

## Article

# Optimizing Financial Allocation for Maintenance and Rehabilitation of Munster's Road Network Using the World Bank's RONET Model

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**Abstract:** This paper applies the Road Network Evaluation Tools (RONET) model to assess the economic impacts of urban pavement maintenance and rehabilitation in the city of Munster, Germany. The city's road network includes main roads, main access roads, residential roads, and paved areas for pedestrians, cyclists, and parking spaces. The specific traffic loads applied to Munster's network demand several different pavement materials, structures, and intervention procedures. This study aims to support stakeholders' decision-making by assessing current expenditures, network conditions, and country-specific data to determine the appropriate financial allocation for recurrent maintenance, periodic maintenance, rehabilitation, and new pavement construction. Six scenarios comprising distinct pavement structures and maintenance strategies are modeled in RONET to perform the analysis. The outcomes include the future deterioration of pavements under different maintenance scenarios, the current and projected asset value of the network, and the total costs (road agency costs + user costs) of the network to society, considering each scenario being applied over a 20-year evaluation period. The RONET model also provides the annual average cost of each maintenance procedure and the additional costs to society while using a budget scenario other than 'Optimal.' The results indicate that Munster's current investment program is in line with the 'Optimal' budget scenario proposed by RONET. In addition, the model suggests that performing recurrent and periodic interventions is more cost-effective than neglecting the conservation of pavements for an extended period and endorsing more extensive interventions in the future, such as rehabilitation or reconstruction.

**Keywords:** urban pavements; economic impacts; sustainability; maintenance strategies; optimization of pavement investments; RONET

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## 1. Introduction

The pavement network plays an essential role in the general flow of traffic and passengers in urban areas, having an important share of responsibility for the development of societies [1].

Taking into account that the pavement life cycle has many stages, starting with the extraction of raw materials, production of asphalt mixtures, construction and rehabilitation procedures, and end-of-life that consists in recycling or landfilling the material, an extensive number of technicalities must be handled by city administrators in order to provide road pavements in a satisfactory condition for users [2].

Municipalities are often required to keep an efficient infrastructure with cost-effective performance and reduced environmental and social impacts. Nonetheless, maintenance and rehabilitation procedures are regularly among the most significant expenditure items in public budgets, which demands lucid strategies [3].

The decision-making is complex and highly demanding due to the need for prioritization and uncertainties encountered throughout the process, especially for pavement lifespans higher than ten years.

Road deterioration is among several uncertainties that must be correctly defined to determine the pavement lifespan and, therefore, highly impact the overall sustainability of the road, affecting general expenses, CO<sub>2</sub> emissions, energy demand, consumption of raw materials, etc. [3].

Over the years, various studies have been carried out to investigate cost-effective maintenance strategies to be applied in urban pavements and support authorities' decision-making around the world [4–12]. Life Cycle Cost Assessment (LCCA) tools have been applied using models that adopt simplified road user costs relationships and simplified road deterioration equations, such as Highway Development and Management Model2 (HDM-4) and the Road Network Evaluation Tools (RONET) [13].

Khan et al. [14], for example, investigated the optimum pavement maintenance strategies for a road network in Australia. The authors divided 34,000 km of the road network into 27 road groups using pavement type, loading, and pavement strength as criteria to set standards and strategies for efficiently managing all of the different classes of roads. They used the HDM-4's road deterioration model to minimize agency costs and maximize the performance of each road group. The results provided ideal standards, cost-effective treatments, and an optimum budget for each road subgroup. The authors observed that composite roads have higher standards (lower International Roughness Index—IRI) than flexible roads at the same level of loading and strength. It is observed that about 17.8 bn Australian dollar (AUD) is needed to maintain flexible and composite roads in the next 20 years at or below an IRI of 4.0 m/km.

Ćirilović et al. [15] integrated the Life Cycle Assessment (LCA) [16] and Life Cycle Cost Analysis (LCCA) [17] optimization models to the Serbian main road network and found an optimal maintenance plan that minimizes the total cost to society. The total road transport cost (or cost to society) is the sum of the costs to (a) the road agency (e.g., construction, maintenance, and rehabilitation costs), and (b) the road users (e.g., fuel, vehicle maintenance, and emission costs), computed over a 20-year analysis period. The authors considered the overall impacts involved within the pavement lifetime. Therefore, all production, transportation, placement and maintenance activities, usage, and end-of-life impacts are included in the analysis. The study found that when the traffic growth rate decreases from 3% to 0%, the total cost reduces by 0.2% and the total emissions by 0.7%. Carbon pricing also has an impact: when the CO<sub>2</sub> emissions costs rise from 20 EUR/t to 30 EUR/t, the total cost increases by 0.2% and the overall emissions reduce by 0.7% during a 30-year analysis period.

Mladenovic et al. [18] used the Road Network Evaluation Tools (RONET) model to obtain an optimum maintenance and rehabilitation (M&R) strategy for the Serbian toll road network. The authors aimed to define the impact of different funding levels on the quality of the toll road network and estimate the economic consequences of budget constraints for its maintenance and rehabilitation. The results showed that part of the toll revenues could be allocated to the non-tolled part of the Serbian road network without a detrimental impact on the tolled network condition. The use of the RNET model helped to find an optimal M&R strategy with a good balance between rehabilitation, periodic, and recurrent maintenance. The study found that implementing higher M&R standards would lead to higher road agency costs and lower net benefits. Conversely, lower M&R standards would lead to worse network conditions.

The Life Cycle Assessment (LCA) is the principal tool used to evaluate the sustainability of products and services [19]. However, using distinct functional units, system

boundaries, inventory data quality, and environmental impact categories complicates comparing LCA/LCCA results with different studies [19,20]. Hence, besides all variables that can be considered or neglected within an LCA/LCCA study, all the aforementioned factors make it hard to draw general conclusions over the overall impacts of pavements, making each LCA/LCCA study nearly unique.

To evaluate the financial impacts of distinct maintenance strategies, this study uses the city of Munster (Germany) as a case study and assesses the best pavement structure combination to be applied within its entire road network. To support the decision-making process, the RONET model is used to calculate the pavement deterioration pattern of several road categories over 20 years, defining an ‘optimal scenario’ that is compared with the current one used by the municipality.

Despite the individualities, this investigation provides an extensive set of data to support future studies of LCCA and may, perhaps, be used as a reference by other municipalities.

### *Research Objectives*

The study presented in this paper is part of the collaboration between the European Union Horizon 2020 project titled SAFERUP! [21] (Sustainable, Accessible, Safe, Resilient, and Smart Urban Pavements) and the Department of Mobility and Civil Engineering of the city of Munster, which aims to improve the sustainability of urban roads by assessing the environmental and economic impacts of Munster’s pavement network.

To support the decision-making of stakeholders, this study evaluates the economic impacts of distinct pavement structures and maintenance strategies applied to the Munster network over a 20-year analysis period using the RONET model [13] as the main tool.

Hence, the main objectives of the study are:

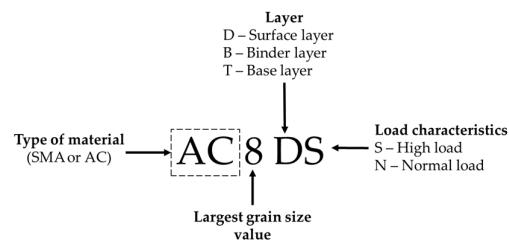
- Evaluating the economic impacts of distinct maintenance strategies applied to the same pavement structure;
- To discover the optimal pavement structure combination to be applied within the entire road network of Munster, considering all road categories;
- To compare the current maintenance strategy applied by the administrators with the optimal scenario suggested in RONET.

## **2. Overview of Munster’s Road Network**

Munster is a city located in the north of Germany, in the center of the Westphalia region. It has approximately 316,403 inhabitants in an area of 302,89 km<sup>2</sup>.

Munster’s road network has an area of approximately 13.63 km<sup>2</sup>—of which 9.4 km<sup>2</sup> are defined as roadways and 4.2 km<sup>2</sup> as secondary areas—distinguished into three main categories: main roads (MR), main access roads (MAR), and residential roads (RSDT), which represent, respectively, 26%, 4%, and 66% of the total area of the network. The rest of the network categorized in this study as ‘Others’ (4%) consists of parking places, bike lanes, pedestrian lanes, etc. In Munster, there are around 173,306 vehicles registered, of which 87% are cars, 6% motorcycles, 5% trucks, and 2% tractors, propelled by gasoline (64%) and diesel (36%) [22].

Depending on the traffic load, the pavement structure consists of two or three asphalt layers known as surface, binder (not applied to low traffic loads), and base layer—that can be either made of stone mastic asphalt (SMA) or asphalt concrete (AC) mixtures—and one unbound layer (subbase). The nomenclature of these asphalt mixtures is explained in Figure 1. Table 1 shows the pavement structures and further details used in this study.



**Figure 1.** Nomenclature of asphalt materials [23].

**Table 1.** Pavement specifications. Colors show the pavement layer where the material is applied.

Pavement Structure		Material	Thickness (cm)
MR	Bk 32	SMA 8 S	3
		AC 22 BS	8
		AC 32 TS	14
		Unbound	45
MAR	Bk 3.2	SMA 8 S	3
		AC 16 BS	5
		AC 22 TS	10
		Unbound	45
RSDT and Others	Bk 1.0	AC 8 DN	3
		AC 22 TN + 40% RAP	10
		Unbound	45
	Bk 0.3	AC 8 DN	3
		AC 22 TN + 40% RAP	8
		Unbound	39
		Surface layer	
		Binder layer	
		Base layer	
		Subbase layer	

According to the city administrators, only the base layer of Bk 1.0 and 0.3 structures are partially produced with Reclaimed Asphalt Pavements (RAP). Further info about the asphalt materials used to construct the pavements in Munster is based on the German Guideline [24] (RStO 12), entitled ‘Guidelines for the standardization of pavement structures of traffic areas’ as shown by Siverio Lima et al. [25].

The load classes (Bk, ‘Belastungsklasse’ in German) are based on the annual average daily traffic (AADT) and the traffic load in terms of 10-ton axle passages (e.g., 10 to 32 million for Bk 32), as can be seen in Table 2.

**Table 2.** Pavement structures applied in Munster according to the traffic.

Category	Load Class	Traffic	Vehicles Per Day
MR	Bk 32	Traffic V	25,000–50,000
MAR	Bk 3.2	Traffic III	10,000–15,000
RSDT and Others	Bk 1.0	Traffic I	2501–5000
	Bk 0.3	Traffic I	0–2500

The city of Munster defines the pavement conditions according to the International Roughness Index (IRI) [26], and when the data used in this analysis was collected (2019), only about 45% of the network was completely analyzed. Table 3 shows the percentage of pavements in each condition and the IRI range:

**Table 3.** Pavement condition according to the IRI.

Condition	IRI Range, m/km	Percentage of Pavements
Very Good	1–1.5	34%
Good	1.5–3.5	43%
Fair	3.5–4.5	21%
Poor	4.5–5	2%

### 3. Maintenance Strategies and Costs

There are different maintenance strategies that can be applied for the pavement categories, as shown in Table 4.

There are three types of intervention: periodic maintenance (in which only the first layer is replaced), rehabilitation (in which the first and second layers are replaced), and the construction (in which the entire pavement is rebuilt).

**Table 4.** Maintenance strategies used in Munster for different pavement categories.

Category	Load Class	Pavement Structure	Maintenance Strategies (Years)											
			A			B					C			
			M1	M2	M3	M1	M2	M3	M4	M5	M1	M2	M3	M4
MR	Bk 32	Surface layer	15	30	40	15	25	30	35	40	15	30	40	50
		Binder layer		30	40					40		30	40	50
		Base layer			40					40				50
		Unbound			40					40				50
MAR	Bk 3.2	Surface layer	15	30	40	50		20	35	50				
		Binder layer		30		50			35	50			-	
		Base layer				50				50				
		Unbound				50				50				
RSDT	Bk 1.0	Surface layer	40	80				20	40	60				
		Base layer		80					40	60			-	
		Unbound		80						60				
	Bk 0.3	Surface layer	40	60	80									
		Base layer		60	80				-				-	
		Unbound			80									

The pavement structure Bk 32, applied to main roads, for example, has three main strategies that can be used. Strategy ‘A’ consists of a periodic maintenance after 15 years (i.e., M1), a rehabilitation after 30 years (i.e., M2), and new construction after 40 years (i.e., M3), while strategy ‘B’ has four periodic maintenances each 5 to 10 years (i.e., M1 to M4) followed by a new construction after 40 years (i.e., M5). Strategy ‘C’ shows an extended lifespan (50 years) of the pavement by applying one periodic maintenance and two rehabilitations prior to the new construction.

The Bk 3.2 structure applied in main access roads may have two distinct maintenance strategies: ‘A’ or ‘B’, both with a lifespan of 50 years, when new construction would be carried out.

The residential roads can either be built with Bk 1.0 or Bk 0.3 pavement structures, while other paved areas, such as parking places and bike lanes, use Bk 0.3 structures. Depending on the traffic load and the maintenance strategy chosen, there might be a variation of 20 years between the lifespans of Bk 1.0 and Bk 0.3 pavements.

The city of Munster provided the costs to carry out the maintenance of different pavement structures and strategies. However, they could not inform us of the periodic maintenance and rehabilitation costs of Bk 3.2, 1.0, and 0.3.

As RONET requires complete information to assess the economic impacts of the strategies, the missing values have been estimated based on the cost data available for the Bk 32 structures. For such structures, the quotient of the cost of periodic maintenance and the cost of new construction is 0.25; and the quotient of the costs of rehabilitation and new construction is 0.41. These results (or coefficients) were applied to estimate the periodic maintenance and rehabilitation costs of Bk 3.2, 1.0, and 0.3 structures. The coefficient was defined by dividing the periodic maintenance and rehabilitation costs by the cost of new construction. Furthermore, to estimate the unit cost of periodic maintenance of Bk 3.2 structures, the coefficient of 0.25 is multiplied by the costs provided by Munster to rebuild the pavement; that is, EUR 711,900.00/km eq.

Table 5 shows the costs in EUR per kilometer of a two-lane equivalent road 7-m wide, which is the unit cost used to perform the analysis with RONET. All estimated values are written in bold.

As the city administrators could not specify the variations between strategies, this study considers the same costs for Strategies A and B for pavement structures Bk 3.2 and Bk 1.0.

**Table 5.** Unit costs to repair urban pavements in Munster.

Category	Strategy	Costs (EUR/km eq)
Bk 32 A	○ Periodic Maintenance	191,940.00
	□ Rehabilitation	243,124.00
	Δ New construction	844,536.00
Bk 32 B	○ Periodic Maintenance	187,096.00
	□ Rehabilitation	402,976.00
	Δ New construction	849,128.00
Bk 32 C	○ Periodic Maintenance	249,900.00
	□ Rehabilitation	382,200.00
	Δ New construction	837,900.00
Bk 3.2	○ Periodic Maintenance	<b>177,975.00</b>
	□ Rehabilitation	<b>291,879.00</b>
	Δ New construction	711,900.00
Bk 1.0	○ Periodic Maintenance	<b>86,625.00</b>
	□ Rehabilitation	<b>142,065.00</b>
	Δ New construction	346,500.00
Bk 0.3	○ Periodic Maintenance	<b>77,000.00</b>
	□ Rehabilitation	<b>126,280.00</b>
	Δ New construction	308,000.00

Based on the data provided by the city, it is possible to estimate the average expenditures and length of interventions made in Munster's road network for the last 5 years, which is presented in Table 6.

**Table 6.** Historical average of interventions made by Munster during the last 5 years.

Network Category	Type of Intervention	Road Expenditures during Last 5 Years (M EUR/Year)	Road Works during Last 5 Years (km/Year)
Main Roads	Rehabilitation	3.7	169.2
	Periodic Maintenance	3.0	169.2
	Routine Maintenance	3.0	169.2

Main Access Roads	Rehabilitation	0.8	27.8
	Periodic Maintenance	0.8	27.8
	Routine Maintenance	0.8	27.8
Residential Roads	Rehabilitation	9.1	426.5
	Periodic Maintenance	7.6	426.5
	Routine Maintenance	7.6	426.5

#### 4. Methodology

To perform the economic assessment of the pavement structures and its maintenance strategies over the 20-year evaluation period, the relevant data was collected through questionnaires answered by the Department of Mobility and Civil engineering of the city of Munster.

The RONET model demands a massive amount of detailed inputs, and some of them could not be provided by the city administrators. Consequently, default data were used for non-essential inputs. On the other hand, the non-available essential data was estimated based on the delivered data (e.g., the estimated costs of periodic maintenance and rehabilitation for Bk 3.2, 1.0, and 0.3 pavement structures shown in Table 5).

The analysis performed with RONET covers the entire pavement network over a 20-year period.

In order to analyze the economic impact of the maintenance strategies and different pavement structures over time, six scenarios are modeled alternating Strategies A, B, and C for main road categories and Bk 1.0/Bk 0.3 pavement structures for residential roads, as shown in Table 7.

**Table 7.** Scenarios modelled in RONET.

Categories	Scenarios		
	1AB	2BB	3CB
<i>Main Roads</i>	Bk 32 B	Bk 32 A	Bk 32 C
<i>Main Access Roads</i>	Bk 3.2	Bk 3.2	Bk 3.2
<i>Residential</i>	Bk 1.0	Bk 1.0	Bk 1.0
<i>Others</i>	Bk 0.3	Bk 0.3	Bk 0.3
	<b>1AC</b>	<b>2BC</b>	<b>3CC</b>
<i>Main Roads</i>	Bk 32 B	Bk 32 A	Bk 32 C
<i>Main Access Roads</i>	Bk 3.2	Bk 3.2	Bk 3.2
<i>Residential</i>	Bk 0.3	Bk 0.3	Bk 0.3
<i>Others</i>	Bk 0.3	Bk 0.3	Bk 0.3

The following steps are performed to run the RONET model:

1. Define the data to be analyzed and comparisons to be made (pavement structures and network scenarios)
2. Basic configuration:
  - a. Define pavement categories (e.g., Main roads)
  - b. Insert the terrain type
  - c. Insert the environmental aspects (i.e., rainfall, temperature)
  - d. Define road condition classes
  - e. Define traffic levels and the structural number for each pavement category
3. Standard Configuration (default)
4. Vehicle Fleet Configuration
  - a. Inform the vehicle fleet composition
  - b. Insert the number of new vehicles registered per year (2500)
  - c. Estimate the percentage of trucks overloaded (2%)

5. Country Data
  - a. Inform basic characteristics of the city (Area, Population, Gross domestic product (17,692 billion EUR), Network length, Number of accidents (1583), and Discount rate)
  - b. Insert the traffic growth rate (1%)
  - c. Define the maintenance costs for each road category (Table 5)
  - d. Insert the cubic polynomial coefficients computed with HDM-4 Road User Costs Model (HDM-4 RUC)
6. Road Network Length
  - a. Define the specific length of each category considering the condition and the traffic (please see the supplementary material)
7. Historical expenditures
  - a. Inform the historical average expenditure and road works of the last 5 years (Table 6)
8. Road User Charges
  - a. Inform the average fuel price
9. Press the button 'PAM' available in the Menu to perform the analysis
10. Gather the most relevant outputs

As RNET automatically calculates the pavement deterioration, there are no entries available to insert the lifespan predefined by the city of Munster during the modeling process. By estimating pavement deterioration over time, RNET predicts the time when rehabilitation or reconstruction should be applied, based on the maximum acceptable International Roughness Index (IRI, m/km) that has been adopted for each pavement category, as defined on RNET's 'Standards Configuration' page.

To perform the modeling in RNET, the unit costs (in EUR/km of an equivalent 2-lane, 7-m wide road) to repair urban pavements in Munster (Table 5) were used as an input under RNET's 'Country Data.' Once the RNET analysis has been performed, an optimal maintenance strategy will be defined for each one of the pavement categories given above.

The RNET model was originally developed to assess road networks of developing countries. Nevertheless, the model provides its users with several physical (e.g., environment) and economic (e.g., costs, discount rate) input parameters that make RNET adaptable to any region. For the particular case of Munster, it is defined as 'flat terrain', 'humid temperate cool' climate, and an average rainfall of 70 mm/month.

RNET's input data also includes a discount rate (i.e., 4% per year) and the structural number of the pavement.

The structural number (SNC) is calculated using Equations (1) and (2), as follows [27]:

$$SNC = 0.04 (a_1 \times h_1 + a_2 \times h_2 + a_3 \times h_3 + \dots) + SN_{sg} \quad (1)$$

where:

SNC: Modified structural number;

$a_i$ : Material strength coefficient of layer  $i$ ;

$h_i$ : Thickness of layer  $i$  (mm);

$SN_{sg}$ : Subgrade contribution, given by:

$$SN_{sg} = 3.51 \log CBR - 0.85 (\log CBR)^2 - 1.43 \quad (2)$$

where:

CBR: in situ California Bearing Ratio of subgrade, %;

The values for the coefficients ' $a_i$ ' are defined in Table 8.



**Table 8.** Strength coefficient\* used to calculate the structural number.

Categories	Strength Coefficient Ai			
	Surface	Binder	Base	Unbound
MR	0.45	0.32	0.32	0.14
MAR	0.4	0.32	0.32	0.14
RSDT and Others	0.3	0.32	0.32	0.14

\* Source: Paterson, 1987 [27].

The structural numbers calculated for each road category are shown in Table 9.

**Table 9.** Structural number used in RONET model.

Categories	Structural Number
MR	6.0
MAR	5.0
RSDT and Others	3.5

RONET also requires the calculation of road user costs (Step 5d). This can be done with the HDM-4 Road User Costs Model (HDM-4 RUC) [28], which is an Excel-based model designed to compute, for different vehicle types and road conditions, vehicle speeds, fuel consumption, vehicle operating costs, passenger time costs, emissions, and accident costs, based on the Highway Development and Management Model (HDM-4) relationships. The HDM-4 RUC model computes unit road user costs, performs sensitivity analysis, computes network road user costs, and performs a simplified economic evaluation of a road project. The current version of HDM-4 RUC (Version 5.0) computes the vehicle operating costs and speeds and the function of roughness in the format of cubic polynomials that are used as the RONET input.

To obtain the road user costs, the HDM-4 RUC model has to be run before RONET. The data used to run HDM-4 RUC, applicable to Munster (default values were used for the remaining parameters), are the following:

1. Vehicle fleet
2. Fuel costs (Diesel: 1.38 EUR/liter; Gasoline: 1.55 EUR/liter)

The International Roughness Index (IRI) [26] is the parameter used by RONET to assess the pavement condition and the deterioration of the roads over time, which depends on the maintenance strategy adopted by the road administration. Further specifications about the roughness prediction equation used by RONET are available at RONET's User guide [13].

## 5. Results

The following sections present the most relevant results to the current analysis given by the RONET model. As RONET estimates the pavement deterioration over time, predicting when maintenance interventions should be carried out, additional results based on the lifespan predefined by the city of Munster are also presented at the end of the analysis for comparison purposes.

The software considers several categories of budget scenarios that represent different levels of road works expenditures over time, including Optimal +2, Optimal +1, Optimal, Optimal −1, Optimal −2, Optimal −3, Do Minimum, and Do Nothing.

The Optimal scenario indicates the lowest present value of total society costs. The other budget scenarios are based on the Optimal scenario. For example, the Optimal +1 scenario represents one level higher than the optimal scenario in terms of road agency expenditures.

The very high scenario (above 'Optimal') represents a policy without budget constraints and with a high frequency of periodic maintenance and rehabilitation works. The

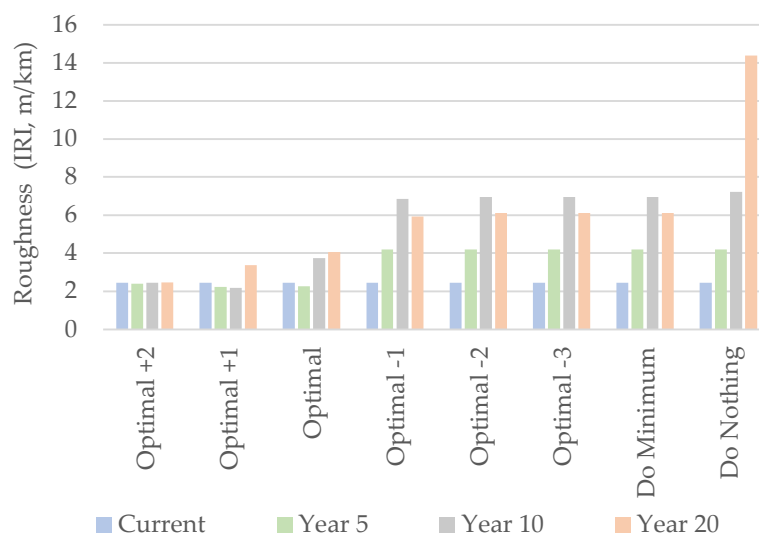
high, medium, low, and very low scenarios represent cases of decreasing frequency of road works and corresponding annualized road works expenditures. The ‘Do Minimum’ scenario represents a policy where the only capital road work applied over the evaluation period is reconstruction at a very high roughness. The ‘Do Nothing’ scenario represents a policy where no capital road works are applied over the evaluation period [13].

Aside from the investments already mentioned applied to maintain urban roads—such as periodic maintenance, rehabilitation and new constructions—RONET also calculates the recurrent maintenance costs, defined as the minimum cost for sustaining the network in its current condition.

### 5.1. Road Deterioration Prediction

Figure 2 presents the road deterioration under different scenarios. The higher the IRI (m/km), the higher the road deterioration. According to the modeling, the IRI of an Optimal scenario ranges from 2.4 to 4.1 m/km over the first 20 years. For Optimal −1 to −3 scenarios, the range varies from 2.4 to 7.0 m/km.

In general, the higher the budget scenario, the lower the IRI variation over the years, a result of stronger or more frequent interventions performed to keep the quality of the network. On the other hand, the ‘Do Nothing’ scenario shows the highest IRI values over the years due to the lack of intervention.



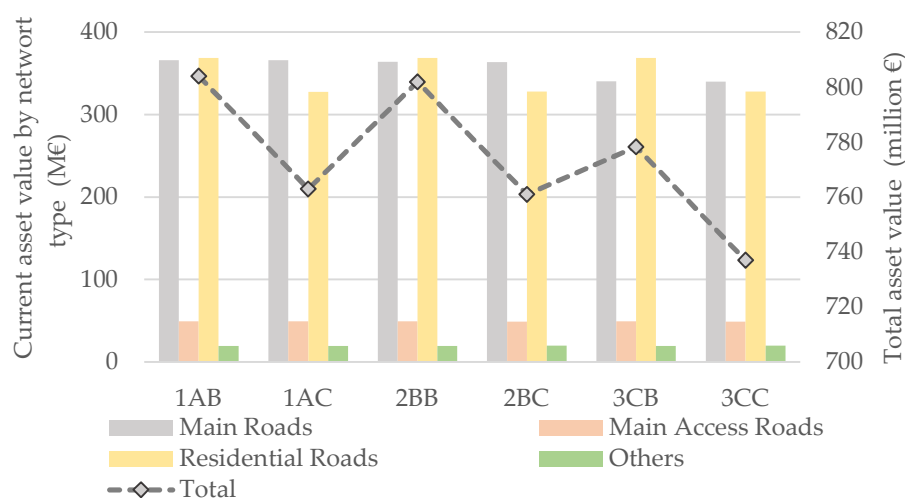
**Figure 2.** Road deterioration under different scenarios.

### 5.2. Road Network Asset Value

As explained in Table 7, six scenarios applying different pavement structures and maintenance strategies were modeled in RONET. The main change between the scenarios are the chosen structure/strategy used for main roads (i.e., Bk 32 A, Bk 32 B, or C) and residential roads (i.e., Bk 1.0 or Bk 0.3).

The asset value of the road network, in this study, changes depending on the pavement structure and maintenance strategy chosen during the modeling process because of the different individual costs.

Figure 3 shows that the current asset value (Million EUR) of Munster’s road network might range between 737 and 804 million EUR considering the distinct scenarios and inputs used in this study.



**Figure 3.** Asset value of the road network for the different scenarios.

As observed in Figure 3, the use of Bk 0.3 to compose the residential roads reduces the value of the road network by 5%, comparing 1AB versus 1AC, 2BB versus 2BC, and 3CB versus 3CC.

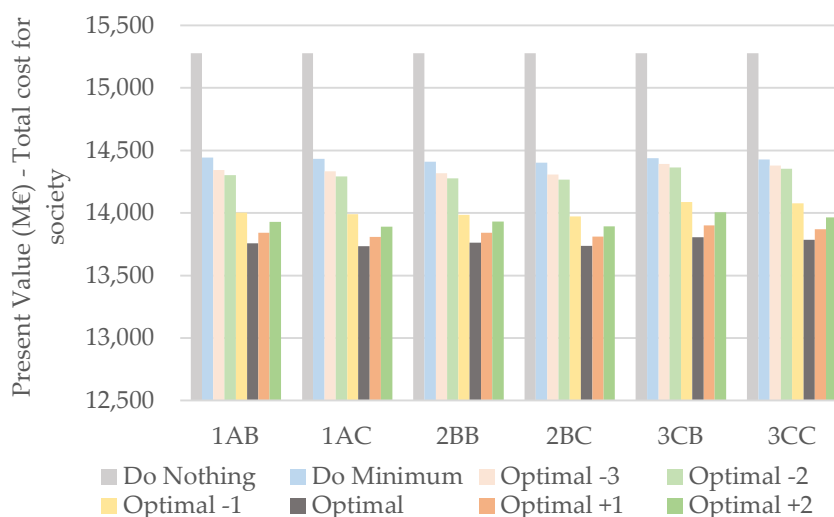
The total asset value is also influenced by the chosen structure for main roads: the use of Bk 32 C instead of Bk 32 A/B reduces the total asset value by 3%.

Main roads and residential roads account for the largest percentage of the network's total asset value. The main roads cost more due to the noble materials used and higher thicknesses built made to support higher traffic loads, which makes its value higher than the others (around 46% of the total asset value). Even though the residential roads do not cost as much as the main roads, 66% of the road network is made of residential roads, which greatly impacts the total asset value (around 45%). Therefore, the categories titled 'main access roads' and 'others'—that comprise less than 8% of the network—do not influence the asset value as much as the other two categories and should be prioritized during a decision-making process.

### 5.3. Present Value of Road Transport Costs

Figure 4 shows the present value of the total road transport cost for six distinct scenarios (i.e., from 1AB to 3CC), as well as eight different budget categories (i.e., from 'Do nothing' to 'Optimal +2'), considering a 4% discount rate. The total road transport cost (or cost to society) is the sum of the costs to (a) the road agency (e.g., construction, maintenance, and rehabilitation costs), and (b) the road users (e.g., fuel, vehicle maintenance, and emission costs), computed over a 20-year analysis period.

As expected, the 'Optimal' budget category shows the lowest total road transport cost for each scenario; that is, from 1AB to 3CC. The total road transport cost for budget category 'Optimal +1' is lower to society than the 'Optimal -1' option, which indicates that, in terms of total cost to society, it is better for Munster to invest a bit more than the 'Optimal' than a bit less than the 'Optimal'. The 'Do nothing' is the most expensive policy that Munster could implement, as it leads to the highest cost to society across all the scenarios analyzed.

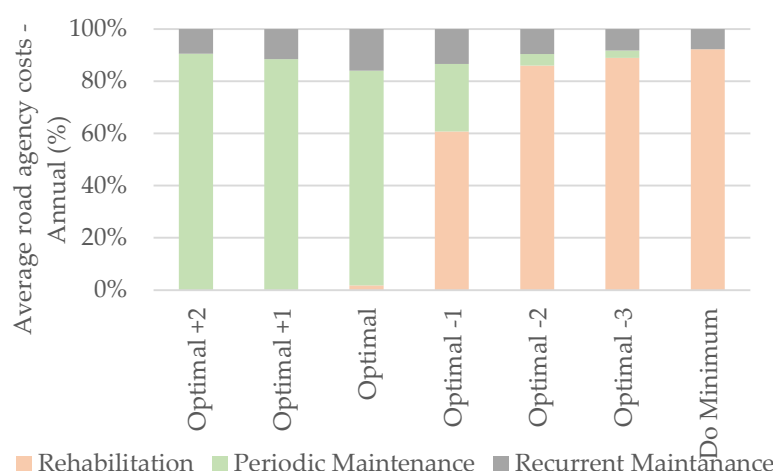


**Figure 4.** Present value of total road transport cost for distinct scenarios.

The 1AC (13,734 million EUR) and 2BC (13,738 million EUR) scenarios have the lowest present value within the range of ‘Optimal’ scenarios, which suggests that the use of Bk 32 A and B structures for main roads together with Bk 0.3 structures to compose residential roads might reduce the total road transport cost for Munster, using the 20-year analysis period. On the other hand, the 3CB scenario modeled with Bk 32 C for main roads and Bk 0.3 structures for residential roads presented the highest cost for society: 13,808 million EUR.

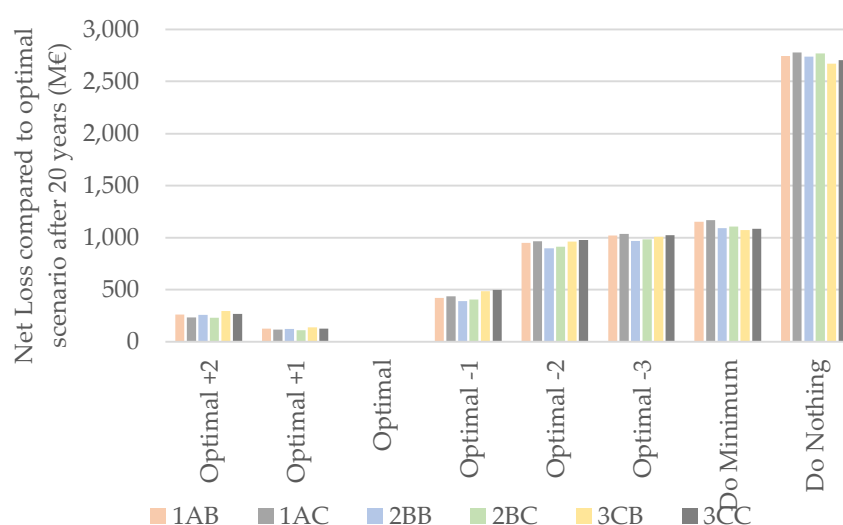
The RONET calculations to estimate the present value do not include the initial construction costs. Adding such costs (which can be done manually or by modifying the RONET software) would show the impact of the higher cost of the Bk 32 A and B pavements, compared to the lower cost of Bk 32 C to build a pavement. In addition, by the end of 20 years (lifetime considered in the analysis), all Bk 32 pavement structures would have passed through only one intervention (i.e., periodic maintenance). Therefore, the reduced present value given by the scenarios modeled with Bk 32 A and B structures demonstrates that a 20-year period of analysis might be too short to assess the long-term economic impacts of pavement constructions with 40 to 80 years of lifespan, as happens in Munster.

As shown in Figure 5, the expenses concerning the ‘Optimal +2’ and ‘Optimal +1’ scenarios are mainly based on periodic maintenance interventions, while the ‘Optimal -2’, ‘Optimal -3’ and ‘Do minimum’ scenarios are mainly based on rehabilitation works. In between, the ‘Optimal’ and ‘Optimal -1’ scenarios are composed of rehabilitation, periodic maintenances and recurrent maintenances. The ‘Optimal’ scenario, however, has a larger amount of money dedicated to periodic maintenances while the ‘Optimal -1’ uses more money on rehabilitation works.



**Figure 5.** Annual average road agency costs for each maintenance strategy (%).

The RONET simulation also shows the economic cost to society when applying a budget scenario other than ‘Optimal’, as shown in Figure 6. The scenario defined as ‘Do Nothing’ is the most expensive for society since the lack of maintenance induces the collapse of the pavements, increasing the road user costs and devaluing the road network.



**Figure 6.** Annual net loss compared with an ‘Optimal’ scenario.

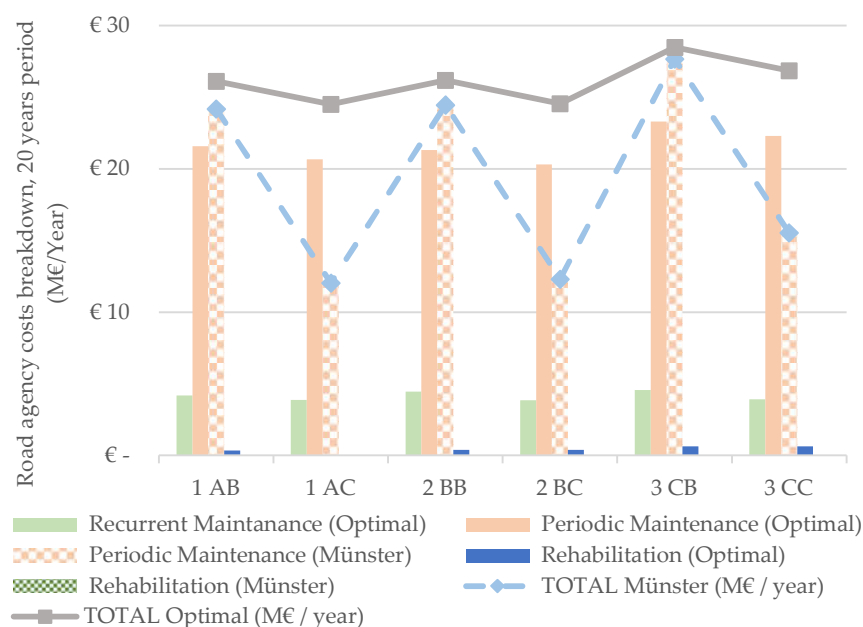
The ‘Optimal’ scenario represents the most recommended condition to maintain the road pavements to provide a good experience for the users with the minimum cost to society. The second-best option is to maintain the road network within the ‘Optimal +1’ scenario. The gap compared to the ‘Optimal’ scenario increases with the adoption of other scenarios.

#### 5.4. Current Investments in Munster versus Optimal Scenario Suggested by RONET

To calculate Munster’s current road agency costs, we estimated the amount invested in each pavement category considering predefined maintenance strategies over a 20-year period and applied a 4% discount rate.

Since the comparison shows the amount invested within each maintenance option (i.e., recurrent, periodic, and rehabilitation), the share dedicated to ‘new constructions’ is neglected in the calculation so that the results can be compared with the RONET output.

Figure 7 compares the current investments made by the city of Munster and the ‘Optimal’ scenario modeled in RONET.



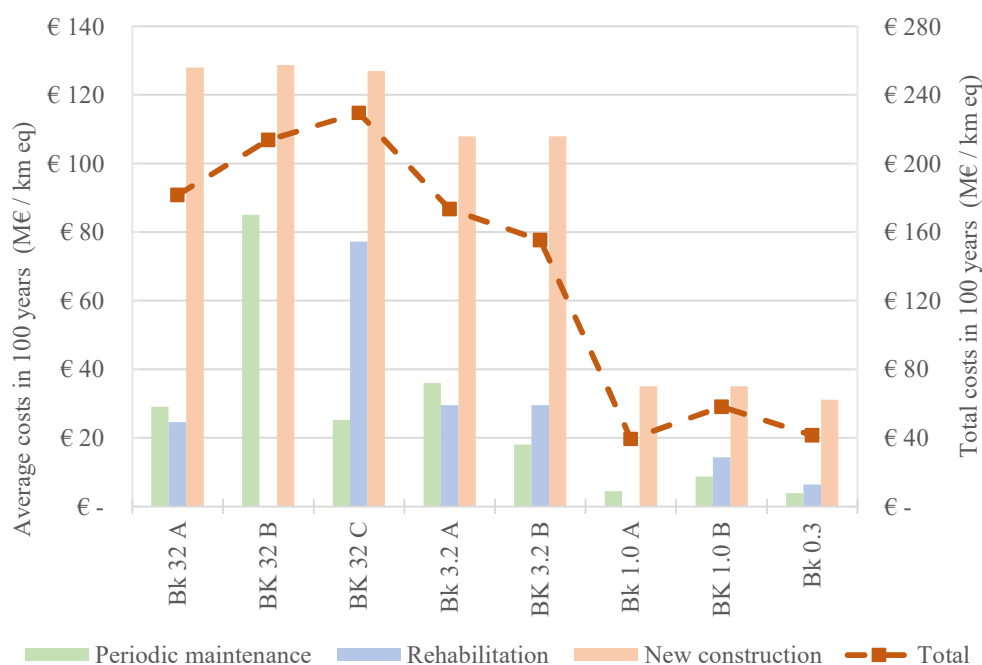
**Figure 7.** Comparison between the real costs invested in Munster and the ‘Optimal’ budget suggested by RONET.

The results show that the total amount planned by the city administrators to maintain the urban pavement network is close to the value suggested in RONET for all scenarios that apply Bk 1.0 pavement structures to the residential roads (i.e., 1AB, 2BB, and 3CB). This suggests that the strategy applied in Munster is in accordance with the deterioration model and other calculations simulated in RONET. On the other hand, when applying Bk 0.3 structures to compose residential road pavements, the overall investments made by Munster would be lower than that recommended by the RONET model.

According to RONET, to maintain the budget scenario at an ‘Optimal’ level, Munster should invest approximately 0.3 million EUR per year in rehabilitation, 21.6 million EUR per year in periodic maintenance, and 4.2 million EUR per year in recurrent maintenance, or a total investment of about 26.1 million EUR per year. Neglecting the scenarios that apply Bk 0.3 pavement structures in residential roads (e.g., 1 AC, 2BC, and 3CC), the current investments made by Munster should be around 25.4 million EUR per year entirely used for periodic maintenance interventions.

### 5.5. Long-Term Analysis

In order to provide a holistic approach to the investments to be made by the city of Munster to maintain the road pavement network over a long-term period, we calculate the overall costs to perform periodic maintenance, rehabilitation, and new constructions based on the predefined strategies. The analysis considers a period of 100 years and a discount rate of 4%, as shown in Figure 8.



**Figure 8.** Average costs of maintenance, rehabilitation, and construction of road pavements.

Figure 8 shows that Bk 32 pavement structures have the highest costs over time. The Bk 32 C structure has the highest costs due to the expenses given by the rehabilitation processes, while Strategy ‘A’ presents the lowest value due to the minor interventions required. All strategies used for Bk 32 have approximately the same sum of costs for new constructions; however, Strategy ‘B’ requires more investment in periodic maintenance than the others (i.e., ‘A’ and ‘C’), considering for Bk 32 structures.

In general, the lower the traffic load of the pavement road, the lower will be the costs over the 100-year period; but the type of strategy chosen highly impacts the long-term costs. The Bk 3.2 pavement structures used in main access roads, for example, applying Strategy ‘B’, can save approximately 500 thousand EUR per km equivalent of road. Although the amount spent constructing new pavement structures is quite similar for both Bk 3.2 A and B, Strategy ‘A’ requires dedicating a greater amount to periodic maintenance, which makes Strategy ‘B’ a less expensive option in the long term.

Over 100 years, the residential roads built with Bk 1.0 B have the largest costs when compared with pavement structures built with Bk 1.0 A or Bk 0.3 structures due to greater investments made in rehabilitation and periodic maintenance. Despite the reduced values invested in new constructions, the Bk 0.3 structures demand greater amounts of rehabilitation work than the Bk 1.0 A structure due to the longer period between interventions.

## 6. Conclusions

This study assessed the economic impacts of urban pavements using the RNET model as the primary tool for the analysis. The urban road network of the city of Munster is used as a basis for the study, considering local pavement structures and maintenance strategies.

The results showed that the current values invested by Munster are close to the ‘Optimal’ budget scenario obtained through RNET, which indicates that the maintenance strategies adopted in situ over a 20-year analysis period are well chosen by the municipality.

According to the predefined maintenance strategies applied in Munster, only one intervention (i.e., periodic maintenance) should be performed during the initial 20 years,

which is the analysis period used in the RONET model. Therefore, it is not possible to state that the actual costs would remain similar to the ‘Optimal’ over a longer analysis period.

In addition, the lifetime used for the analysis might influence the decision-making process over the most cost-effective pavement structure or network scenario for a city. For example, for 20 years, the results showed that using Bk 32 B would lead to reduced costs to society. However, the long-term analysis demonstrated that the Bk 32 A pavement structure is possibly the most cost-effective choice to build the main roads.

The pavement structures applied to main access roads (i.e., Bk 3.2 A and B) have the same costs and are distinguished only by the timing and type of intervention. As RONET defines the condition and the maintenance interventions by applying a road deterioration model, it was not possible to differentiate the Bk 3.2 A/B structures during the modeling. However, in the long-term analysis, it is possible to observe that applying Bk 3.2 B pavement structures to compose the main access roads is slightly less expensive than using Bk 3.2 A because it demands one less intervention over time.

According to the RONET model, Munster would need fewer investments if all residential roads were built with Bk 0.3 structures—as shown in 1AC, 2BC, and 3CC scenarios. The long-term analysis showed similar results, either applying Bk 0.3 or Bk 1.0 A structures.

To reach an ‘Optimal’ budget scenario, the results suggest performing recurrent and periodic interventions to maintain the IRI levels between 2 m/km and 4 m/km instead of neglecting maintenance for an extended period, which would require larger interventions in the future, such as reconstruction. The strategy of ‘Do Nothing’ is the most expensive practice that could be adopted by city administrators.

As this study used data from the city of Munster to compare maintenance strategies and pavement structures, its results may not apply directly to other cities or environments. Furthermore, it is recommended to repeat the analysis for Munster once more-complete data relative to the expenditures on all pavement structures have become available, which would enhance the accuracy of the results.

The RONET model was initially developed to assess road networks in developing countries. However, this study shows the possibility of also using it for developed countries.

In general, the municipalities can forecast the financial requirements for a period of 5 to 10 years, especially for urban areas, which are considerably more complicated to make solid assumptions that lead to meaningful results. As a part of a broader analysis, this study aims to incentive the use of LCA and LCCA tools to be used for municipalities as key performance indicators (KPIs) to control the Performance Measurement Systems (PMS) for long periods of analysis; thus far, there is limited use of PMS by municipalities.

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