Integrating Thermo-Viscoelasticity into an Optimization Framework for Economically and Environmentally Sustainable Flexible Pavement Design

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ABSTRACT: This study presents a comprehensive framework for optimizing flexible pavement designs by balancing environmental impacts and economic aspects while ensuring that the designs comply with thermo-viscoelastic stability. The framework comprises five components: a material database, design variables (layer properties), two objective functions that account for the environmental impact and economical aspects related to the pavement life cycle phases ranging from material extraction to construction, a genetic algorithm-based optimization solver, and two constraints. Two case studies were considered to demonstrate the influence of temperature effects on the optimization of pavement designs, with Case 1 assuming seasonal temperature variations and Case 2 assuming a constant temperature in the top layer. The results show that accounting for temperature effects increases required layer thicknesses.

1 INTRODUCTION

For a given climate, designing flexible pavements involves defining layers — number, thickness, and materials — to bear mechanical loads. Rising construction costs have prompted efforts to optimize these layers to reduce expenses (Statistisches Bundesamt, 2024). Concomitantly, the European Green Deal aims for EU climate neutrality by 2050. It also highlights the construction sector's role, which is responsible for 5 % to 12 % of total Greenhouse Gas (GHG) emissions (European Commission; European Commission, 2019). Reducing emissions in road construction is therefore crucial for achieving this goal. Optimizing layer properties has the potential to reduce costs and emissions but focusing solely on one or the other might lead to either economically unviable or environmentally unfriendly solutions. Thus, the optimization process must balance cost and environmental impact.

In this regard, several studies have been carried out with the goal of optimizing pavement layer properties (or a subset of those) with respect to performance, economic, and environmental impacts (or a subset of those). This is typically achieved through the application of a multi-objective optimization (MOO) framework. Layered elasticity and temperature-independent layered viscoelasticity (not simultaneously) are usually used to assess the mechanical performance. The materials, their transportation, and construction costs were taken into account for the economical aspects. The materials extraction, transportation, and construction were considered for the environmental impact. The developed frameworks were applied to assess the effectiveness of balancing performance, costs, and environmental impact. For the studies (Inti and Anjan Kumar, 2021) and (Wang and Chong, 2014) the benefits of their framework are not clearly indicated, while (Demir et al., 2023) demonstrated a reduction of 30 % and 31 % in environmental impact and economic aspect (not simultaneously). The frameworks were solved with a particle swarm algorithm, Genetic Algorithm (GA), or manually. However, none of the aforementioned studies considered the behavior of the asphalt layers as thermos-viscoelastic.

2 OBJECTIVE AND METHODOLOGY

The objective of this paper is to present a MOO framework to optimize the layer properties — such as number, thickness, and materials — of flexible pavements, considering environmental and economic impacts, while ensuring thermo-viscoelastic stability. For this, an optimization framework is developed.

The framework consists of five components: (1) a material database, (2) the set of decision variables, (3) two constraints, (4) the objective functions and (5) an optimization algorithm solver. The material database hosts information about the costs, environmental impacts, and mechanical properties of each material. Two objective functions are defined; one accounts for the environmental impacts and the other for the economic aspect. Ultimately, the two objective functions are combined by weighing of each aspect to create a single objective function. Accessing this material database, a GA is applied to this objective function, in order to minimize the environmental impact and the economic aspect. In general terms, as part of the GA, several designs — herein defined as an arrangement of the layers numbers, materials, and thicknesses —

are generated. To ensure thermo-viscoelastic stability compliance with the German guidelines (Forschungsgesellschaft für Straßen- und Verkehrswesen, 2024) these combinations are constrained through assessment of the fatigue, i.e., horizontal tensile strains at the bottom of the bituminous base layer. The strains are calculated according to thermo-viscoelasticity theory applied to a layered domain (representing a flexible pavement) subjected to loadings (representing traffic). In addition, the minimum and maximum layer thickness is limited by further constraints. The layer properties providing the minimal value of the fitness function and complying with the thermo-viscoelastic stability are selected as the optimal solution. This framework is subsequently applied to two cases, differentiating themselves from each other by the temperature imposed within the top layer (representing Asphalt Concrete (AC)), one considering a constant temperature and the other varying within the year.

3 MULTI-OBJECTIVE OPTIMIZATION FRAMEWORK DEVELOPMENT

3.1 *Material database*

Table 1 presents the properties of several materials utilized in a typical German pavement. The top layers, comprising the surface, binder, and base layers, are made of AC and are assumed to exhibit thermo-viscoelastic material behavior. To account for this behavior, we assume thermo-rheological simplicity and apply the time-temperature superposition principle with Williams-Landel-Ferry (WLF) constants $C_1 = 30$ and $C_2 = 200$ °C (Morland and Lee, 1960). The Adaptive Layered Viscoelastic Analysis (ALVA) software (Skar and Andersen, 2020) is utilized to compute thermo-viscoelastic strains; the viscoelastic properties utilized herein are the default values of ALVA. The remaining layers are time- and temperature-independent and further characterized by a Poisson's ratio and a Young's modulus. Also presented in Table 1 are the GHG emissions and costs related to the A1-A3 phases of each material.

3.2 *Decision variables*

The decision variables of the MOO framework are the type and material of the layers to be included in the pavement structure and the respective thickness. Amongst the materials detailed in Table 1, the framework is allowed to optimize a pavement containing one to three layers. Also included in Table 1 is the information on whether a given layer type and material is mandatory to be included in the pavement.

3.3 *Objective functions*

The single objective function is additively composed of OF_1 (CO_2-eq) and OF_2 (€) accounting respectively for the environmental impacts (Eq. (1)) and costs (Eq. 2)) associated with the pavement life cycle phases A1-3, A4, and A5:

$$OF_1 = \sum_{i=1}^{n} \rho_i \cdot d_i \cdot w_i \cdot l_i \cdot (GHG_{\mathrm{A1-A3},i} + GHG_{\mathrm{A4}} \cdot y + GHG_{\mathrm{A5}} \cdot t) \quad (1)$$

where n is the number of layers, ρ_i (kg·m^{-3}) is the density of layer i, d_i (m) is the thickness of layer i, w_i (m) is the width of layer i, l_i (m) is the length of the layer i, $GHG_{\mathrm{A1\text{-}A3},i}$ (CO_2-eq.·kg^{-1}) are the GHG emissions associated with phases A1-A3 of layer i, GHG_{A4} (CO_2-eq.·kg^{-1}·m^{-1}) are the GHG emissions associated with phase A4, y (m) is the distance between the asphalt mixing plant and construction site, GHG_{A5} (CO_2-eq.·kg^{-1}·day^{-1}) are the GHG emissions associated with phase A5, and t (kg·day^{-1}) is the construction rate;

$$OF_2 = \sum_{i=1}^{n} \rho_i \cdot d_i \cdot w_i \cdot l_i \cdot (C_{A1-A3,i} + C_{A4} \cdot y + C_{A5} \cdot t) \quad (2)$$

where $C_{\mathrm{A1\text{-}A3},i}$ (€·kg^{-1}) are the costs associated of phases A1-A3, C_{A4} (€·kg^{-1}·m^{-1}) are the costs of phase A4 , and C_{A5} (€·kg^{-1}·day^{-1}) are the costs of phase A5. The two objective functions are normalized (Eq. (3)):

$$OF_{j,\mathrm{norm}} = \frac{OF_j - \min(OF_j)}{\max(OF_j) - \min(OF_j)} \quad (3)$$

where $j = 1$ or $j = 2$ and $OF_{j,\mathrm{norm}}$ is the normalized objective function OF_j.

OF_1 and OF_2 are combined into one single objective function through the weighted sum method with user-defined weights w (Eq. (4)):

$$OF_{\mathrm{c}} = w \cdot OF_{1,\mathrm{norm}} + (w - 1) \cdot OF_{2,\mathrm{norm}} \quad (4)$$

Table 1. Structural, mechanical, environmental, and economic properties of the layer structure

Layer type	Layer materials	Mandatory	Poisson's ratio v	Young's modulus E	GHG emissions A1-A3	Costs A1-A3
			[–]	[MPa]	[CO_2-eq.·kg^{-1}]	[€·kg^{-1}]
Top layer	Asphalt	x	0.35	-	0.07732	0.09335
Base layer	Hydraulic bounded layer		0.25	2000	0.08	0.04135
	Stabilization layer		0.25	2000	0.08	0.035
	Crushed stone base layer		0.5	325	0.04	0.0135
Frost protection layer	Frost protection layer		0.5	150	0.03	0.02033
	Frost resistant material		0.5	75	0.03	0.18
Ground		x	0.5	45	-	-

3.4 *Constraints*

There are two constraints; one associated with the decision variables and the other with the compliance of the bottom-up fatigue criteria. The decision variable constraint sets lower and upper thickness limits for each layer to ensure that the created pavement design complies with the German guidelines (Forschungsgesellschaft für Straßen- und Verkehrswesen, 2024). The bottom-up fatigue criteria consist of quantifying the accumulation of strains caused by the traffic over the lifetime of a pavement. For this, the ALVA software (Skar and Andersen, 2020) was utilized to calculate the strains caused by a given number of Equivalent Standard Axle Loads (ESALs). Multiple runs were executed for the quantification, each representing a pavement structure subjected to these ESALs over one day, assuming a uniform and constant temperature within the top layer over this timespan. The temperature effects on the viscoelastic default properties were incorporated within the ALVA through the application of a shift factor (Williams et al., 1955). The collection of simulations for each day — i.e., calculated strains — required for the lifetime of a pavement were accumulated through the following formula (Forschungsgesellschaft für Straßen- und Verkehrswesen, 2024):

$$N_{\text{acc}} = m \cdot a \cdot \varepsilon_{\text{horz}}^{k} \quad (5)$$

where N_{acc} is the variable representing the acceptable load repetitions, m represents the adaption factors presented in Table 2, $a = 2.8283$ and is the fatigue regression parameter, ε_{horz} (‰) is the horizontal strain, and $k = -4.194$ is a fatigue regression parameter. The parameters m, a, and k were calibrated to match the German guidelines (Forschungsgesellschaft für Straßen- und Verkehrswesen, 2024).

Table 2. Adaption factors *m*

Pavement layer	Value
Frost protection layer	37373.73
Hydraulic bounded base layer	1028.3
Stabilization layer	918.72
Crushed stone base layer	30094.0
Ground (Fully bounded layer structure)	26297.0

The thermo-viscoelastic stability of the pavement designs is assessed for each simulation against the Miner rule (Miner, 1945).

3.5 *Optimization algorithm*

The MOO problem was solved with a GA. The motivation for the use of an evolutionary algorithm lies in its ability to handle complex constraints without any requirement for gradient information or function continuity and its ability to avoid getting trapped into local optima compared to traditional optimization methods. The formulation of the MOO framework was written in Matlab® programming language, version R2022b.

4 APPLICATION OF THE FRAMEWORK

To demonstrate the importance of accounting for thermo-viscoelasticity in the context of pavement design, two cases were considered for the application of the framework. They differ by the temperature levels within the top layer, detailed hereafter.

4.1 *Case studies setup*

The first case, named Case 1, considers the top layer's temperature to vary daily in a sinusoidal shape according to Eq. (5):

$$T_{\text{day}} = 15 + 20 \cdot \sin\left(\frac{L \cdot 2 \cdot \pi}{365}\right) \quad (6)$$

where T_{day} (°C) is the yearly temperature variation at day L, and L (day) stands for the considered day of the year. The second case, named Case 2, considers the mean average annual temperature of T_{day}. The shift factor uses as temperature level the difference between the top layer's temperature and its annual average, i.e., 15 °C (Williams et al., 1955).

The non-default values of the ALVA software parameters were: the traffic speed (80 km/h) and the load level (0.69 MPa, equivalent to one ESAL). A total of $1 \cdot 10^8$ ESALs were considered over a design period of 30 years.

Environmental impact and economic costs were considered to have equal importance, i.e., $w = 0.5$. The parameters considered in the objective functions are presented in Table 3, whereas the parameters related to the GA are listed in Table 4.

Table 3. Objective function parameters

Parameter name	Units	Value
GHG emissions A4	[CO_2-eq.·kg^{-1}·m^{-1}]	$1 \cdot 10^{-5}$
GHG emissions A5	[€·kg^{-1}·day^{-1}]	0.04
Costs A4	[€·kg^{-1}·m^{-1}]	$2 \cdot 10^{-6}$
Costs A5	[€·kg^{-1}·day^{-1}]	0.02
Distance between mixing plant and construction site	[m]	50000
Construction rate	[kg·day^{-1}]	$1 \cdot 10^{-5}$

Table 4. Genetic algorithm parameters

Parameter name	Units	Value
Population size	[–]	100
Generation size	[–]	35
Crossover rate	[%]	90
Tournament size	[–]	3
Mutation rate	[%]	15
Penalty factor	[–]	500
Elite rate	[%]	15
Function tolerance	[–]	$1 \cdot 10^{-5}$
Constraint tolerance	[–]	0

4.2 *Results*

The results, obtained after three days of computational time for both cases, are presented in Table 5. As can be seen, Case 1 — which fulfilled the 30 years design period — considering seasonal temperature effects yields a thicker AC layer and an additional frost protection layer. As expected, the subsequent environmental impact and total costs are higher for Case 1. Utilizing the layer properties of Case 2 with daily temperature variation would not satisfy the constraint related to thermo-viscoelastic stability. This led to a design that withstands the applied traffic loads and daily temperature variations only for 6.34 years.

Table 5. Optimization results for both case studies

Optimization results	Unit	Case 1	Case 2
Asphalt layer thickness	[m]	0.435	0.375
Second base layer thickness	[m]	0	0
Frost protection layer thickness	[m]	0.2	0
Environmental impacts	[CO_2-eq.]	$3.0 \cdot 10^7$	$1.8 \cdot 10^7$
Total Costs	[€]	$6.2 \cdot 10^6$	$3.8 \cdot 10^6$

5 CONCLUSION

In this study, a framework was developed to optimize the pavement design with respect to environmental impact and economic aspects, while ensuring compliance with thermo-viscoelastic stability. The framework consists of five components: a material database, design variables, two objective functions (environmental impact and cost), a genetic algorithm-based optimization solver, and two constraints, of which one is related to thermo-viscoelastic stability.

To demonstrate the significance of thermo-viscoelastic considerations, the framework was applied to two cases: one with a sinusoidal temperature variation in the top layer and another one with a constant temperature. The resulting pavement design of the case with temperature variation resulted in higher environmental impact and higher costs. However, using the layer properties from the constant temperature case while accounting for temperature variation did not meet the constraint related to thermo-viscoelastic stability.

The integration of seasonal temperature effects into the optimization process of pavement design ensures cost efficiency and a reduction of environmental impact. This work marks the first step towards the acceptance of a more realistic optimization framework for pavement design.

In future work, it is worth exploring the inclusion of several thermo-viscoelastic layers with non-uniform temperature levels, and the expansion of the material database.

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