

Article

Optimization of Bituminous Road Surfacing Rehabilitations Based on Optimization of Road Asset Value

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Abstract: The article presents a complex pavement management system method that utilizes a novel optimization method of rehabilitation plans for individual road sections based on asset value optimization. This method is being implemented and tested by the Slovak Road Administration. The performance-based asset value optimization objectives are Socio-Economic Value and Technical Value of Assets, which breaks down into the Value of Structural Condition and Operational Capacity Value. Life cycle cost analysis is used to find the optimal rehabilitation year of individual road sections to optimize the asset value and minimize financial and economic costs while considering the life cycle extension provided by the rehabilitation in a given year. For the method to be reliable, two main preconditions need to be met. First, the residual bearing capacity calculation method needs to be based on rheological parameters of surfacing materials. This is significant because the residual bearing capacity is used for both choosing the correct rehabilitation technology and calculating the life cycle extension by the rehabilitation action. The second precondition is a reliable pavement performance model. This is significant because pavement deterioration is used to calculate road user costs, which serve as a key input to calculate assets' Socio-Economic and Operational Capacity value.



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Keywords: asset management; asset value; road network funding; residual service life; cross-asset allocation

1. Introduction

Road infrastructure management is usually based on pavement management system (PMS) methods. The key principles of functioning PMS are data collection and management procedures, diagnostic methods for assessing Pavement Serviceability (PS) and bearing capacity, pavement and rehabilitation design methods and decision-making procedures to create strategic and operational rehabilitation plans [1–4].

Road data collection and database management rely on diagnostic devices. These devices such as Profilograph GE, Skiddometer, Videocar, Roadscanners, Georadar, Thermal Diagnostics, and for needs of Bearing Capacity—Falling Weight Deflectometer can collect a large amount of data in a short time. This data is subsequently processed and stored. When performed continuously over the span of several decades, this data can be used to derive pavement performance models (PPM), this method is known as long-term pavement performance monitoring [5] and is an alternative to pavement performance modeling [6] with accelerated pavement testing facilities described in other author's publications [7,8]. The bearing capacity is the operational capability of a pavement. Falling Weight Deflectometer, described in [9], is used to measure the deflection bowl after a falling weight impact and through back-calculation, the stiffness of pavement layers is evaluated and residual life expectancy of the pavement can be assessed [10,11]. New in-motion techniques and equipment (TSD-Traffic Speed Deflectometer) for measuring bearing capacity are being developed, yet undesirable downsides of this approach persist [12].

Pavement design and pavement overlay design methods are usually empirical or mechanistic-empirical depending on the standards used in a given country [13–15]. Optimal

pavement structure, materials, and overlay thickness are chosen by cost-benefit analysis [16]. The optimization criterion is usually based on a comparison of the price and life expectancy of rehabilitation and user costs for individual technologies and the year of rehabilitation [17]. The innovation of the proposed method is the use of asset value instead of road user cost in the Life-Cycle Cost Analysis (LCCA) [18–20] that precedes CBA [21]. The optimization method for overlay timing and costs is described in Section 3.

The implementation output of this method is an operational rehabilitation plan of specific sections. These section rehabilitation plans can be used for subsequent prioritization or optimization on a road network level creating short medium or long-term network-level rehabilitation plans [22–24].

The added value of this method is the incorporation of asset management, as a systematic method based on the principle of asset value assessment and thereby achieving effective road network management [25–29]. The proposal of an optimal rehabilitation plan thus consists not only of calculations of the economic efficiency of rehabilitation technology variants but also of the total asset value of road sections. The assessment of asset value has a wider scope than just road user and road administrator costs, thus, substituting road user costs with an asset value in the LCCA and CBA transfers this broader scope into the road administrator rehabilitation plans [30–32].

Implementation of Asset Value into the pavement rehabilitation optimization process requires the creation and implementation of new calculation methodologies and functions. Asset value differs depending on the stakeholder and his viewpoint [33]. Asset valuation is the financial expression of economic means which are expected to lead to an increase in financial and economic benefits for stakeholders [34–36]. The presented method uses Socio-Economical value, which represents the community and road user point of view, and the road administrators' point of view focuses on asset technical condition and operational capacity.

The socio-economical value of a road asset represents the value of mobility, accessibility of services, urban and regional development, customer influx for business, emergency reaction forces accessibility, improved traffic safety, and positive environmental impacts [37–40].

The technical condition of a road asset relates to pavement performance. The value of the technical condition of an asset represents the value of material, human, time, energy, and financial resources used for the construction of the road and the subsequent depreciation of this value during the pavement life cycle [41]. The value comes from the resiliency to withstand traffic loading during the residual service life of a road asset. The value of operation capacity represents the operational capability and serviceability which impacts traffic quality, i.e., speed, vehicle operating costs, comfort, and emissions [28,42,43].

Since the quality of optimized results is only as good as the inputs fed into the calculation, the reliability of those inputs is a substantial part of the article and is dedicated to the calculation of residual service life based on the experimental calculation of asphalt paving materials fatigue characteristics and creation of reliable pavement performance models through accelerated pavement testing or long-term pavement performance monitoring.

2. Road Asset Value Calculation

Road asset value is the financial expression of stakeholder benefits and liabilities related to the asset's existence and operation. In the following sub-chapters, four different road asset value calculation methods are presented. These can be used in rehabilitation optimization either as an individual criterion or a combination of socio-economic value or technical condition value optimization.

2.1. Socio-Economic Value of a Road Asset

Socio-economic benefits consist of road infrastructure performance value and community benefits. Both criteria set the requirements for traffic service provided by the road infrastructure.

The road infrastructure performance value is a percentile asset value ratio of the current traffic service quality provided by the road asset and potential improvement in the traffic service quality provided by an improved or new asset. The traffic service quality is the financially expressed asset value provided by the road asset carriageway width and vertical and horizontal road alignment.

$$RIPV = \frac{TSQV_c}{TSQV_p} * 100 \tag{1}$$

where:

RIPV: road infrastructure performance value indicator [%],

TSQV_c: current traffic service quality [€],

TSQV_p: potential traffic service quality [€].

The indicator gives a potential percentile increase, i.e., reserve, that can be gained by road infrastructure investment to achieve the full potential of the road connection.

The socio-economic value is the financially expressed net present value of community benefits that can be achieved by investment in the asset reduced by the financial cost of the investment discounted by the discount rate over the asset life cycle.

$$SEV = \sum_{T=TZP}^T \frac{B_{t(a-b)} - AP_t - MC_t}{(1 + 0.01 * u)^t} \tag{2}$$

where:

SEV: Socio-economic value [€],

B_{t(a-b)}: community benefits as a difference between scenario “Do nothing” (a) and “Do something” (b) in year “t” [€],

AP_t: acquisition price in “Do something” scenario in year “t” [€],

MC_t: maintenance cost increase in “Do something” scenario in year “t” [€],

u: discount rate [%],

TZP: year of the beginning of the life cycle [year],

t: evaluation of individual years of the life cycle [years].

2.2. Value of Road Asset Technical Condition

The technical condition of a road asset consists of structural condition value, i.e., material, human, time, energy, and financial resources used for the construction of the road and the operational capacity of the pavement, i.e., value of the remaining pavement serviceability.

The structural condition value is financially expressed current valued acquisition price of the pavement depreciated by the pavement degradation. The degradation can be financially expressed as the residual service life of the pavement and its ratio to the required service life.

$$SCV = AAP_{PC} * \frac{RLE}{DLE} \tag{3}$$

where:

SCV: structural condition value [€],

AAP_{PC}: acquisition price of the asset in a pristine condition [€],

RLE: residual life expectancy [year],

DLE: designed life expectancy [year].

The proposed calculation of the current design value of an asset in relation to the optimal value, i.e., projected life can be expressed by the Equation:

$$CVR = 1 - \frac{\sum_{a=1}^{n_{assets}} \sum_{n=1}^{n_{sections}} (AAP_{PC} - AV_{CC})_{a,n}}{\sum_{a=1}^{n_{assets}} \sum_{n=1}^{n_{sections}} AAP_{PC\ n,a}} \tag{4}$$

where:

CVR: is the ratio of the current value of the asset to the current acquisition price of the asset in pristine condition [%].

Operation Capacity Value financially expresses pavement serviceability in relation to users, i.e., traffic quality impacting road user costs. The value can be increased by improving the surface characteristics of the pavement, which results in road user cost savings, i.e., vehicle operating cost savings and travel time cost savings. From the road user point of view, the increased value of the asset is a net present value of road user benefits achieved by pavement rehabilitation achieved during the whole asset life cycle.

The benefits are expressed as the difference between the user costs of the desired pristine condition and its present state as seen in Equation:

$$OCV = \sum_{t=1} [(UC_{DN} - UN_{AR}) * k_{DEG} * k_{GAADT}]^t \quad (5)$$

where:

OCV: operation capacity value [€],

UC_{DN}: total road user costs for the asset in present state (Do nothing scenario) [€],

UN_{AR}: total road user costs for the asset after rehabilitation (Do something scenario) [€],

k_{DEG}: degradation coefficient,

k_{GAADT}: growth coefficient of annual average daily traffic.

3. Rehabilitation Planning Optimization Model

Road network administrators should base their funding requirements on the current state of their road network value and the leverage effect of additional funding to increase this value. The rehabilitation plan should give direct answers about how the funding will be used, i.e., timing of works, technologies used, and construction costs. The increase in road network value achieved by the proposed rehabilitation plan needs to be expressed as economic benefits justifying the increased funding. To determine the year of rehabilitation, it is necessary to use optimization techniques that can find the optimal time of rehabilitation at which the repair technology costs and produced benefits result in optimal asset value increase. The asset value increase is thus the optimization criterion that should be optimized under certain funding constraints. Using the financial expressed asset values and indicators from the previous Section we can formulate two optimization criteria. The financial optimization criterion is a net present value of the sum of the asset's socio-economic value, structural condition value, and operation capacity value, and it is expressed in financial units as seen in Equation (6). Rehabilitation timing and technology should produce a maximum financial value of this criterion.

$$NPAV = \sum_{T=TZP}^{TUU} \left[\frac{EV + SCV + OCV}{(1 + 0.01 * u)^t} \right] \quad (6)$$

where:

NPAV: net present asset value [€],

SEV: socio-economic asset value [€],

SCV: structural condition asset value [€],

OCV: operation capacity asset value [€],

u: discount rate [%],

TZP: year of the beginning of the life cycle [year],

TUU: last year of the life cycle [year],

t: years of the life cycle, $t = TZP - TUU$, [year].

The indicator optimization criterion is a net present value of the sum of the asset's road infrastructure performance value indicator and the ratio of the current value of the asset to the current acquisition price of the asset in pristine condition. This criterion is expressed in

percentages. Rehabilitation timing and technology should produce a maximum percentage increase of this in this criterion as seen in Equation (7):

$$NPAVI = \sum_{T=TZP}^{TUU} \left[\frac{RIPV + CVR * 100}{(1 + 0.01 * u)^t} \right] \quad (7)$$

where:

NPAVI: net present asset value indicator [%],

RIPV: road infrastructure performance value indicator [%],

CVR: ratio of the current value of the asset to the current acquisition price of the asset in pristine condition [%].

The cost of the rehabilitation technology, used in the calculation of socio-economic value (see Section 2.1.) and operation capacity value (see Section 2.2.) depends on the time at which the rehabilitation is performed. Thick overlays performed in the later stages of the pavement life cycle are less economical than thin overlays, slurry seals and surface dressings which are done proactively. The Life Cycle Cost Analysis is used to calculate construction costs and maintenance costs during the pavement life cycle. Pavement serviceability as well as the operational performance of a pavement gradually deteriorates due to traffic load and climatic conditions. This reduces the comfort of traffic and increases vehicle operating costs and travel time costs. These economic costs are added to the capital costs of the road administrator in the LCCA, however, an increase in the road administrators' capital costs tends to decrease road user costs. The sum of discounted annual cash flows is the present value of total life cycle costs. Pavement rehabilitation extends the pavement life-cycle. Comparison of rehabilitation alternatives, i.e., rehabilitation timing and technology will produce different amounts of total life-cycle costs and life-cycle extensions. See Figure 1 and Equation (8).

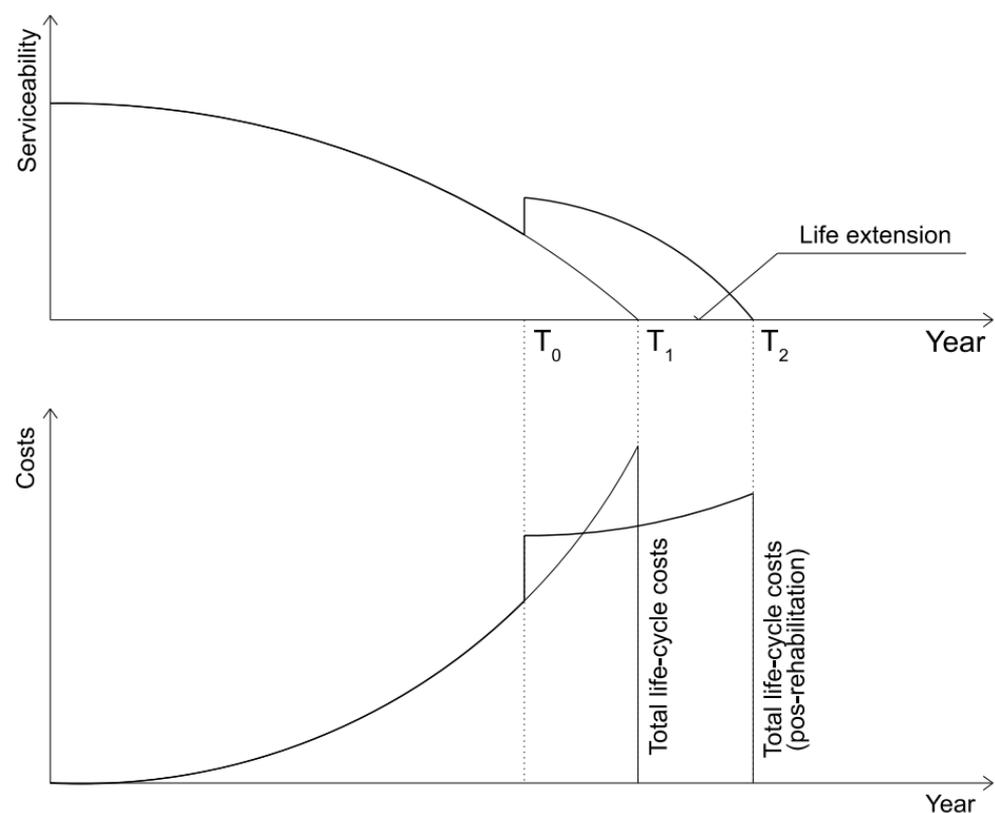


Figure 1. Pavement rehabilitation timing.

Capital costs are easy to monetize based on standard pricing techniques in civil engineering. For the calculation of road user costs, different techniques can be used applied such as PIARC's Highway Development and Management tool [44] or different national calculation tools such as RoSy or ISEH [45].

$$RLCE = T_2 - T_1 \quad (8)$$

where:

$RLCE$: real life-cycle extension [year],

T_0 : year of rehabilitation [year],

T_1 : expected end of the life-cycle [year],

T_2 : extended end of life-cycle after rehabilitation [year].

Optimization is performed following Equation (9). The optimization index is calculated in each year of the life-cycle. Every year, rehabilitation technology is chosen according to pavement serviceability predictions (see Section 4.2), the technology must be designed to completely restore the pavement serviceability. This rehabilitation extends the life-cycle of the pavement by the time span equal to the period at which the rehabilitation is performed, i.e., rehabilitation in year 10 extends the life-cycle by 10 years. Rehabilitation restarts the degradation process. The optimization index is calculated for each year of the life cycle following formula 9; the index is a unitless number. When plotted into a chart, the optimization indexes in each year form a U-curve, and the optimal rehabilitation timing is the lowest point on the U-curve; see Figure 2.

$$OI = \frac{RC + NPAV_{BR} + NPAV_{AR}}{T_t} \quad (9)$$

where:

OI : optimization index,

RC : rehabilitation costs [€],

$NPAV_{BR}$: net present asset value before rehabilitation [€],

$NPAV_{AR}$: net present asset value after rehabilitation [€]

T_t : extended life-cycle [€].

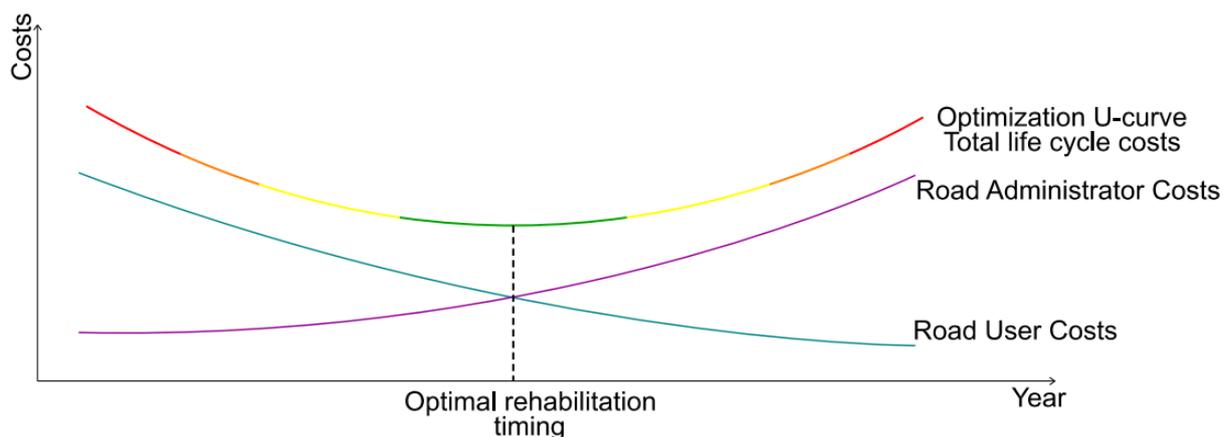


Figure 2. U-curve represent the optimal rehabilitation timing.

4. Residual Service Life and Pavement Performance Model

The residual life expectancy calculation is based on the pavement structure design methodology. Calculation of the rheological characteristics of pavement structure layers, and experimental measurement of fatigue characteristics of asphalt mixtures of the pavement surfacing. The relationship for the assessment of pavement construction used in pavement and overlay design is shown in Equation (10) [46,47].

4.1. Residual Service Life Calculation

Equation (10) is used for the calculation of the residual life expectancy of existing pavements:

$$\sum_{i=1}^n Q_i \times \frac{\delta_{r,i}}{S_N * R_{i,I}} \leq 1 \quad (10)$$

where:

Q_i : temperature condition coefficient during the period “i” (0.2 winter, 0.3 summer, 0.5 spring and autumn),

$\delta_{r,i}$: radial stress at the lower edge of the surfacing layer, which arises in the period “i” when loaded by the design axle [MPa],

$R_{i,I}$: calculated value of the flexural tensile strength of the material under consideration for the conditions in period “i” [MPa] normatively prescribed for new pavements or experimentally measured on samples from existing pavements,

n : number of standard axle load cycles,

S_N : fatigue coefficient.

To calculate the fatigue coefficient, it is necessary to derive the actual modulus of elasticity and strength in the pavement surfacing layer. These moduli are estimated during diagnostics of the pavements’ load-bearing capacity utilizing a falling weight deflectometer [9]. FWD induces and measures a flexible reaction of the pavement produced by an impact on the pavement surface. This reaction can be graphically represented by a deflection bowl. The shape of this bowl shows the deflection ordinates measured by sensors attached to the pavement at varying distances from the impact point. The actual modulus of elasticity of the individual pavement layers is calculated by a process called back-calculation. The back-calculation gives elastic modulus estimates of the pavement layer by calculation in the layered elastic half-space model [48–51]. Subsequently, based on the modulus of elasticity and pavement layer thickness, the stresses in the individual layers of the road structure are calculated.

The residual life expectancy is calculated following Equation (11). The reliability of this calculation is dependent on the reliability at which the fatigue coefficients a and b are derived. These fatigue coefficients are derived from experimental measurements of fatigue characteristics, which expresses pavement resilience against repeated loading. The test measures pavement resilience against repeated loading. This is done by repeated bending of a pavement surfacing layer test sample. Fatigue tests are carried out following European standards [52]. The results of the fatigue test are plotted in the form of a Wohler diagram shown in Figure 3.

$$\log \epsilon_{0j} = a_j + b \times \log N \quad (11)$$

where:

ϵ_{0j} : maximum amplitude ordinate of proportional deformation during the test conditions at the beginning of the test,

a, b : fatigue parameters measured during the fatigue tests is the stress lines coefficient in the range of N ,

N : the number of load repetitions.

Following the calculation of ϵ_j , the calculation of maximum design axle load repetitions that the pavement can withstand can be determined from Equation (12) [53]:

$$DAL = 10^6 \times \left(\frac{\gamma \times \epsilon_6}{\epsilon_j} \right)^B \quad (12)$$

where:

DAL : number of design standard axle loads,

ϵ_6 : average deformation derived from fatigue curve after 10^6 loading cycles in microstrain [$\mu\text{m}/\text{m}$],

ϵ_f : calculated relative deformation at the bottom of the bituminous bound sub-layer in the pavement construction (based on a multilayer system in homogenous half-space, calculation model with input values presented by Remek [54]),
 γ : fatigue test reliability factor—(in our case 1.6 in the line with [55]).
 B : fatigue characteristics—falling gradient of the fatigue line, $B = -1/b$.

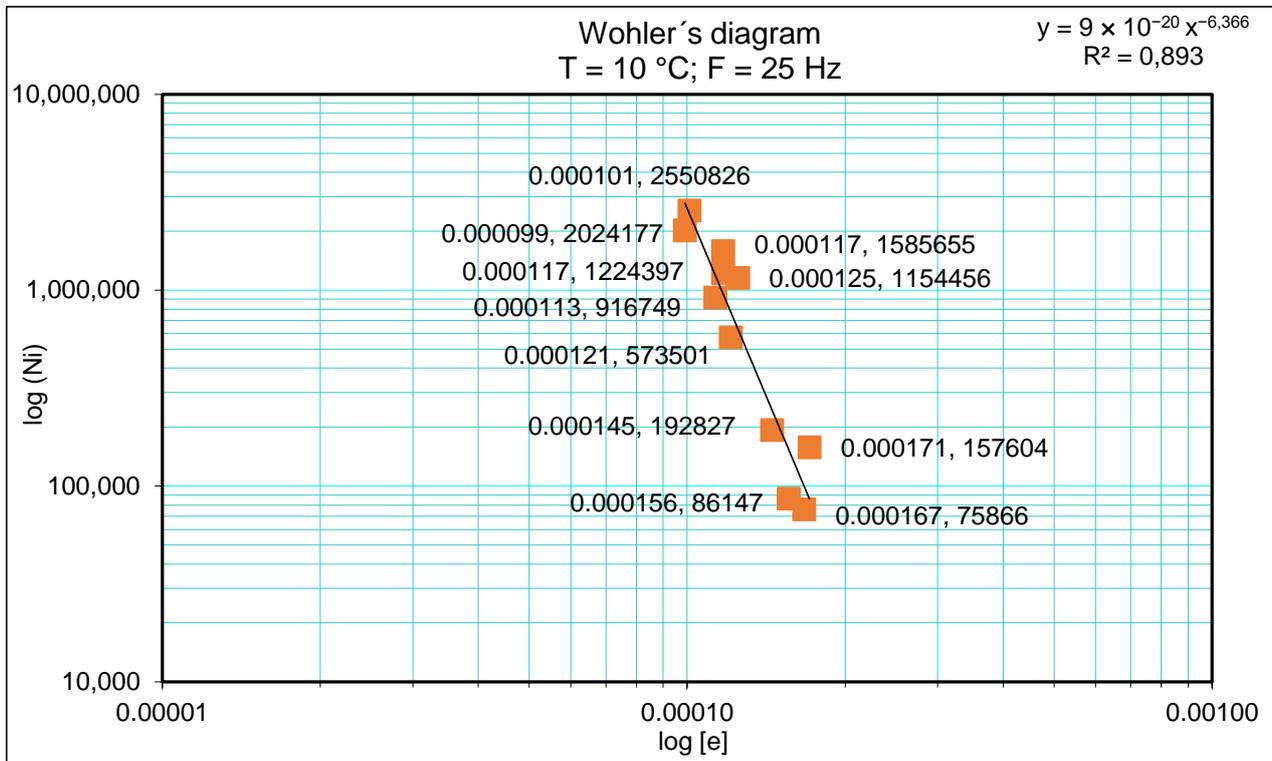


Figure 3. Wohler diagram.

For the implementation of this method into asset value calculation described in the second Section, measurements were performed for the standard asphalt modified layer: AC 16 L. The resulting shape of the deflection curve and the achieved parameters are shown in Figure 3 and Table 1. More detailed results for such fatigue tests and other parameters presented in Table 1 can be found in [55–58].

Table 1. Fatigue parameters of AC 16 L.

Parameter	A_0	B	b	ϵ_6
Fatigue values	−19.0452	−6.3656	−0.1571	116.29

where ϵ_6 is strain level required for 1 million cycles of fatigue life; b is the slope parameter of the fatigue line, B is falling gradient of the fatigue line, $B = -1/b$ and A_0 is an intersection point between the logarithmic function of strain measured at a sample failure (or reached 50% decrease of the complex modulus) with a logarithmic function of loading cycles at a sample failure (or reached 50% decrease of the complex modulus) during fatigue testing.

If we calculate the residual life of selected pavement construction shown in Table 2 with fatigue parameters shown in Table 1, we receive a total number of standard axle loads (DAL) that pavement can carry on, which in our case is $DAL\ 2.3 \times 10^6$ axle loads.

Table 2. Pavement construction parameters.

Layer	Complex Modulus	Strength	Poisson Number	Layer Thickness
Surface course AC 11	7577	3.2 MPa	0.33	40 mm
Base course AC 16	9967	2.4 MPa	0.33	80 mm
Mechanically bound aggregate, 31,5	586	0.1 MPa	0.30	180 mm
Gravel Sub-base, 31,5	365	0.07 MPa	0.30	200 mm
Sub-grade	100	-	0.35	-

4.2. Pavement Performance Models

PPM are a key part of determining the value of road assets. PPM are used to predict the development of pavement serviceability, which is the main factor influencing road user costs and socio-economic value of an asset. Pavement degradation occurs during the pavement life-cycle due to traffic load and climatic conditions.

PPM can be deterministic or stochastic. The deterministic models include primary response, structural and function performance, and damage models. The stochastic models are represented by the Markov transition process based on transition probability matrices.

Most deterministic models work as traffic-related or time-related mathematic functions which produce degradation curves of individual pavement performance parameters [59]. The general shape of the degradation curves expresses the dependence of the relative value of the monitored parameter on time or the number of load repetitions as is shown in Equation (13). The generalized shape expressed mathematically is an exponential function in which the exponent changes the shape of the curve. This makes them simple to calibrate by regression analysis of measured data, with two coefficients A and B:

$$\begin{aligned} P_t &= 1 - A * \left(\frac{t}{T}\right)^B \\ P_n &= 1 - A * \left(\frac{n}{N}\right)^B \end{aligned} \quad (13)$$

where:

P_t : relative value of performance parameter in relation to time t ,

t : time from the beginning of the life-cycle [years],

T : predicted life expectancy of the pavement in terms of the performance parameter [years],

P_n : relative value of performance parameter in relation to traffic load,

n : standard axle load cycles from the beginning of the life cycle [SAL],

N : predicted life expectancy of the pavement in terms of the performance parameter [SAL],

A : coefficient of pavement class and paving materials $0 < A \leq 1$,

B : coefficient of degradation shape of performance parameter $0.2 < B \leq 6.0$.

Figure 4 is a regression analysis of measured data, collected on APT facility pavement, and it shows a relationship between traffic load and pavement parameter RUT. The PPM is a polynomic-shaped curve and equation describing this relationship. On the right side of Figure 4 is again a regression analysis, but in this case, the PPM is created with a limited data source and a large part is only a prediction. On this chart, the parameter is defined within an interval 1–0, where 1 is the perfect condition and 0 is the limit value of pavement failure. The traffic load is described as a ratio of loading cycles (n) and loading capacity (N). This general expression of PPM makes its application easier between different pavements (but of the same type).

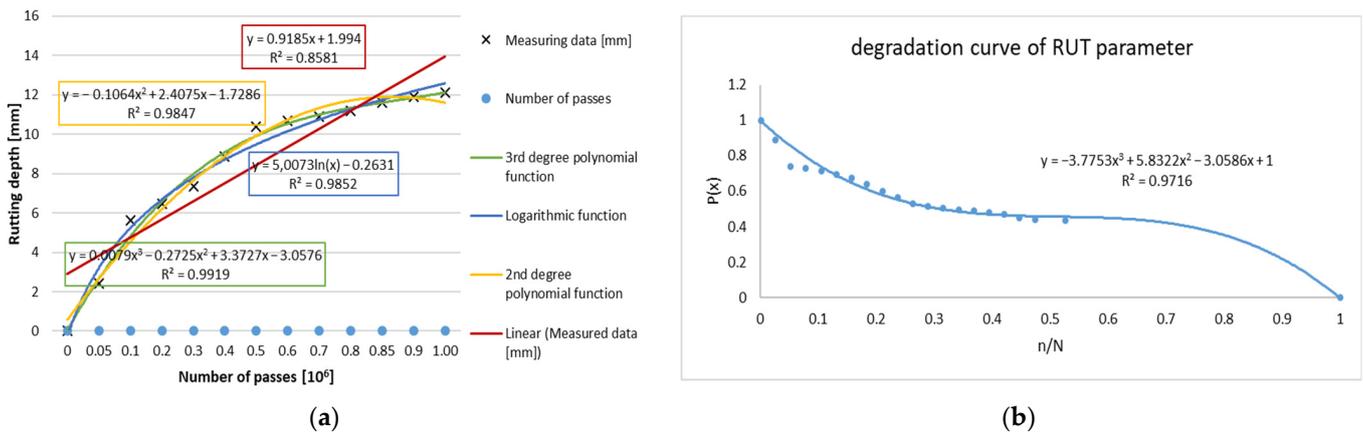


Figure 4. Example of pavement performance model—(a) graphic evaluation of RUT parameter increase, (b) deterioration function of RUT parameter (P) measured on APT facility.

5. Case Study—Practical Application

As described in Section 3, LCCA needs to be performed for different timing of rehabilitation technology. Table 3 shows pavement serviceability through the parameter of longitudinal unevenness ranging from IRI 0–16 m.km⁻¹ through 20 years of the pavement life cycle. Each line in the table is a scenario with one rehabilitation in years 1–20. The rehabilitation technology changes with the pavement distress in the year of rehabilitation. The rehabilitation technology and overlay thickness are chosen to completely restart the pavement life-cycle. This is a fairly simple concept, but the same method can be used to create scenarios with more than one rehabilitation throughout the pavement lifecycle and sub-optimal technology timing and technology that improves but does not restart the pavement life-cycle. The graphical representation of Table 3 is a chart shown in Figure 5; however, here, the longitudinal unevenness is expressed as p(x) ranging from 0–1 as described in Equation (13).

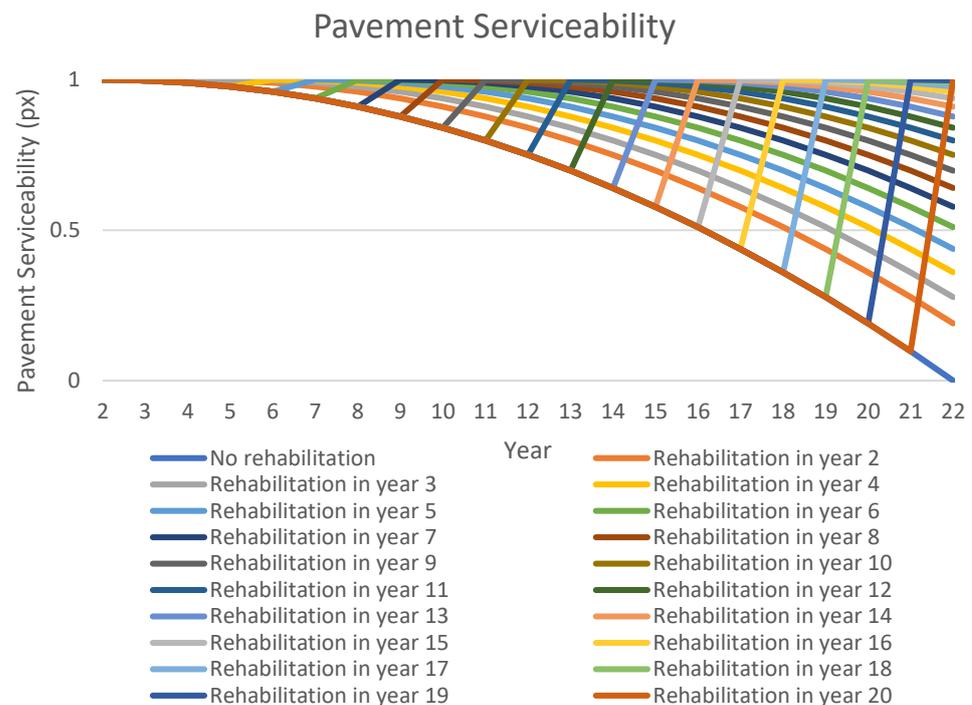


Figure 5. Pavement serviceability—case study.

Table 3. Pavement serviceability—case study.

Year	Rehabilitation technology	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Average pavement serviceability during life-cycle
Pavement serviceability—IRI		0	0.04	0.16	0.36	0.64	1	1.44	1.96	2.56	3.24	4	4.84	5.76	6.76	7.84	9	10.24	11.56	12.96	14.44	16	
No rehabilitation	No rehabilitation	0	0.04	0.16	0.36	0.64	1	1.44	1.96	2.56	3.24	4	4.84	5.76	6.76	7.84	9	10.24	11.56	12.96	14.44	16	5.47
Rehabilitation in year 2	Rejuvenation	0	0.04	0.16	0	0.04	0.16	0.36	0.64	1	1.44	1.96	2.56	3.24	4	4.84	5.76	6.76	7.84	9	10.24	11.56	3.41
Rehabilitation in year 3	Rejuvenation+	0	0.04	0.16	0.36	0	0.04	0.16	0.36	0.64	1	1.44	1.96	2.56	3.24	4	4.84	5.76	6.76	7.84	9	10.24	2.88
Rehabilitation in year 4	Dressing 1 layer	0	0.04	0.16	0.36	0.64	0	0.04	0.16	0.36	0.64	1	1.44	1.96	2.56	3.24	4	4.84	5.76	6.76	7.84	9	2.42
Rehabilitation in year 5	Dressing 2 layers	0	0.04	0.16	0.36	0.64	1	0	0.04	0.16	0.36	0.64	1	1.44	1.96	2.56	3.24	4	4.84	5.76	6.76	7.84	2.04
Rehabilitation in year 6	Thin overlay 20 mm	0	0.04	0.16	0.36	0.64	1	1.44	0	0.04	0.16	0.36	0.64	1	1.44	1.96	2.56	3.24	4	4.84	5.76	6.76	1.73
Rehabilitation in year 7	Thin overlay 30 mm	0	0.04	0.16	0.36	0.64	1	1.44	1.96	0	0.04	0.16	0.36	0.64	1	1.44	1.96	2.56	3.24	4	4.84	5.76	1.50
Rehabilitation in year 8	Mill & Replace 20 mm & 30 mm	0	0.04	0.16	0.36	0.64	1	1.44	1.96	2.56	0	0.04	0.16	0.36	0.64	1	1.44	1.96	2.56	3.24	4	4.84	1.35
Rehabilitation in year 9	Mill & Replace 40 mm & 50 mm	0	0.04	0.16	0.36	0.64	1	1.44	1.96	2.56	3.24	0	0.04	0.16	0.36	0.64	1	1.44	1.96	2.56	3.24	4	1.28
Rehabilitation in year 10	Mill & Replace 50 mm & 60 mm	0	0.04	0.16	0.36	0.64	1	1.44	1.96	2.56	3.24	4	0	0.04	0.16	0.36	0.64	1	1.44	1.96	2.56	3.24	1.28
Rehabilitation in year 11	Mill & Replace 60 mm & 70 mm	0	0.04	0.16	0.36	0.64	1	1.44	1.96	2.56	3.24	4	4.84	0	0.04	0.16	0.36	0.64	1	1.44	1.96	2.56	1.35
Rehabilitation in year 12	Mill & Replace 70 mm & 90 mm	0	0.04	0.16	0.36	0.64	1	1.44	1.96	2.56	3.24	4	4.84	5.76	0	0.04	0.16	0.36	0.64	1	1.44	1.96	1.50
Rehabilitation in year 13	Mill & Replace 80 mm & 120 mm	0	0.04	0.16	0.36	0.64	1	1.44	1.96	2.56	3.24	4	4.84	5.76	6.76	0	0.04	0.16	0.36	0.64	1	1.44	1.73
Rehabilitation in year 14	Mill & Replace 100 mm & 140 mm	0	0.04	0.16	0.36	0.64	1	1.44	1.96	2.56	3.24	4	4.84	5.76	6.76	7.84	0	0.04	0.16	0.36	0.64	1	2.04
Rehabilitation in year 15	Mill & Replace 120 mm & 180 mm	0	0.04	0.16	0.36	0.64	1	1.44	1.96	2.56	3.24	4	4.84	5.76	6.76	7.84	9	0	0.04	0.16	0.36	0.64	2.42
Rehabilitation in year 16	Mill & Replace 150 mm & 200 mm	0	0.04	0.16	0.36	0.64	1	1.44	1.96	2.56	3.24	4	4.84	5.76	6.76	7.84	9	10.24	0	0.04	0.16	0.36	2.88
Rehabilitation in year 17	Surfacing replacement	0	0.04	0.16	0.36	0.64	1	1.44	1.96	2.56	3.24	4	4.84	5.76	6.76	7.84	9	10.24	11.56	0	0.04	0.16	3.41
Rehabilitation in year 18	Surfacing + Base Course replacement	0	0.04	0.16	0.36	0.64	1	1.44	1.96	2.56	3.24	4	4.84	5.76	6.76	7.84	9	10.24	11.56	12.96	0	0.04	4.02
Rehabilitation in year 19	Surfacing + Base + Sub-base Course replacement	0	0.04	0.16	0.36	0.64	48	1.44	1.96	2.56	3.24	4	4.84	5.76	6.76	7.84	9	10.24	11.56	12.96	14.44	0	6.94
Rehabilitation in year 20	Total reconstruction	0	0.04	0.16	0.36	0.64	1	1.44	1.96	2.56	3.24	4	4.84	5.76	6.76	7.84	9	10.24	11.56	12.96	14.44	16	5.47

Figure 6 shows the optimization index calculated from LCCA (Figure 7) in each year (each scenario) following Equation (9). The optimal year of rehabilitation, i.e., rehabilitation scenario is to perform Mill 50 mm and Replace 60 mm of surfacing in year 10 with an optimization index of 1.28. Scenarios 8–13 are also considered suitable (see Figure 8) and can be chosen depending on the administrators’ technical capacity to perform the rehabilitation in this interval on this road section.

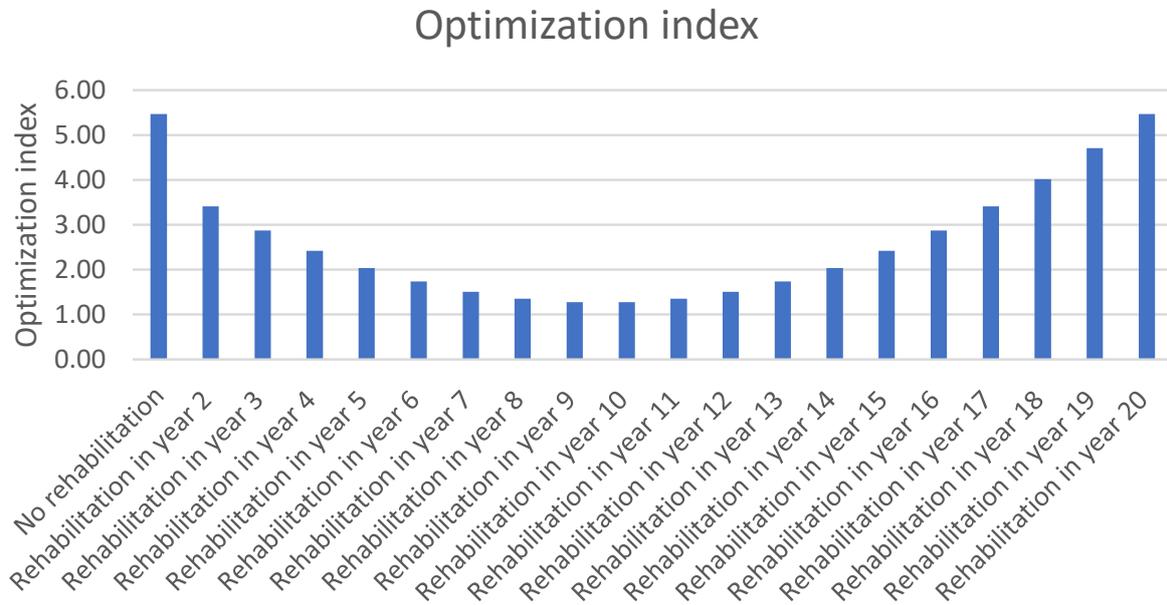


Figure 6. Optimization index calculated following Equation (9).

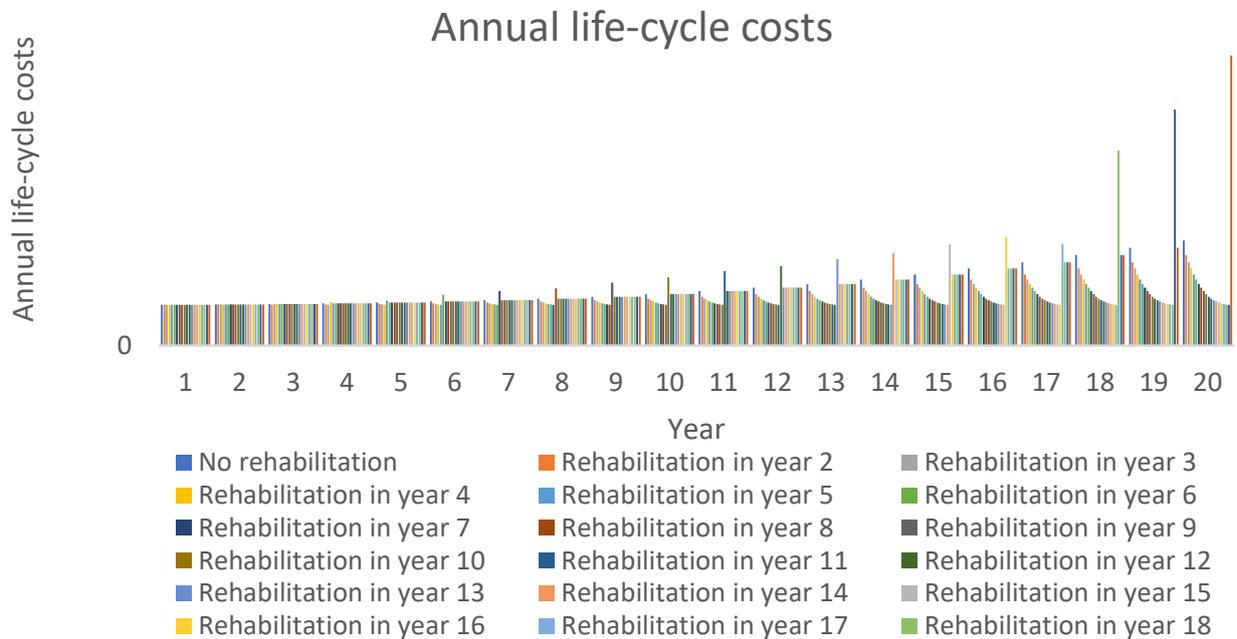


Figure 7. Annual life cycle cost—case study.

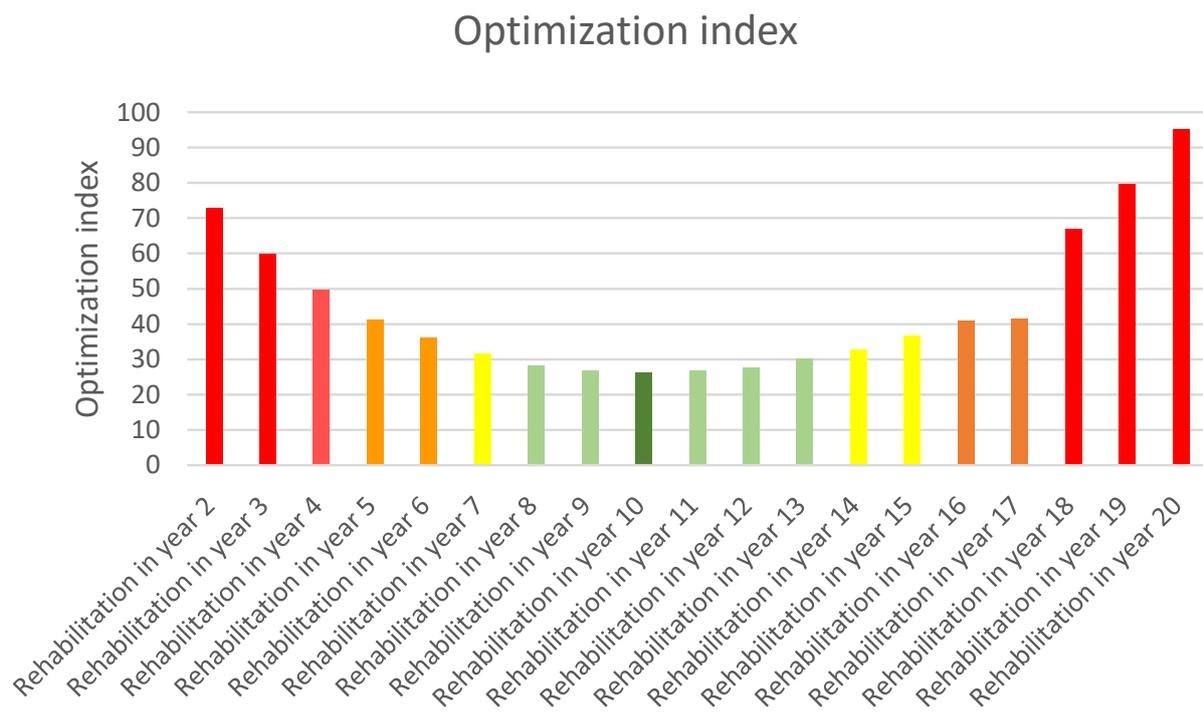


Figure 8. Optimization index—case study.

6. Conclusions

Asset management (AM) is considered a crucial tool needed for the management of a road network to satisfy the requirements of different stakeholders. The usual practice of operative rehabilitation planning is to rely on a pavement management system (PMS) that considers technical aspects of pavement operation and perhaps rudimentary cost-benefit analysis methods. PMS are usually viewed as essential, but subsidiary sub-modules of the AM.

Here, the presented method incorporates the AM principles of optimizing asset value under financial constraints directly into the pavement rehabilitation planning procedures. AM usually omits or simplifies technicalities such as pavement bearing capacity and residual service life calculations based on the rheological properties of paving materials and pavement performance models. It relies on PMS to deal with these technicalities and uses the results and indicators of PMS as input for asset value calculation on a road network level. The practical application of the presented method proves that AM can be used, not only for strategic planning but at a lower level of decision making when operational rehabilitation plans of roads and road networks are created.

This method, however, is highly dependent on the quality of data and the reliability of the calculation methods that are used. Therefore, these supplementary calculation methods were described in the article. These calculation methods can differ based on national legislation and standards, but road administrators should always search for ways how to increase their precision.

This method is currently being implemented on a national road administration level. For a successful implementation, we found that the following steps were necessary to implement the presented method:

- definition of the road administrator organization's goals; these should be measurable and attainable within a specified time,
- changes in the road administrator organizational structure with regard to the needs of the asset management system,

- identification of the road administrator requirements, e.g., legal, financial, but mainly personal, due to high requirements on an understanding of PMS and AM procedures and techniques
- accelerated pavement testing capabilities; if this is not available, road database that has been in operation for 20 years or longer with enough data to use regression analysis to derive pavement performance models for main pavement parameters and most used pavement classes,
- material testing equipment and calculation methods to derive fatigue characteristics of frequently used paving materials that can be used to calculate bearing capacity and residual service life of pavements,
- risk management to evaluate and react to risks related to the implementation process.

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