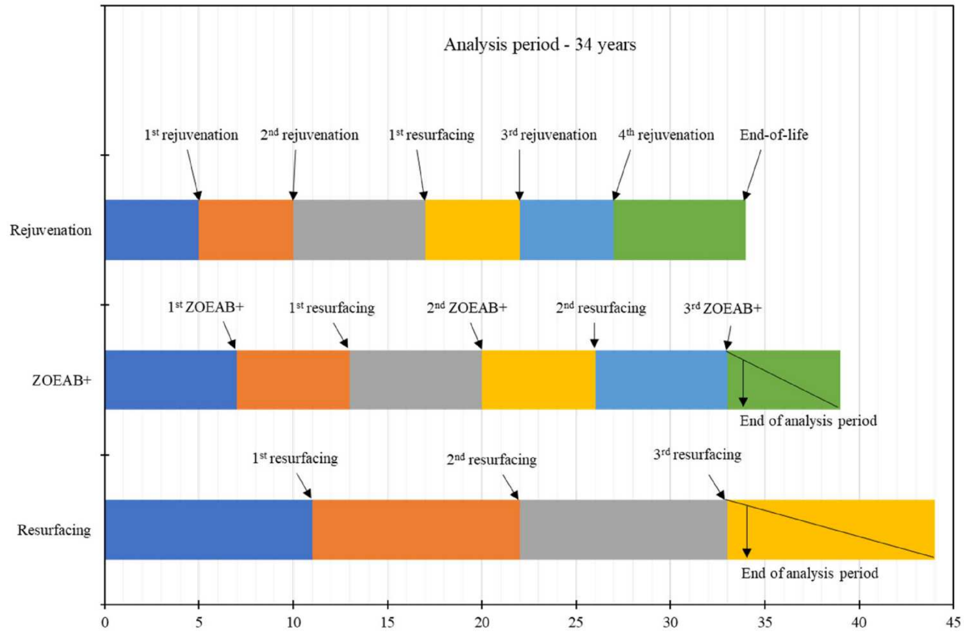

Figure 1. Timeline of maintenance activities.

maintenance alternatives, i.e. in-situ rejuvenation, ZOEAB+ and resurfacing with virgin materials. The functional unit for the analysis was a single-lane road, 1000 m long, 3.5 m wide and 0.05 m thick. The analysis period for the study was 34 years, which was determined in accordance with the FHWA guidelines (Harvey, 2016). In the NL, the typical service life of a heavily trafficked PA surface-wearing course layer is 11–12 years (Bendtsen et al., 2012; The et al., 2016; Zhang, 2016, Van Der Kruk *et al.* 2022). As per the Dutch experience, rejuvenation treatment is performed once in 5 years and every rejuvenation cycle extends the service life of pavement somewhere between 2 and 6 years, typically 3 years (The et al., 2016). Therefore, rejuvenation in years 5 and 10 will facilitate in extending the initial service life by about 6 years. In addition, the ZOEAB + surface treatment is known to increase the service life of PA by 1–3 years depending upon the extent of ravelling (Van Der Kruk *et al.* 2022). Research has shown that the PA layers perform satisfactorily in the NL with no major signs of distress until 7–8 years since construction, after which the ZOEAB + treatment is applied (RWS, 2023). Furthermore, the conventional resurfacing cycle is typically undertaken once every 11–12 years.

The typical timeline of different maintenance activities for the three alternatives considered in this research is presented in Figure 1. Based on discussions with pavement construction/maintenance stakeholders, it was understood that the underlying layers of pavements remain structurally sound, and full-depth reclamation is typically performed once in 50 years. Therefore, the maintenance of only the PA surface layer for an analysis period of 34 years was considered pragmatic and rational. Furthermore, the initial construction phase was excluded from the analysis as it would result in equal impacts for the considered alternatives. Additionally, the end-of-life phase was not included in the absence of information pertinent to the recycling and disposal of the pavement materials. In this research, the ZOEAB + and resurfacing maintenance options were given credit based on their remaining service life and were expressed as salvage value. Figure 2

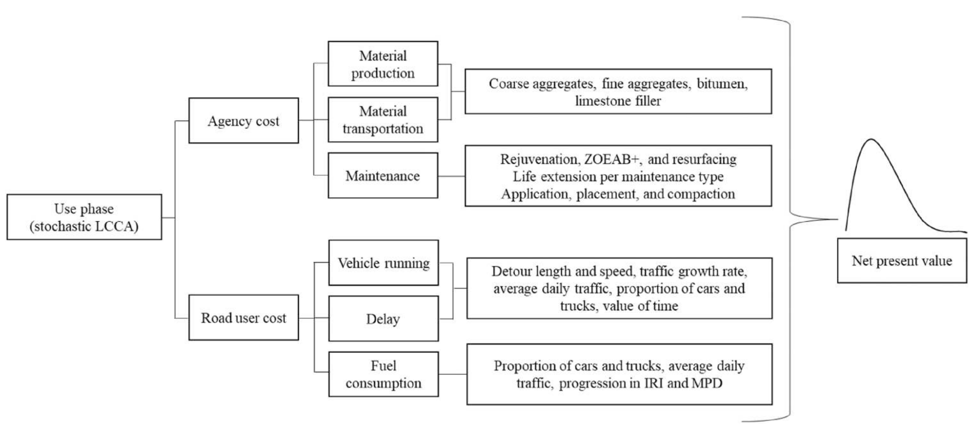

Figure 2. Processes and system boundary for LCCA.

*Note – ZOEAB+: very open-graded asphalt emulsion; IRI: international roughness index; and MPD: mean profile depth.

below depicts the system boundaries of the study. As can be seen, it covers all the material resources and utilities that are required for the different maintenance options.

3.2. Lifecycle inventory

The lifecycle inventory was generated by collecting the data from primary and secondary sources. To collect the primary data, a series of meetings, interviews, and questionnaire surveys were organised with representatives from different road agencies and material suppliers. The sequence of activities performed in the field and associated unit processes were understood. The secondary data was collected from the information available within the product category rule (Van Der Kruk *et al.* 2022) for asphalt, standard maintenance guidelines (Koster, 2013) specific to the NL, Eurostat's database (Eurostat, 2022a, 2022b, 2022c) and national statistics board (CBS – Statistics Netherlands, 2018). Next, a deterministic LCCA was undertaken to quantify the economic burdens of the three pavement maintenance alternatives. In addition, a one-factor–at-a-time sensitivity test was performed to identify the influence of different input variables on the NPV. It is important to mention that the LCCA studies require comprehensive input data gathered from different sources, thereby having several uncertainties associated with them.

To account for the input uncertainties, a stochastic LCCA was undertaken, where the inputs were defined as random variables following an appropriate probability distribution function (PDF) to quantify the range of possible outcomes. The uncertainties associated with the timing of maintenance activities and their probable contribution to life extension were incorporated into the analysis. Based on discussions with pavement stakeholders and available literature, it was understood that the discount rate varies from 1 to 5% (Federal Highway Administration (FHWA) 2002; Braham, 2016; Chen et al., 2019; Rodríguez-Fernández, 2020). The wide variability in the discount rate is bound to generate NPV values with lower reliability, thereby characterised as an uncertain input. The traffic growth rate was uniformly varying from 1 to 8%. Historical gasoline and diesel prices were used to statistically identify their PDFs, which followed lognormal distributions (BMWK, 2021, 2022; CBS – Statistics Netherlands, 2023; Global petrol prices, 2023a, 2023b).

Due to the unavailability of extensive historical data, a triangular PDF was defined for other inputs considered in this research. It is a continuous PDF that is defined by three parameters, namely maximum (upper limit), minimum (lower limit), and most likely estimates as shown in Figure 3 (Inti, 2016). The utilisation of a triangular PDF is particularly helpful when estimates are largely based on expert opinion and limited historical inventory. Although the triangular distribution accounts for uncertainty, it does not consider the price de(-escalations) as the expected mean value remains constant over time (Van Den Boomen *et al.* 2022). Nonetheless, the scarcity and confidentiality of lifecycle cost data as well as the absence of standards for establishing the lower and upper bounds of unit prices and life extension from different pavement maintenance strategies called for the adoption of triangular PDF. Other researchers have also suggested that the

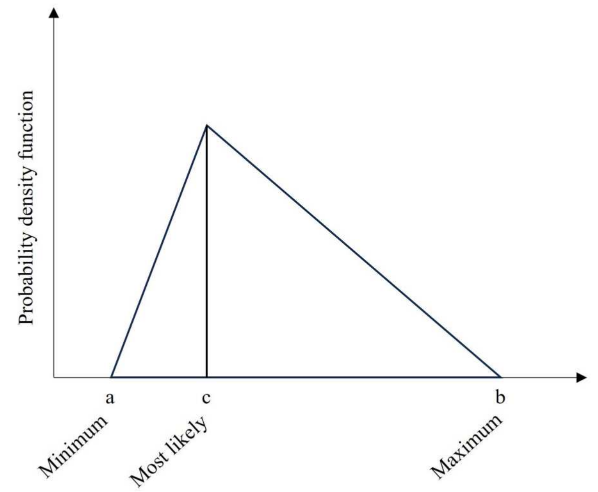

Figure 3. Triangular distribution.

triangular distribution provides a reasonable approximation for construction projects (Inti, 2016; Heidari et al., 2020).

Once the statistical distributions for different inputs were ascertained, MCS was performed to determine the uncertainty in the lifecycle cost of three pavement maintenance alternatives. MCS is a statistical technique that is used to predict the possible outcomes for uncertain events based on random sampling (Federal Highway Administration (FHWA) 2002; Stevens, 2023). In this study, the output PDFs were generated by performing 10,000 simulations based on 15 stochastic inputs identified using a sensitivity test (detailed discussion in Section 4.1) and keeping the other variables constant. The major inputs are shown in Table 1, while the details relevant to different deterministic and stochastic inputs are presented in Tables A1 through A3 of the supplementary material. The annual average daily traffic was set to 1800 vehicles/h, and a truck percentage of 11% was used for the analysis.

3.3 Lifecycle assessment

Once the pavement scenarios and other inputs were identified, the agency and road user costs were computed. The agency

Table 1. Major inputs for LCCA.

Input parameters	Value	Source*
Rejuvenation cost (€/sq.m)	1.96	*P*
Application rate of sand after rejuvenation (kg/sq.m)	0.35	*P*
Sand spraying cost (€/sq.m)	0.16	*P*
Application cost of ZOEAB (€/sq.m)	3	*P*
Discount rate (%)	2	*P* and S
Milling charges (€/sq.m)	10.57	*P* and S
Porous asphalt mix production cost (€/t)	72.5	*P* and S
Coarse aggregate cost (€/t)	10.2	*P* and S
Fine aggregate cost (€/t)	12	*P* and S
Limestone filler cost (€/t)	37.37	S
Bitumen cost (€/t)	200	S
Traffic growth rate (%)	3	*P* and S
Gasoline price (€/L)	1.53	S
Diesel price (€/L)	1.20	S
Paver charges (€/h)	269.25	S
Roller charges (€/h)	16.94	S
Porous asphalt concrete transportation cost per trip (€/t)	6.5	S
Transportation cost of all raw materials (€/T-km)	0.10	S

*Source: P – primary data source and S – secondary data source.

costs refer to the expenditure incurred by the road agency. The costs that were common for the various considered pavement alternatives (such as initial construction) were excluded from the analysis. Further, the routine maintenance costs such as cleaning were ignored as their contribution to the NPV is negligible (Walls and Smith, 1998, Federal Highway Administration (FHWA) 2002). Another parameter that affects the total agency expenditure is salvage value, which refers to the remaining value of the pavement alternative at the end of an analysis period. This has been incorporated as a negative cost in the LCCA. The salvage value, expressed in terms of serviceable value, represents the differences in remaining service life between various pavement alternatives at the end of the analysis period and was computed using Equation (1).

$$\text{Salvage value} = \text{cost of last treatment} \times \frac{\text{remaining life of last treatment}}{\text{service life of last treatment}} \quad (1)$$

User costs refer to the costs incurred by road users over the design life of a pavement. Typically, the user costs depend on the duration (days/weeks/months), time (working hours) and number and type of maintenance/rehabilitation/reconstruction activities associated with different pavement alternatives. In this study, user costs comprised vehicle running costs (VRC), delay costs (DC) and cost of additional fuel consumption due to deterioration of the pavement condition. User costs are expressed as the sum of the quantity of user cost components, and the unit 'Euro' value was assigned to the respective components. The DC (price/person-hour) is based on the value of time made up of factors such as average wage, type of vehicle, goal of the trip, travel type and vehicle occupancy. Data for the evaluation were mainly identified from the national and European databases. The VRC and DC were determined using Equations (2) and (3) (Decò and Frangopol, 2011; Khakzad and Gelder, 2016). Note that the highway lanes that underwent maintenance were completely closed to the traffic during maintenance operation. Therefore, the user cost for only detours was considered.

$$VRC = \left[C_{Run,Car}\left(1 - \frac{T}{100}\right) + C_{Run,Truck}\left(\frac{T}{100}\right)\right] \times D \times A(t) \times d \quad (2)$$

$$DC = \left[C_{AW}O_{Car}\left(1 - \frac{T}{100}\right) + (C_{ATC}O_{Truck} + C_{Goods})\frac{T}{100}\right] \times \frac{D \times A(t) \times d}{S} \quad (3)$$

where

T = average daily truck traffic (%);

$C_{Run,car}$ = average running cost for cars per km (Euro/km);

$C_{Run,truck}$ = average running cost for trucks per km (Euro/km);

D = detour length (km);

$A(t)$ = average daily traffic on year t;

d = duration of the detour (days);

i = annual discount rate (%);

n_k = year into the future of cash flow of activity k;

C_{AW} = average wage of car driver per hour (Euro/h);

O_{Car} = average vehicle occupancy for cars;

C_{ATC} = average wage of truck driver per hour (Euro/h);

O_{Truck} = average vehicle occupancy for trucks;

C_{Goods} = time value of the goods transported in cargo (Euro/h);

S = average detour speed (km/h).

The additional fuel consumption due to changes in pavement condition was estimated by using the MIRIAM models, which were developed by investigating multiple road surfaces of distinct textures (micro to mega) and roughness in Europe (Hammarström, 2012). Note that the fuel consumption in MIRIAM models is mainly dependent on the pavement surface characteristics and texture such as the international roughness index (IRI) and mean profile depth (MPD). Therefore, first, the IRI was computed using the methodology described by other researchers (Santos et al., 2017). The IRI progression rate for NL typically varies between 0.027 and 0.084 m/km (Sweere, 1996). Furthermore, it was considered that the application of a maintenance activity tends to restore the IRI equivalent to that of a newly constructed PA layer, which typically varies between 0.6 and 1 m/km in the NL (Silva, 2013). Investigators indicated that the MPD of PA varies from 1.5–1.9 mm and decreases at a rate of 0.041 mm/year. Once all the scenarios, associated timings of the activities, and the costs were established, future costs were discounted to the base year. The discounted future costs represented by the NPV were computed using Equation (4).

$$NPV = \sum_{k=1}^{n} MC_k\left[\frac{1}{(1+i)^{n_k}}\right] - \frac{SC}{(1+i)^k} \quad (4)$$

where

MC_k = maintenance cost of activity k in the year under consideration and it includes both agency as well as road user costs and

SC = salvage cost (serviceable value)

$\frac{1}{(1+i)^{n_k}}$ = discount factor.

4. Analysis and interpretation

4.1. Deterministic LCCA

The deterministic LCCA was undertaken based on the inputs supplied in Tables A1 through A3 in the supplementary materials. The results indicated that the respective cost of rejuvenation and ZOEAB + maintenance alternatives was almost 28 and 10% lower than resurfacing. In order to investigate the influence of different input variables, a sensitivity test was conducted by varying 22 input variables by a magnitude of ±60%, and the variation in NPV is presented in Figure 4. A longer bar indicates that the NPV is more sensitive to that particular variable. Furthermore, the sensitivity was expressed as the ratio of the percentage change in output to the percentage change in corresponding input.

Results indicated that the NPV was extremely sensitive (> 10%) to variations in the traffic growth rate, fuel prices (gasoline and diesel), discount rate, maintenance-related inputs

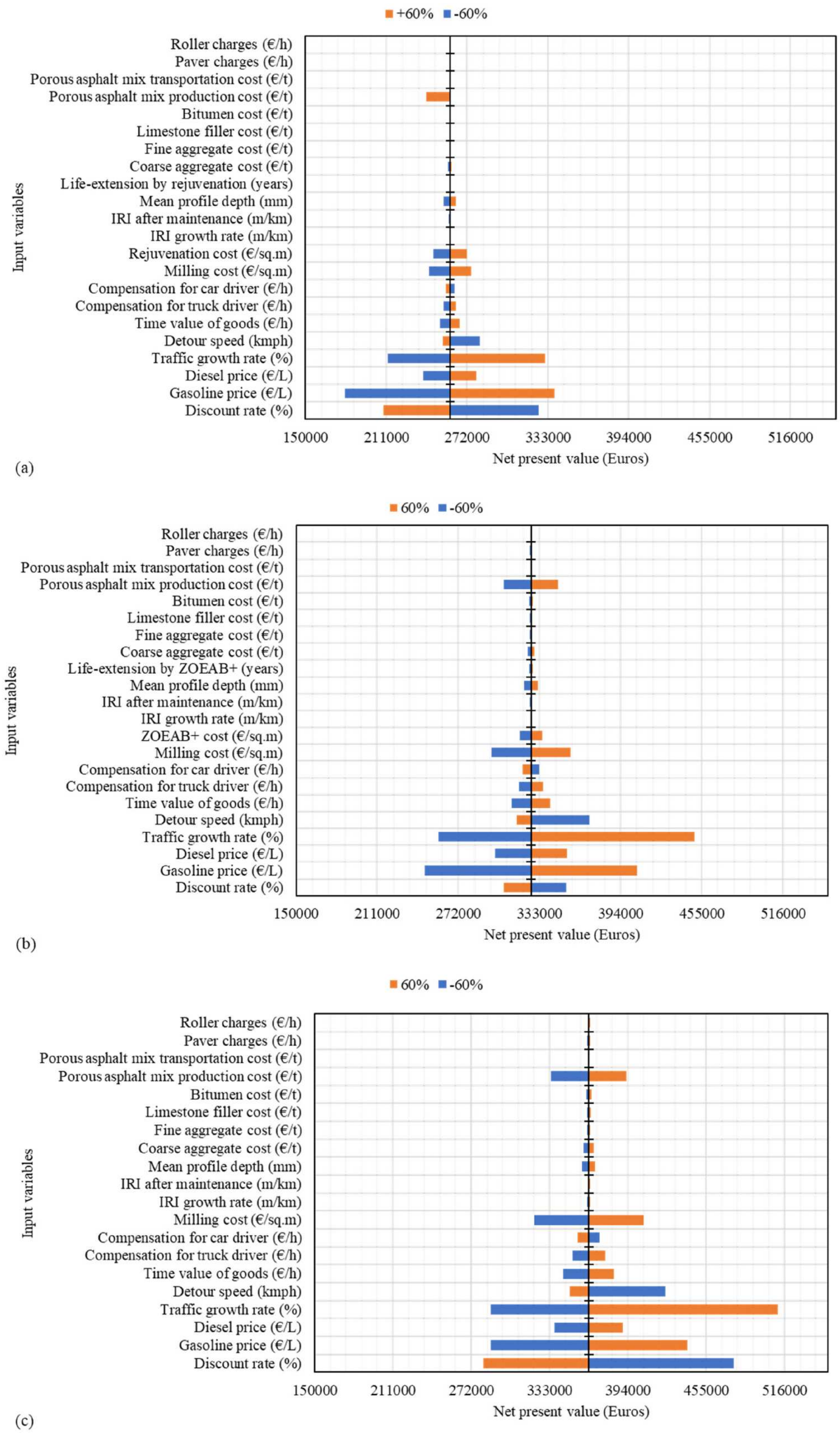

Figure 4. Input sensitivity for different maintenance alternatives: (a) rejuvenation, (b) ZOEAB+ and (c) resurfacing.

(rejuvenation, ZOEAB+ and milling) and PA production. On the contrary, NPV was least sensitive (< 1%) to the cost of raw materials (coarse and fine aggregates, filler and bitumen), PA transportation, paving, rolling or compaction, IRI growth rate and IRI after maintenance. Although pavement surface characteristics are known to influence operational costs, the IRI growth rate had a very weak correlation with the NPV. This can be ascribed to the fact that the pavements in the

NL are designed and maintained such that they do not reach their threshold value of 3.5 m/km (initial IRI from 0.6-1.0 m/km) during the service life (Silva, 2013; Santos, 2015), thereby not significantly contributing to uncertainty in the lifecycle costs. Variations in other inputs had a moderate influence (1-5%) on the NPV.

The vehicle operation phase accounted for almost 72% of the lifecycle costs for rejuvenation, while the corresponding proportions for ZOEAB + and resurfacing were 66% and 62%. Other researchers have also suggested that the vehicle operation phase has the highest contribution to the lifecycle costs (Santos, 2017). Therefore, a change in the traffic growth rate is anticipated to result in significant variations in the NPV. The uncertainty due to the change in the unit price of gasoline can be explained by the fact that the majority of passenger cars in the NL operate on gasoline, which comprises 82% of the traffic. Although the NPV was extremely sensitive to price variations in diesel, its influence was lower than the gasoline price attributed to the consideration of a lower proportion of diesel-fuelled trucks during the lifecycle. Further, the impact of the discount rate on NPV was significant, and a higher discount rate was consequential of lower NPV and vice-versa. Maintenance-related inputs also introduced uncertainty in the NPV with milling being the most influential parameter for all three alternatives ascribed to its higher unit cost compared to rejuvenation and ZOEAB + . Further, the variability in production cost of the PA mixture had a pronounced effect on resurfacing compared to ZOEAB + and rejuvenation attributed to a higher number of milling and overlay cycles (refer to Figure 1), which required more volume of PA mix during the analysis period.

The results of the deterministic analysis demonstrated that the adoption of in-situ rejuvenation for PA maintenance could lead to significant lifecycle cost savings. However, experience has shown that the life extension varies by 2–6 years from in-situ rejuvenation, 1–3 years from ZOEAB+, and 8–17 years from PA resurfacing depending on the level of traffic. Further, the NPV was moderate to extremely sensitive to 12 distinct inputs (as already shown in Figure 3), and uncertainties in these variables will have a significant influence on the lifecycle cost of three maintenance alternatives. These uncertainties in the life extension and input parameters motivated me to undertake a stochastic LCCA whose results are presented in the subsequent section.

4.2. Stochastic LCCA

Once the uncertain inputs and their PDFs were identified, MCS was performed to generate a range of NPV for three maintenance alternatives as presented in Table B1 of the supplementary materials. In order to visually understand the distribution of outputs, histograms were plotted as presented in Figure 5. Each bin of the histogram covered an NPV of 0.058 Million Euros. Clearly, the data in Figure 5 exhibits a strong positive or right skew as the majority of the MCS resulted in lower NPV with relatively fewer higher outputs. For instance, almost 75% of the 10,000 MCS generated the NPV for rejuvenation, ZOEAB+ and resurfacing lower than 0.97, 1.08 and 1.15 Million Euros, respectively. The histograms also indicate that there is a greater probability for occurrence of higher NPV for resurfacing followed by ZOEAB + and rejuvenation.

To further understand the shape of distributions or deviation of NPV from a symmetric normal distribution, kurtosis (a measure of data spread around the mean) and skewness (a measure of deviation from symmetric bell curve) were determined. The kurtosis for rejuvenation, ZOEAB+ and resurfacing alternatives was 1.22, 1.18 and 1.46, respectively, while the corresponding values for skewness were 1.11, 1.13 and 1.24. Clearly, the skewness for the three alternatives was beyond the typical convention of − 1 to +1 for a normal distribution, while the kurtosis was well within the limits of − 3 to +3 (Kallner, 2018). Further, the Anderson–Darling (A–D) test statistic revealed that the NPV for three maintenance alternatives did not follow a normal distribution. To check the difference in the central tendency of NPV between three maintenance types, Mood's median test was conducted with the null hypothesis that the median of NPV was the same across all categories, and findings are summarised in Table 2. The test revealed (two-tailed significance <0.05) that the median of NPV for at least one of the maintenance types was different from the other. Therefore, a pairwise comparison was performed to identify the alternatives that were different. As shown in Table 2, the median NPV for all three alternatives differed from each other. A relatively lower significance value (0.013) was observed for ZOEAB + and resurfacing maintenance pairs, indicating that the median of their NPV was closer to each other.

As the NPV deviated from normality, it was essential to identify the distribution that best represented the outputs for three maintenance alternatives. A–D test revealed that a 3-parameter gamma distribution was the best fit to NPV for rejuvenation and ZOEAB + alternatives. For the resurfacing option, the A–D statistic for lognormal distribution was lower than gamma. Note that a lower A–D value confirms a better fit. However, the newly transformed data obtained after taking the natural log of the original NPV did not follow a normal distribution. Thus, it was logical to use a 3-parameter gamma distribution for the resurfacing option, which also allowed for consistent assessment of uncertainty in NPV for the three maintenance types. A 3-parameter gamma distribution is a generalised form of gamma distribution that is used to model continuous positive random variables and is characterised by its shape, scale and threshold (Bowman and Shenton, 2011). It is particularly useful when the data is right skewed as already seen in Figure 5.

During the lifecycle, a pavement undergoes different maintenance schemes, whose cost is borne by the road agency. Further, road users incur costs due to travel delays and vehicle operation during the movement from origin to destination. Therefore, the agency and road users will always bear a minimum cost, which may be represented by the threshold parameter (γ). Further, the variation in the expenditure incurred over the analysis period due to input uncertainties may be represented by the shape parameter (α). Finally, the range of possible NPV outcomes during the analysis period may be represented by the scale parameter (β). The PDF curves for the three maintenance alternatives are presented in Figure 6. Note that the objective of identifying the best fit was to use an appropriate distribution function, whose

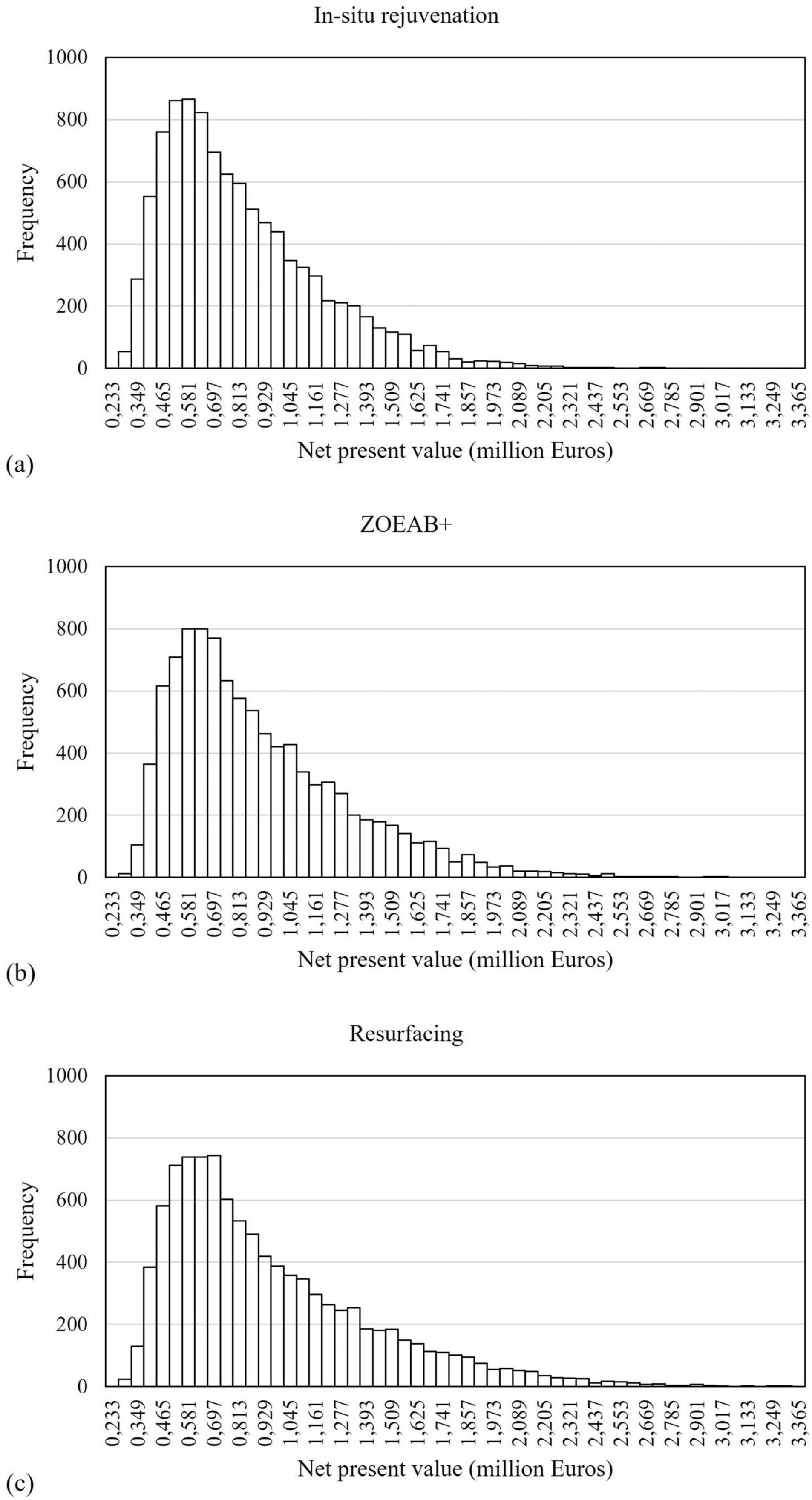

Figure 5. Stochastic LCCA results for three maintenance methods: (a) in-situ rejuvenation, (b) ZOEAB+ and (c) resurfacing.

Table 2. Summary of Mood's median test and pairwise comparison for three alternatives.

Test summary				
Total observations	Median	Test statistic	Degree of freedom	2-tailed significance
30000	0.756	172.655	2	0.000
Pairwise comparison summary of maintenance alternatives				
Paired samples		Test statistic		2-tailed significance
In-situ rejuvenation and ZOEAB+		102.53		0.00
In-situ rejuvenation and resurfacing		148.61		0.00
ZOEAB + and resurfacing		6.19		0.01

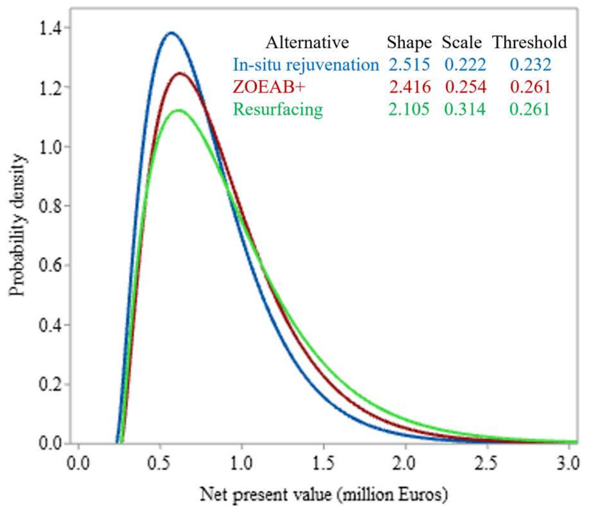

Figure 6. Probability distribution functions of 3-parameter gamma distributions for different maintenance options.

estimates (such as mean, median, etc.) could be used for uncertainty assessment of the LCCA outputs.

The cumulative distribution plot for the different PA pavement maintenance alternatives is presented in Figure 7. Further, the uncertainty profile is shown in Table 3, where the uncertainty index was computed using Equation (5). The uncertainty index may be defined as a measure of reduction in the economic uncertainty (or risk) associated with a particular maintenance type when compared with a baseline alternative. Although it is a common practice to use the mean and standard deviation to report the uncertainties in NPV, this research recommends that the uncertainty index must be expressed by considering median and quartile ranges. It is attributed to the fact that mean and standard deviation are highly sensitive to skewness (as seen before in Figure 5) and median and quartile ranges can be used as more robust measures to understand the centre and spread of NPV.

$$\text{Uncertainity index}_{X-Y} = \left(\frac{\text{Uncertainty parameter}_X - \text{Uncertainty parameter}_Y}{\text{Uncertainty parameter}_X}\right) \times 100 \quad (5)$$

where

Uncertainty index$_{X-Y}$ = uncertainty reduction when alternative Y is considered instead of baseline alternative X,

Uncertainty parameter$_X$ = the parameter (X) of baseline maintenance alternative used to quantify uncertainty, and.

Uncertainty parameter$_Y$ = the parameter (Y) of the alternative maintenance scenario used to quantify uncertainty

Although both the deterministic results and the uncertainty index yielded similar findings, the uncertainty index provided

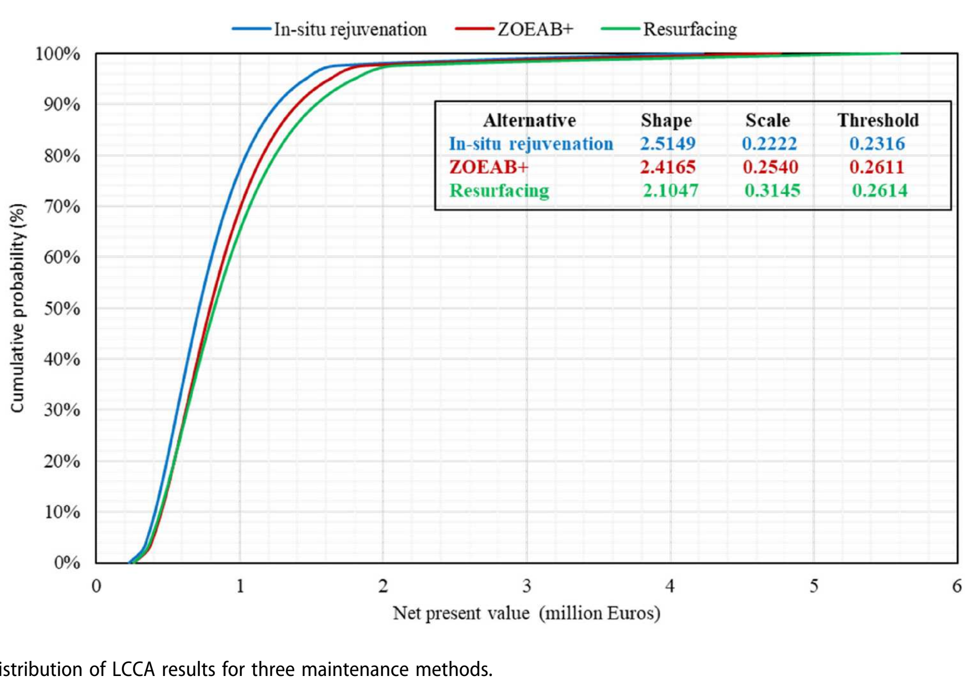

Figure 7. Cumulative distribution of LCCA results for three maintenance methods.

Table 3. Uncertainty profile of three pavement maintenance alternatives.

Cumulative distribution value (Million Euros)	Resurfacing	ZOEAB+	Uncertainty index (%)	In-situ rejuvenation	Uncertainty index (%)
Mean	0.92	0.87	5.43	0.79	14.13
Standard deviation	0.46	0.39	15.21	0.35	23.91
25th percentile/lower quartile	0.59	0.58	1.69	0.53	10.17
Median	0.82	0.79	3.66	0.72	12.19
75th percentile/upper quartile	1.15	1.08	6.09	0.97	15.65
95th percentile	1.86	1.66	10.75	1.48	20.43

more information that can be useful for decision-making. For instance, the deterministic LCCA revealed that the lifecycle costs of in-situ rejuvenation, ZOEAB+ and resurfacing were 0.26, 0.33 and 0.36 Million Euros, respectively. However, the uncertainty index showed that these values fell below the 25th percentile, indicating that there was more than a 75% probability for the actual lifecycle costs to exceed the deterministic outputs. Further, the 95th percentile showed that there was only a 5% probability for the lifecycle costs associated with rejuvenation, ZOEAB+ and resurfacing to exceed 1.48, 1.66 and 1.86 Million Euros, respectively. Hence, the underestimation of the NPV can have serious consequences on the budgets that must be allocated for pavement maintenance during the financial planning and tendering phases.

The median uncertainty in NPV associated with the use of rejuvenation and ZOEAB + maintenance was 12.19 and 3.66% lower than resurfacing. Further, the lower and upper quartile uncertainty with rejuvenation maintenance was about 10 and 16% lower than resurfacing, while for ZOEB+, it reduced by 1.69 and 6.09%. On another account, the mean value of uncertainty for rejuvenation and ZOEAB + was approximately 14 and 5% lower than resurfacing. The differences in the uncertainty index for mean and median clearly indicate that the mean is pulled towards higher NPV, resulting in an underestimation of the uncertainties associated with different maintenance alternatives. Further, the lower NPV for rejuvenation is attributed to the extension in service life, which allowed for only one resurfacing before reaching the end of the analysis period. Note that resurfacing is the most expensive maintenance amongst the three alternatives considered herein. Therefore, more number of resurfacing activities will bring in higher uncertainty and consequently result in increased costs during the assessment of NPV for longer analysis periods. Although ZOEAB + also contributed to life extension, it involved two resurfacing cycles, which led to increased uncertainty in NPV compared to rejuvenation.

As can be seen in the cumulative distribution plot (Figure 7), the slope for rejuvenation was steeper compared to ZOEAB + and resurfacing. It must be noted that the variability of NPV for three maintenance alternatives is inversely proportional to the slope, i.e. a curve with a steeper slope is indicative of lower variability in NPV. This observation also indicates that higher uncertainty was associated with resurfacing followed by ZOEAB + and rejuvenation. This conclusion can also be corroborated with the histogram plots (see Figure 5) and PDF in Figure 6, where resurfacing had the longest tail and consequently higher data spread and variability followed by ZOEAB + and rejuvenation.

5. Limitations and future direction

This study utilised a triangular PDF to capture uncertainty in various input parameters based on the information collected from different pavement stakeholders. Although triangular distribution assists in financial planning when little historical data and only expert opinion are available, it is prone to generating higher lifecycle cost values. Note that extremely high costs are usually associated with unexpected events and have a lower chance of occurrence. Therefore, the use of triangular distribution may lead to overestimation of NPV, necessitating the evaluation of results with caution. Second, the uncertainty in NPV for the three maintenance alternatives may not hold good if the lifecycle inventory differs significantly from the one presented in this research. Third, the triangular distribution fails to capture the variation in the price of materials and activities over a period of time. Fourth, the influence of multi-unit trucks and electric vehicles on the lifecycle cost was not considered.

Furthermore, this study utilised the typical range of IRI and MPD as well as their progression rates in the NL for estimating the impacts of the operational phase. Note that the pavement condition influences the fuel consumption rates, calling for the need to develop time-dependent models specific to PA capable of predicting the variation in IRI and MPD due to changes in traffic characteristics volume and environmental conditions. Furthermore, the output NPV was represented by a 3-parameter gamma distribution, which was used to capture the uncertainty characteristics of the data in the context of this research and may not always provide an accurate representation of the underlying process if additional historical data is available in future. In addition, future studies must also collect data pertinent to the sub-inputs that constitute compensation and time value such as the proportion of passenger cars on business or personal travel, hourly time value on business travel, average bonus and others (wherever feasible) to more accurately predict the road user costs.

Therefore, it is essential to develop a detailed repository that lists the change in unit costs of materials, activities, traffic features and volume, and changes in pavement performance characteristics with the passage of time. Further, all the minor to major maintenance activities and associated timings as well as durations must be recorded. Importantly, attempts must be made to understand the mechanisms that are consequential of price fluctuations. Such an approach will help in accurate data analysis, generation of more reliable PDFs based on real-time information, and assist in evaluation of uncertainties with higher confidence.

6. Conclusions and recommendations

The objective of this research was to evaluate the economic credentials of in-situ rejuvenation and ZOEAB + maintenance technologies and assess their suitability compared to traditional resurfacing. The inputs required to conduct this research were gathered from different stakeholders, available literature and national/international databases. Suitable PDFs were defined for the uncertain inputs, and the output NPV was generated using MCS. The following major conclusions can be drawn:

- For deterministic LCCA, the cost of in-situ rejuvenation was about 28% lower than the cost for corrective maintenance of milling and inlay with virgin materials, while the corresponding cost of ZOEB + was 10% lower.
- The NPV was sensitive to 12 distinct input variables and the inputs causing the highest variability in the NPV were traffic growth rate, discount rate and fuel prices.
- As the NPV for three maintenance strategies deviated from normality, a 3-parameter gamma distribution was found to best represent the variations in NPV. Further, an uncertainty index was proposed to investigate the reduction in economic risks for different maintenance types and data variability compared to the baseline alternative.
- The stochastic LCCA results indicated that the lowest and highest uncertainties in the NPV were associated with the use of in-situ rejuvenation and resurfacing, respectively. For instance, the NPV for in-situ rejuvenation was about 10–16% lower than resurfacing, while the corresponding uncertainty reduction in NPV with ZOEAB + was 1.69–6.09%.

The proposed approach and research outcomes can be used by different pavement stakeholders for financial planning and management. Further, the results of this study suggested that in-situ rejuvenation and ZOEAB + pavement life-extension technologies are economical alternatives to traditional resurfacing maintenance attributed to their ability to extend the service life of pavements. However, additional efforts must be made to develop region-and-project-specific repositories comprising long-term pavement performance data as well as information relevant to other lifecycle inputs. Such an approach will minimise uncertainties in pavement lifecycle analysis and ensure compliance with evolving standards and specifications having sustainability and circularity at their core.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

Author contributions

The authors confirm contribution to the paper as follows: Conceptualisation: Avishreshth Singh and Aikaterini Varveri; Data curation: Avishreshth Singh and Aikaterini Varveri; Formal analysis: Avishreshth Singh; Funding acquisition: Aikaterini Varveri; Investigation: Avishreshth Singh and Aikaterini Varveri; Methodology: Avishreshth Singh; Project administration: Aikaterini Varveri; Resources: Aikaterini Varveri; Software: Avishreshth Singh; Supervision: Aikaterini Varveri; Validation: Avishreshth Singh and Aikaterini Varveri; Visualisation: Avishreshth Singh and Aikaterini Varveri; Roles/Writing – original draft: Avishreshth Singh; and Writing – review & editing: Aikaterini Varveri.

Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article [and/or] its supplementary materials.

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