Lifecycle costs of in-situ rejuvenation and warm-mix porous asphalt technologies

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ABSTRACT: This study evaluated the lifecycle costs associated with in-situ rejuvenation and the use of warm-mix porous asphalt mixtures (WM-ZOAB) and compared them with traditional resurfacing maintenance. The results indicated that the economic impacts of in-situ rejuvenation maintenance strategies were lower by about 6% compared to their counterpart resurfacing. Further, the sensitivity analysis suggested that the gasoline prices, traffic growth rate, discount factor, milling costs, and asphalt mix prices were the most influential factors affecting the lifecycle costs. In addition, the study highlighted that the WM-ZOAB alternatives must function satisfactorily for a design life of at least about 13 years in order to be recognized as cost-effective pavement solutions. The research findings support the transition towards sustainable pavement technologies, while emphasizing the importance of comprehensive economic assessments in decision-making.

1 INTRODUCTION

Lifecycle cost analysis (LCCA) is a structured method for estimating the costs associated with a project or facility throughout its lifecycle. This approach ensures a comprehensive assessment of both initial investments and long-term operational costs, supporting informed decision-making (Durairaj, 2002). Recent government mandates for sustainable infrastructure development highlight its role in project management and tendering processes. Consequently, LCCA has become integral to evaluating and comparing pavement alternatives, ensuring their economic feasibility over time (Walls, 1998).

To meet sustainability goals, road administrations have adopted strategies such as increasing the use of reclaimed asphalt pavement (RAP) and recycled materials (Qiao et al., 2019), adopting low-emission material production such as warm mix asphalt (WMA) (Binnenlands Bestuur, 2024), and prioritizing pavement preservation measures such as in-situ rejuvenation (Thé et al. 2016). These practices enhance cost-effectiveness and impart broader sustainability benefits.

Dutch roadway systems on average comprise 50 % RAP (Solids, 2023). Typical practice is to use about 20-30% RAP to design a durable porous asphalt surface layer (also regarded as DZOAB in the Netherlands) with much higher proportion of recycled materials in the underlying layers (Tsakoumaki et al. 2024). Research has shown that partial and/or complete substitution of virgin aggregates with RAP in asphalt mix reduces the road agency costs, thereby making it a cost-effective material (Qiao et al. 2019).

In-situ rejuvenation, a life-prolonging pavement maintenance technique, is extensively used on Dutch highway network to extend the service life of pavements (Thé et al. 2016). It involves spraying a bitumen-like compound over pavement's surface that fills in micro-cracks and rejuvenates the aged bitumen in the mortar (Thé et al. 2016). In-situ rejuvenation reduces lifecycle cost by 13% compared to resurfacing maintenance (Singh & Varveri, 2024).

Further, WMA being an energy-efficient and environmental-friendly technology (Ma et al. 2019) is known to reduce the fuel costs by 11-35% compared to hot-mix asphalt (Tutu & Tuffour, 2016). However, other researchers have claimed that the lower fuel costs may not be large enough to offset the capital costs and require further investigation (Anderson & May, 2008). In line with these advancements, Dutch asphalt producers have committed to reducing production temperatures, with a collective decision to cease production of asphalt exceeding 140ºC starting January 1, 2025 (Binnenlands Bestuur, 2024).

Therefore, Netherlands is witnessing a significant push towards integrating sustainable technologies, namely, WMA, RAP, and in-situ rejuvenation, into road construction and maintenance. While in-situ rejuvenation has shown promise in extending pavement service life, and WMA is being evaluated as a viable alternative to traditional hot-mix asphalt, there is a lack of historical input data and comprehensive research on the economic feasibility of these methods over their entire lifecycle. Additionally, there is uncertainty regarding the minimum service life WMA must achieve to be considered a sustainable and cost-effective option. Addressing these gaps is critical to ensuring informed decision-making. This work is part of a larger stochastic analysis aimed at assessing the risks associated with these maintenance methods.

Therefore, the primary objective of this research is to evaluate the economic impacts of in-situ rejuvenation and the use of WMA in DZOAB mixtures and compare them with traditional resurfacing maintenance. The study also aims to identify key financial uncertainty factors and determine the desired service life that WMA must meet to be recognized as a cost-effective solution.

2 METHODOLOGY

2.1 *Goal & Scope*

The goal of this research is to assess the economic feasibility of four different pavement construction and maintenance alternatives as below:

- Resurfacing with hot-mix asphalt (HMA): removal of 50 mm thick DZOAB layer comprising 30% RAP having a service life of 12 years (typical for right lane in The Netherlands) (van der Kruk & Overmars, 2022).
- Rejuvenation over HMA: a bituminous emulsion is applied on DZOAB in years 5 and 10 after the construction (Thé et al. 2016). Each rejuvenation treatment prolongs the service life of road by 3 years, with two activities resulting in 6 year life-extension. Therefore, the first resurfacing maintenance (50 mm DZOAB thickness with 30% RAP) will occur in year 18.
- Resurfacing with WMA: this strategy is similar to resurfacing, with the only difference being that the DZOAB is now constructed with WMA comprising 30% RAP.
- Rejuvenation over WMA surface: this strategy follows the same maintenance plan as in-situ rejuvenation, with the only difference being that instead of DZOAB a warm-mix DZOAB (WM-DZOAB) comprising 30% RAP is considered.

The timeline of different pavement alternatives is shown in Figure 1. Based on discussions with roadway stakeholders in the Netherlands, it is anticipated that WM-DZOAB possess a higher durability and may achieve a service life approximately five years longer than conventional DZOAB. Other researchers have also suggested that the durability of WMA is higher than conventional HMA (Rodríguez-Fernández et al. 2020; Gaarkeuken et al. 2016). However, given the limited availability of scientific research to substantiate this hypothesis, a conservative approach was adopted. Accordingly, the initial design life of WM-DZOAB scenarios was aligned with that of conventional DZOAB. Sensitivity analyses was subsequently conducted to determine the minimum service life required for WM-DZOAB to be recognized as a cost-effective alternative.

The analysis period was 36 years, determined in accordance with International guidelines (Walls, 1998) and the functional unit was a single lane ZOAB having dimensions 1000 m × 3.5 m × 0.5 m (Rijkswaterstaat, 2019). Further, the different processes considered in this research are presented in Figure 2. The end-of-life costs were not taken into account due to the lack of appropriate data for modelling this phase.

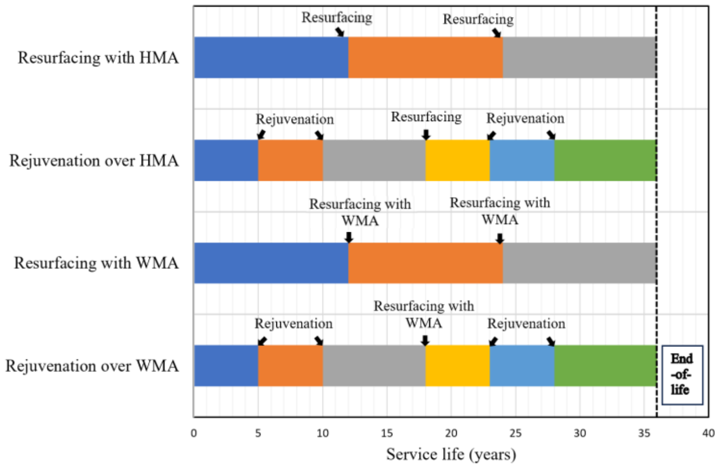

Figure 1. Timeline for all four strategies.

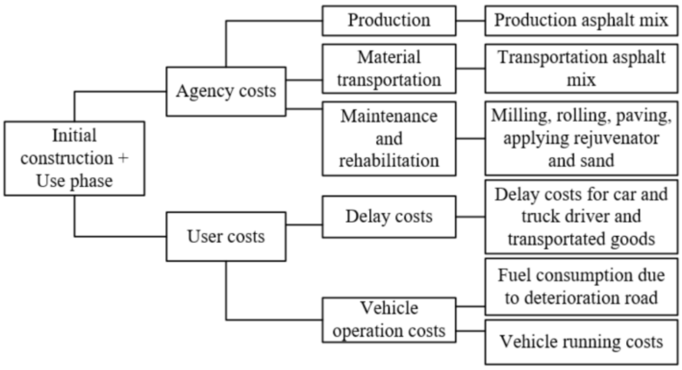

Figure 2. Processes and system boundaries for LCCA.

2.2 *Lifecycle inventory*

The lifecycle cost inventory was generated by collecting the data from primary and secondary sources. The primary data comprised material (note that the production of asphalt mix includes the costs of raw material extraction, processing, and transportation) and activity costs collected through interviews and online meetings with Dutch roadway contractors and material suppliers. Further, secondary data sources comprised national statistics board (CBS - Statistics Netherlands, 2018), Eurostat's database (Eurostat, 2022a, 2022b, 2022c), standard Dutch maintenance guidelines (Koster, 2013) and other available literature (Silva, 2013, Decò & Frangopol, 2011). The most important input parameters used in the LCCA are presented in Table 1 and others can be found elsewhere (Singh & Varveri, 2024).

Table 1. Most important input parameters.

Input parameters	Value	Source*
DZOAB 30%RAP (€/t)	82	P
WMA DZOAB 30%RAP (€/t)	83	P
Average detour speed (km/h)	50	P
Rejuvenation cost (€/sq.m)	1,96	P
Sand spraying cost (€/sq.m)	0,16	P
Detour during rejuvenation (days)	0,33	P
Design speed (km/h)	90	P
Traffic growth rate (%)	3	P and S
Discount rate (%)	2	P and S
Milling charges (€/sq.m)	10,57	P and S
Average running cost of cars (€/km)	0,08	P and S
Annual average daily traffic (vehicle/h)	2300	S
Initial MPD (mm)	1,7	S
MPD change rate (mm/year)	0,041	S
Initial IRI (m/km)	0,8	S
IRI growth rate (m/km)	0,08	S
Gasoline price (€)	1,96	S

**Source: P = primary source and S= secondary source*

2.3 *Lifecycle cost assessment*

In the context of pavement LCCA, costs are typically categorized as agency and road user costs. Agency costs encompass all expenses directly incurred by the managing road agency (including asphalt mix prices, transportation, milling, rolling and paving charges, among others for the considered functional unit) to ensure the pavement meets required service level. On the other hand, road user costs represent the costs borne by the public during the operation and use of vehicles (Walls, 1998).

Road user costs were calculated as the sum of vehicle operating costs (VOC) and delay costs (DC). VOC account for increased fuel consumption caused by pavement deterioration over the analysis period and vehicle running costs (VRC) is given by Equation 1. The DC reflect the economic impact of delays resulting from reduced speeds during maintenance activities and computed using Equation 2 (Decò & Frangopol, 2011, Khakzad & Gelder, 2016).

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

$$\mathrm{DC} = \left[C_{\mathrm{AW}}O_{\mathrm{Car}}\left(1-\frac{T}{100}\right)+\left(C_{\mathrm{ATC}}O_{\mathrm{Truck}}+C_{\mathrm{Goods}}\right)\frac{T}{100}\right]\times\frac{D\times A(t)\times d}{S} \quad (2)$$

Where, T = average daily truck traffic (%), $C_{Run,car}$ = average running costs for cars (€/km), $C_{Run,truck}$ = average running cost for trucks (€/km), D = detour length (km), A(t) = average daily traffic, d = duration of the detour, C_{AW} = average wage of car driver (€/h), C_{ATC} = average wage of truck driver (€/h), C_{Goods} = time value of goods transported (€/h), O_{Car} = average vehicle occupancy of cars, O_{truck} = average vehicle occupancy for trucks, and S = average detour speed (km/h).

The increased fuel consumption was computed using the MIRIAM models (Hammarström, 2012). The economic impacts were determined using the net present value (NPV) (see Equation 3) as it provides a direct monetary value, making it easier to compare and rank alternatives with different lifespans or costs (Moins et al. 2020).

$$NPV = Initial\ costs + \sum_{k=1}^{Q} Future\ cost\frac{1}{(1+d)^n} - Residual\ value\frac{1}{(1+d)^n} \quad (3)$$

Where, n = year into the future cash flow activity and d = discount rate.

2.4 *Results, interpretation, and sensitivity analysis*

The lifecycle cost for the four pavement maintenance alternatives is provided in Figure 3. As observed in Figure 3, the traditional resurfacing maintenance strategies both with and without WMA resulted in higher NPV compared to their counterpart in-situ rejuvenation maintenance. This is mainly attributed to the higher agency costs associated with the resurfacing (milling and laying) which encompassed three cycles compared to rejuvenation where only two resurfacing activities were undertaken. The life-extension maintenance delayed the resurfacing timeline and as a consequence of the discounting effect, resulted in lower NPV. Further, the contribution of costs due to fuel consumption was highest and accounted for about 63-68% of the total NPV. As the timeline of rejuvenation maintenance was lower than resurfacing, it resulted in lower VRC and DC, consequently lower NPV. Furthermore, the production cost of WM-DZOAB mixture was higher (due to higher initial plant investments) resulting in a greater NPV for the WMA alternatives.

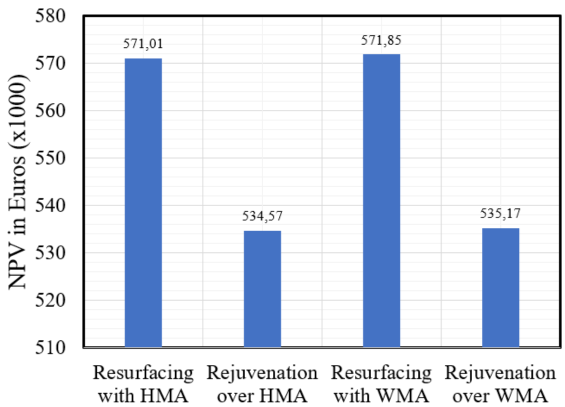

Figure 3. NPV results for the deterministic LCCA.

To identify the inputs that cause highest uncertainty in LCCA, a one factor at-a-time sensitivity test was conducted by varying 18 input variables by a magnitude of ±50% and the results are presented in Figure 4. NPV was most sensitive to gasoline prices, traffic growth rate, discount factor, milling charges, asphalt mix price, and detour speed.

Furthermore, the service life of pavement alternatives was varied by 5 years to identify the required minimum service life of WM-DZOAB to be recognized as sustainable solutions. The results indicated that the pavement alternatives designed with WMA and undergoing resurfacing must possess a service life of at least 12.39 years to be cost-effective. On the other hand, the in-situ rejuvenation of WM-DZOAB is the preferred choice if the pavement serves a minimum life of 12.68 years.

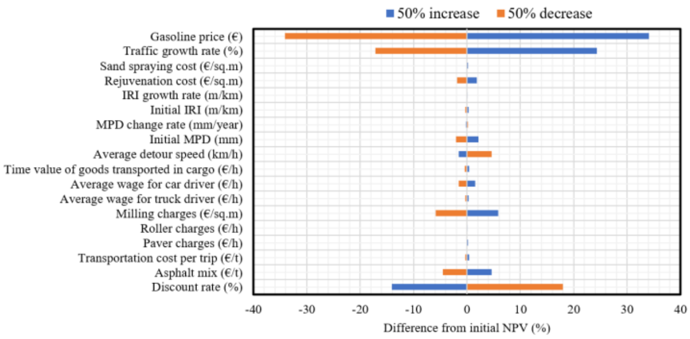

Figure 4. Sensitivity analysis for resurfacing.

3 CONCLUSIONS & RECOMMENDATIONS

This study investigated the lifecycle costs associated with four different pavement alternatives and the major findings are summarized below:

- Maintenance strategies involving in-situ rejuvenation yielded lower lifecycle costs (by about 1.07 times) compared to conventional resurfacing.
- NPV was highly sensitive to gasoline prices, traffic growth rates, discount factor, asphalt prices, and milling charges.
- WMA alternatives had higher costs than conventional systems due to higher initial investments required at plants for production.
- WMA-based pavements demonstrate financial viability when coupled with service life extension (in addition to the typical 12 year life of DZOAB) of at least 0.39 years for resurfacing and 0.68 years for rejuvenation.

Future research must focus on developing predictive models for estimating the service life of WM-DZOAB and progression of distresses in these systems. While LCCA is an important tool, it cannot be solely used for decision making as such processes are also based on environmental and social benefits. Thus, policymakers should prioritize options that align with the three pillars of sustainability.

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