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RIGA TECHNICAL UNIVERSITY

Artūrs Riekstiņš

DEVELOPMENT OF ROAD PAVEMENT SUSTAINABILITY ASSESSMENT METHODOLOGY AND TOOL AND APPLICATION FOR EVALUATION OF VARIOUS MATERIALS AND TECHNOLOGIES

Summary of the Doctoral Thesis

RTU Press
Riga 2023

RIGA TECHNICAL UNIVERSITY
Faculty of Civil Engineering
Institute of Roads and Bridges

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Doctoral Student of the Study Programme "Construction"

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Scientific supervisor
Dr. sc. ing.
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DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science (Ph. D.), the present Doctoral Thesis has been submitted for defence at the open meeting of RTU Promotion Council on 12 May 2023 at 14.15 p. m. at the Faculty of Civil Engineering of Riga Technical University, 6A Ķīpsalas Street, Room 342.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for promotion to the scientific degree of Doctor of Science (Ph. D.) is my own. I confirm that this Doctoral Thesis has not been submitted to any other university for promotion to a scientific degree.

Arturs Riekstins ……………………………. (signature)
Date: …………………….

The Doctoral Thesis has been written in Latvian. It consists of an Introduction, 8 chapters, Conclusions, 80 figures, 29 tables; the total number of pages is 144. The Bibliography contains 96 titles.

CONTENTS

1. INTRODUCTION

1.1. Importance of the topic

The road network is the circulatory system of the country, region and continent. Its density and condition are essential for providing the basic needs of human beings and development. At the same time, maintaining this network requires our planet's large financial and non-renewable resources. The total length of the road network in the European Union alone is 5.5 million kilometres, and it is estimated that the total value of the infrastructure is approximately 8 trillion. The total length of Latvia's road network is only 1.27 % of this amount. However, due to the relatively small population, we have the 9th highest amount of road kilometres of 0.0363 km per inhabitant in the world. Its density is 1094 km per 1 km^2. As the population decreases in many countries, the amount per capita increases, which proportionally requires an even larger share of the annual state budget for its reconstruction and maintenance.

Regardless of population decline, the road network must be maintained so that it is accessible to everyone and does not disrupt economic processes. Despite the limited funding, the road network needs to be reconstructed and maintained sustainably, which is especially relevant now regarding the European Green Deal. One of the goals of the European Green Deal is to reduce total emissions by 50 % by 2030. At the same time, next to the economic and environmental aspects, there are also society's wishes or social factors. The community wants longer-lasting roads, driving comfort, safety, and a low noise level. Therefore, it is understandable that all the aspects mentioned above (economic, environmental, social) should be included and evaluated in decision-making. The road network manager defines the weight of each factor in the decision process, harmonising requirements with wishes and possibilities.

During the Thesis research, the sustainable development assessment methodology and calculation tool PAVE/LCA/LCCA were developed. It is a step forward in the objective, quantitative-based evaluation of materials, technologies and/or rehabilitation strategies in road construction and related processes.

1.2. The scientific novelty of the study

The Thesis developed a methodology and a tool for assessing the sustainability of road pavement materials, technologies and reconstruction strategies, including environmental, economic and social factors. Although the methodology is designed to include all three sustainability parameters in the assessment, the tool developed includes two of them – environmental and economic. There is no similar tool with which it is possible to calculate a road pavement's environmental and economic parameters for a freely designed reconstruction and maintenance plan. The tool is developed in Microsoft Office Excel, supplemented with Visual Basic for Applications (VBA). The method is essential in promoting the road industry's understanding of the costs and environmental impacts of materials, technologies and/or strategies used, thereby improving policy making. The developed tool is publicly available and can be further evolved and adapted to the needs of those interested.

1.3. Aim of the Doctoral Thesis

The Doctoral Thesis aims to develop a sustainable development assessment methodology and a tool for road pavement project assessment by analysing industry-binding standards, existing practices, and used tools to validate it and carry out an evaluation of the sustainability parameters of various materials and technologies.

1.4. Tasks of the Doctoral Thesis

1. Analysis of related regulations and standards for sustainability assessment.
2. Analyses of the tools available for evaluating sustainability parameters.
3. Development of a methodology based on the life cycle techniques that would assess the environmental, economic and social aspects of various road pavement materials, technologies and/or applied reconstruction and maintenance strategies used.
4. Development of the tool to evaluate environmental and economic values of road pavement materials, technologies and/or applied reconstruction and maintenance strategies.
5. Collection of data from the literature, databases, material manufacturers and local road construction companies.
6. Validation of the tool developed.
7. Assessment of potentially sustainable materials and technologies by developed methodology and tool.

1.5. Practical application of work

The developed methodology and tool will be available to any road owner/manager in Latvia, and outside it to improve the decision-making policy for more sustainable reconstruction and maintenance of the road network. The developed tool is free of charge and available for download, use, and evaluation (https://drive.google.com/drive/folders/1dhiyB1wVq_-aGzuybQrc83dihoi4oKNY?usp=sharing). Also, the developed method can be use scientific purposes.

1.6. Approbation in conferences

1. 11th International Conference on the Bearing Capacity of Roads, Railways and Airfields, June 28–30, 2022, Trondheim, Norway.
2. "Use of local materials and by-products of industry in road construction" 8.10.2020. Workshop.

3. BUP VII PhD Students Training in Rogow, Poland, 24–28 November 2019.
4. 18th International Scientific Conference, Engineering for Rural Development, May 22–24, 2019, Jelgava, Latvia.

1.7. List of publications developed during doctoral studies

1. Riekstins, A., Haritonovs, V., & Straupe, V. (2022). Economic and environmental analysis of Crumb Rubber Modified Asphalt. Construction and Building Materials, 335, 127468. https://doi.org/10.1016/j.conbuildmat.2022.127468
2. Riekstins, A., Haritonovs, V., Merijs-Meri, R., & Zicāns, J. (2021). Ethylene-Octene-Copolymer as an alternative to Styrene-Butadiene-Styrene bitumen modifier. Eleventh International Conference on the Bearing Capacity of Roads, Railways and Airfields, Volume 1, 96–107. https://doi.org/10.1201/9781003222880-10
3. Riekstins, A., Baumanis, J., Krastins K., Kalinka K. (2021). Assessment of Surface Characteristics of Coarse Aggregates by Flow Coefficient Method. *Baltic Road Conference 2021.*
4. Riekstins, A., Baumanis, J., & Barbars, J. (2021). Laboratory investigation of crumb rubber in dense graded asphalt by wet and dry processes. Construction and Building Materials, 292, 123459. https://doi.org/10.1016/j.conbuildmat.2021.123459
5. Riekstins, A., Haritonovs, V., & Straupe, V. (2020). Life Cycle Cost Analysis and Life Cycle Assessment for Road Pavement Materials and Reconstruction Technologies. The Baltic Journal of Road and Bridge Engineering, 15(5), 118–135. https://doi.org/10.7250/bjrbe.2020-15.510
6. Riekstins, A., Haritonovs, V., & Balodis, A. (2019). Evaluation of adhesion between bitumen and aggregate with the digital image processing method. IOP Conference Series: Materials Science and Engineering, 660, 012047. https://doi.org/10.1088/1757-899x/660/1/012047
7. Riekstins, A., Haritonovs, V., Abolins, V., Straupe, V., & Tihonovs, J. (2019). Life cycle cost analysis of BBTM and traditional asphalt concretes in Latvia. *Engineering for Rural Development*. doi:10.22616/erdev2019.18.n400
8. Riekstins, A., Haritonovs, V. (2017). Research on Restoration and Reconstruction Technologies of Asphalt Concrete for Very Thin Layers. *Baltic Road Conference 2021.*

2. BACKGROUND

2.1. Sustainable development

Scientists and governments have widely debated sustainability issues for decades. The concept of sustainability was defined for the first time in 1987 in the United Nations (UN) Commission on Environment and Development report "Our Common Future". A simplified definition of sustainable development is a development that meets the needs of the present without compromising the needs of future generations. The definition states that we must sustainably take care of our planet, resources and people. Also, the condition of planet Earth in the future must be at least the same as we received it.

Based on the principles mentioned above, it is believed that sustainable development is based on three dimensions – environmental, economic and social. (see Fig. 2.1). The principles of sustainable development can differ significantly between different economic sectors. Despite that, it is clear that sustainable development principles can be introduced in all sectors. For doing this, it is crucial to be aware of the current situation and set short and long-term goals.

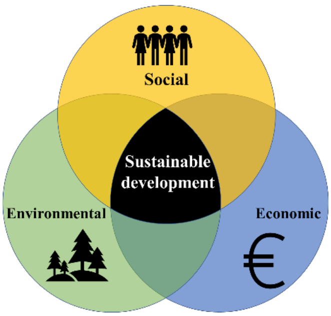

Fig. 2.1. Sustainable development dimensions.

The primary catalyst for implementing a sustainable development policy has been climate change. Since 1880, the global average sea level has risen by 50 cm and is predicted to rise by another 20–30 cm by 2050. Such an increase has significant implications for meteorological, climatic and hydrological processes.

Realising that the human impact on the environment is more significant than previously thought, in 1972, the first UN conference on international environmental issues was held. It marked a turning point in the development of international environmental policy. Several essential meetings and agreements followed, such as the Rio Earth Summit, the Kyoto Protocol, and the Paris Agreement.

Even though mitigating the impact on the environment and climate is the highest priority, economic opportunities and social factors must be included in the decision process. At the same time, maintaining the road network requires extensive financial and non-renewable resources from our planet. Thus, it is crucial to use the road budget as efficiently as possible, basing it on the principles of sustainable development. Balancing financial resources with environmental requirements and social needs is the main challenge of the field in the 21st century.

Despite the size and importance of the road industry, there is currently no standard that defines how to assess the sustainability of technologies, materials and/or maintenance strategies. It is known that work on such a standard for sustainability of construction works is currently underway – EN 17472, which includes sustainability assessment of civil engineering works and calculation methods.

2.2. Sustainable development assessment techniques

Implementation of sustainable development principles in real life requires an understanding of the basics of how different materials, technologies and/or strategies can be compared. One of the techniques, which is also the basis of the method developed by the author, is the life cycle techniques, which are described in more detail in the following subsections.

2.2.1 LIFE CYCLE ASSESSMENT (LCA)

LCA is an environmental impact assessment technique that quantitatively analyses the impact of a given system throughout its planned life cycle. Ideally, including all processes related to the product from the "cradle" of material extraction to the "grave" or end of life. The calculation can be performed only for some life cycle stages if it does not conflict with the aim and the defined system boundaries. For LCA, scientists and practitioners mainly refer to the International Organization for Standardization (ISO) Standard 14040:2006.

The standard mentioned is general and can be applied in any field. It does not describe in detail the techniques for performing LCA, nor does it specify the methodology for performing different types of LCA. In road construction, the document Pavement Life Cycle Assessment Framework developed in the United States (USA) is widely used to perform LCA. The report extensively describes the application of LCA in a road assessment, which was taken as the basis for fulfilling the aim of the Doctoral Thesis.

2.2.2 LIFE CYCLE COST ANALYSIS (LCCA)

LCCA is an analysis with which it is possible to estimate the total economic value of a project scenario and its alternatives (optionally) by analysing initial costs and discounted future costs, such as road maintenance, user, reconstruction, or rehabilitation costs throughout the life of the project. The analysis can be performed both at the project level and at the road network level. The calculation helps to compare the initial and future investment of different competing materials, technologies and/or reconstruction strategies over the planned calculation period. With LCCA, it is possible to compare the costs of the road owner (manager) and the road user for the planned project.

No international standard has been developed and approved for LCCA analysis. However, since the 1970s, LCCA principles have been incorporated into various projects in the USA. The principles of LCCA analysis are widely described in several documents issued by the Federal

Highway Administration of the US Department of Transportation, which were also taken as the basis for fulfilling the aim of the Doctoral Thesis.

2.2.3 SOCIAL LIFE CYCLE ASSESSMENT (SLCA)

SLCA is an analysis with which it is possible to assess the social impact of a project and compare it with other planned project alternatives. SLCA is a relatively new concept, so no standard has been developed nor is any methodology widely used. Therefore, this life cycle technique, in general, and specifically for the road sector, has a long way to go. It is known that work on developing the standard is currently underway. However, as of now, there are no specific guidelines for performing SLCA. Therefore, it was not further explored in this study. Unlike LCA and LCCA, the results of the SLCA may not be easily compared. Some social factors are subjective, so their inclusion should be evaluated. Some of the most well-known social factors are ride quality, safety, and frequency of reconstructions.

2.3. Challenges of sustainable development assessment

2.3.1 TOOLS

Various tools and programs are available to calculate a road pavement's environmental impact and/or costs. However, no universal tool or program covers environmental and economic dimensions for the entire pavement life cycle. The best-known tool/program for this feature is PaLATE 2.0 and its subsequent versions. Researchers and practitioners have appreciated that various tools can produce significantly different results, and such differences are strongly characteristic of LCA tools. In addition, these tools may have different system boundaries, assumptions, and material flows. Therefore, using only one tool when performing analyses and comparisons is recommended. When the selected tool covers only part of the required information, careful consideration should be given to ensure that the flows of materials among the tools are identical.

2.3.2 DATA QUALITY

When performing LCA, the commonly used tools already include the environmental impacts of materials and processes. Some commercial tools even allow a choice between databases to select the most relevant data for your region. With the use of commercial tools, the most significant benefit is the higher reliability of the data, as well as the fact that data are frequently updated and complemented. The sources of LCA data are databases (the most famous being EcoInvent or GaBi), literature, environmental product declarations (EPD) or self-obtained data. Although environmental data have regional specificity, they can mostly be adapted to the regions for which such data are unavailable.

The cost data has a significant regional specificity, which can be affected by inflation, geopolitical events, supply and demand, supply chains and other factors. Therefore, comparing

LCCA results even within a single country can be challenging. Cost data must be updated yearly, in some cases even more often.

2.3.3 DEFINING SYSTEM BOUNDARIES

Depending on the aim of the research or the tool used (environmental and/or economic), it is essential to determine the proper boundaries or scope of the analyses. When comparing, for example, a rigid pavement with a flexible pavement, the scope of the analysis must include the raw materials acquisition stage. Otherwise, the results are likely to be incorrect.

Some tools only include specific pavement life cycle stages. In the LCCA the final price accurately reflects the cost of the material or technology, thus simplifying the task. It is not like that in LCA, where each life cycle's stages have a separate impact.

2.3.4 DETERMINATION OF ASSUMPTIONS

Making incorrect assumptions to simplify calculations or not recording them is one of the most typical mistakes in LCA and LCCA calculations. Making assumptions is a critical prerequisite for obtaining a correct result and can significantly facilitate and simplify the analysis. Therefore, evaluating whether the specific assumption substantially affects the final result is essential. Also, all assumptions must be indicated to make the calculation traceable and understandable to everyone.

2.3.5 PREDICTION OF SERVICE LIFE

Lifetime prediction of materials, technologies and/or strategies is a massive challenge for any life cycle analysis. For example, the difference in sustainability for a wearing course that will be replaced after 10 or 11 years is 10 %. Traditionally, service life prediction is based on historical data or expert opinions on the technologies used. It should be noted that longevity can be affected by many factors, and such predictions may differ significantly. In addition, with the development of innovations (materials and technologies), making such predictions based on experience is no longer possible. Therefore, service life prediction is the biggest challenge for sustainability assessment.

3. AVAILABLE LCA AND LCCA TOOLS

Various tools are available nowadays to calculate a road pavement's environmental impact or cost. These tools can be divided into several essential categories: (1) designed for environmental and/or cost calculations; (2) cross-sectoral or specific to the road sector; and (3) commercial or free of charge (see Fig. 3.1). The PAVE/LCA/LCCA tool developed by the author is also included in the tool comparison.

The best known LCA tools are SimaPro, GaBi, DubuCalc, and ECORCE M. The best known LCCA tools are RONET and Real Cost analyses 2.5. Currently, only PaLATE-2.0 can be considered as a tool for both environmental and cost calculation.

An important classification of tools is by the fact whether they are specifically for the road industry or cross-sectoral. Those intended for the road industry already have a customised interface to make an analysis. They are also relatively easy to learn. LCCA tools can be distinguished into two categories – calculation of road owner costs and calculation of road user costs. LCA and LCCA tools developed specifically for the road industry are DuboCalc, ECORCE M, RONET, Real Cost analyses 2.5, PaLATE-2.0, and PAVE/LCA/LCCA. The most significant advantage of these tools is their simplicity, allowing the rapid creation of the model needed for analysis. LCA tools SimaPro and GaBi have a wide range of applications. With these tools, it is possible to perform both types of LCA – attributional and consequential. With the SimaPro and GaBi, unlike other no-charge LCA tools, it is possible to perform a more detailed LCA because they have significantly larger databases of environmental indicators for various solid wastes or by-products. Also, the extensive and regularly updated data in the databases gives confidence in the accuracy of the results.

The third category is tools that are commercial or free of charge. Of the tools reviewed, only for some LCA, it is necessary to pay a fee, and the main reason for that is valuable databases.

Considering that the materials and processes of LCA and LCCA partly overlap, there are several advantages of including both analyses in one tool: (1) potentially less time needed to create the calculation approach; (2) information is in one place; (3) more transparent impact assessment. Based on these considerations and the fact that there is currently no tool available in the industry that combines LCA and LCCA with the possibility of developing a desirable reconstruction and maintenance strategy, it was decided to develop one. Also, to make it freely available for use and for additions by other researchers and practitioners.

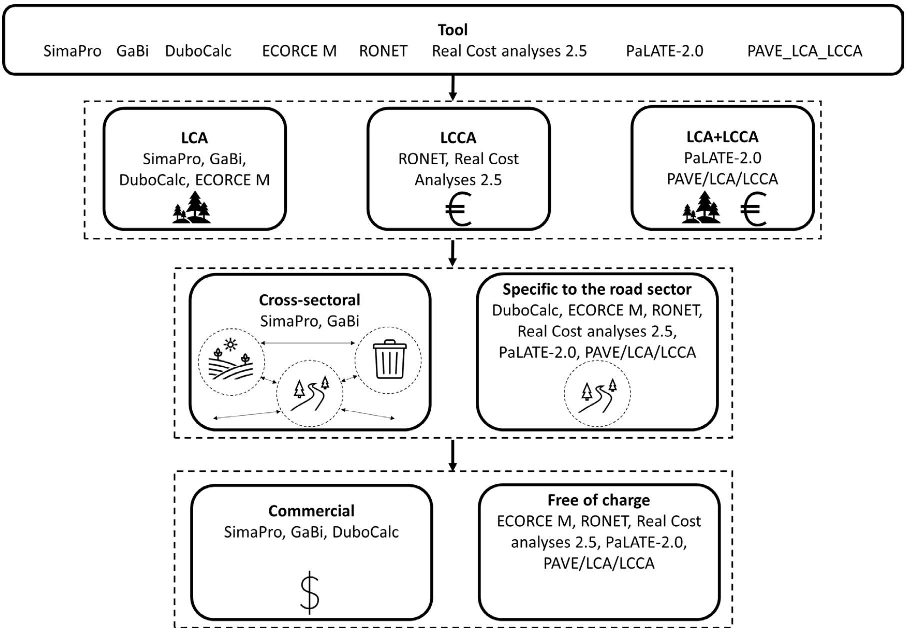

Fig. 3.1. Classification of tools for the assessment of sustainability parameters.

4. DEVELOPMENT OF A METHODOLOGY FOR ASSESSING THE SUSTAINABILITY OF ROAD CONSTRUCTION MATERIALS, TECHNOLOGIES AND STRATEGIES

4.1. Sustainability assessment

In accordance with the aim of the study, a framework for evaluating project scenarios was developed using life cycle techniques (see Fig. 4.1). This framework can be used for full-depth reconstruction projects and for simplified preventive maintenance approaches. The methodology for determining a sustainable road design and rehabilitation strategy can be divided into four steps: (1) pavement design, development of various scenarios if necessary; (2) assessment of sustainability parameters using life cycle techniques LCA, LCCA, SLCA; (3) results processing, and rating creation; (4) evaluation and optimization of results The method is described in the following subsections.

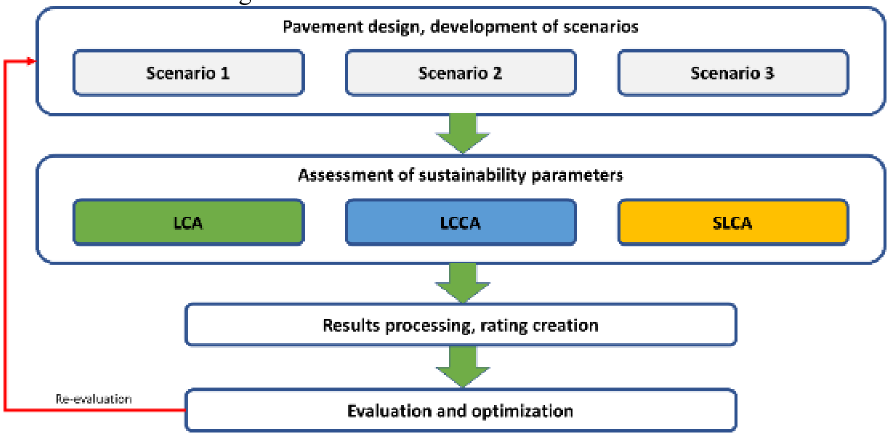

Fig. 4.1. The framework of sustainability assessment of project scenarios.

4.1.1 PAVEMENT DESIGN, DEVELOPMENT OF SCENARIOS

The primary purpose of this step is to develop potentially several (at least one) scenarios or approaches. It is possible to start the pavement design immediately after receiving the necessary data (in the case of full-depth reconstruction objects). The data are essential to design an appropriate road pavement for future traffic intensity. The following data have a high impact on the decision-making: the soil composition, the level of groundwater, the properties of the materials in the road pavement, the homogeneity of the road pavement, and the bearing capacity. Building materials and technologies could impact the thickness of the pavement. In cases where the foundation layers of the road pavement already have good properties, they can be left untouched and included in the development of the pavement design.

The road section proposed for reconstruction can be heterogeneous along its entire length (pavement condition, thickness of structural layers, soil, etc.). Different methods (full-depth reconstruction, recycling, etc. solutions) or layer thickness could be needed to be used. In such cases, the road needs to be divided into sections (see Fig. 4.2). However, the recommendation is to avoid creating an excessive number of sections, which can significantly complicate the calculation and the process of evaluating the most sustainable scenario.

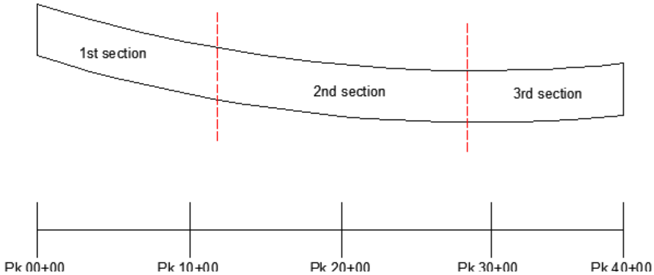

Fig. 4.2. Illustrative division of a road project into sections that use the same type of materials, thickness of structural layers, and/or construction technologies.

Regardless of the chosen reconstruction method – full-depth reconstruction or reinforcement of the old pavement, the designed road pavement must meet the requirements of the used design methodology for the predicted traffic intensity and composition. The design methodology may not support the inclusion of non-traditional or innovative materials or technologies in the calculation. In such cases, the inclusion of materials or technologies in the pavement design is recommended by adapting them to existing materials. Testing of materials in the laboratory is also practical, thus obtaining information about the performance-based properties of the material. Laboratory results are essential to justify that the material/technology is equivalent or better/worse than those traditionally used for inclusion in the calculation.

When creating alternative pavement designs, it is essential to compare them properly. In Fig. 4.3, you can see two potentially similar designs based on the author's methodology: a) full-depth reconstruction of the road pavement and b) reinforcement of an old pavement. The designs were made according to the "Latvian State Roads" mechanistic-empirical pavement design methodology. Both constructions are considered equivalent, and the modulus of elasticity of the pavement is within the 1 % range in both pavements.

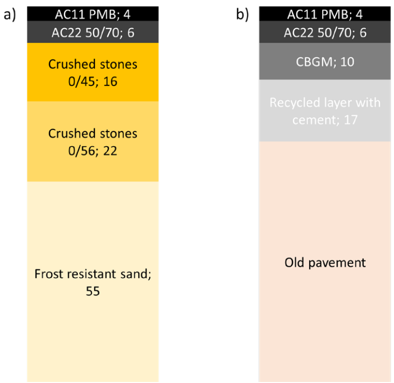

Fig. 4.3. a) Full-depth reconstruction of the road pavement; b) partial recycling of an old pavement.

The evaluation of the sustainability of the scenario can be divided into two parts – the initial construction and the reconstruction and maintenance during the use phase. The analyst must select the most suitable length of the analysis period according to the planned reconstruction and maintenance plan. The analysis period should be long enough so that the differences between the alternatives can be correctly assessed. The recommended length of the analysis period is 30 to 50 years for high-intensity roads, 20 to 30 years for medium-intensity roads with an asphalt surface, and 10 to 20 years for gravel roads. In the case of preventive maintenance technologies (chip seal, microsurfacing, fog seal, etc.), the life cycle length should be based on the experience of the methods used.

According to the length of the analysis period, a detailed reconstruction and maintenance strategy is developed for each scenario. Reconstruction and maintenance strategy should include activities such as a warranty period, daily maintenance, rehabilitation, or other work impacting the environment, costs or social factors. The strategy developed should be realistic, based on historical data on the service life of various technologies or materials, data available in the literature, laboratory performance testing results, expert opinions, or combinations of the above. When using data from the experience of other countries, it should be carefully evaluated whether they are comparable to locally used technologies, materials, climatic conditions, and geology. Service life prediction has a high impact on sustainability results.

A visualized example of the simplified calendar plan from the initial construction of the pavement to the end of the service life is shown in Fig. 4.4. After the construction of the initial structure, a warranty period follows depending on the scale of work performed. During this time, the contractor will repair all defects at his own expense. After the end of the warranty period, the daily maintenance phase begins in which, at the cost of the road owner, cracks and potholes are repaired. After a certain period, the pavement needs reconstruction, for example, the replacement of the wearing course, which involves milling of the old layer and laying a new one. After the damaged part of the pavement is reconstructed, the warranty period and daily maintenance follow. At the end of it, it is assumed that the end of the road's service life is reached.

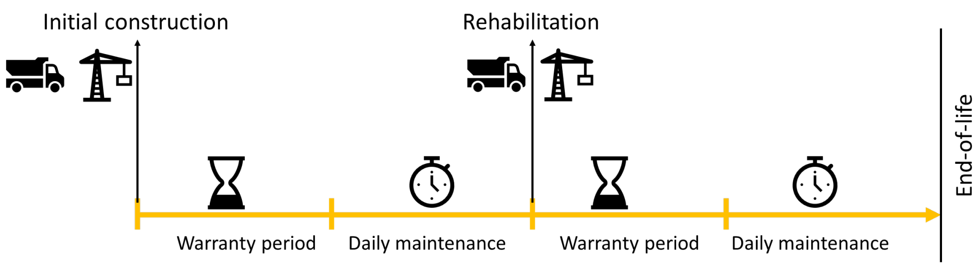

Fig. 4.4. Visualization of the simplified calendar plan.

4.1.2 ASSESSMENT OF SUSTAINABILITY PARAMETERS

After developing scenarios for the entire analysis period, it moves to the next step, which is the assessment of sustainability parameters using life cycle techniques. Environmental, economic, and social factors are considered as the dimensions of sustainability. Choosing a suitable analysis makes it possible to evaluate each dimension. This can be done using a self-developed calculation or tool or an already free or commercially available program. The analyst chooses the most suitable solution depending on the aim of the analysis and the scope of calculation. While developing your own calculation, ensure that the scope of the research is appropriate and will allow you to reach its aim, the quality of the data is high, and the assumptions made are valid. As mentioned in Chapter 3, there is currently no tool that could evaluate sustainability in road construction from all three dimensions – environmental, economic, and social. Certain tools such as PaLATE 2.0 and PAVE/LCA/LCCA (a tool developed by the author) assess some of the quantities influencing sustainability – environmental and economic factors.

As already mentioned, there is no standard or approved methodology for SLCA, and this life cycle technique is still under development to be adapted for road construction. Currently, LCA and LCCA are mainly used to assess sustainability parameters. Environmental and economic dimensions also indirectly affect social factors and vice versa, already giving useful information about the overall sustainability of the scenario.

4.1.3 RESULTS PROCESSING, RATING CREATION

The results obtained from the inventory analysis are processed and grouped. The result processing is different if deterministic and/or probabilistic analysis are used. Only those indicators that correspond to the aim are further used. Results are assigned to selected impact categories. For example, the results of the LCA inventory analysis can be divided into impact categories such as climate change, eutrophication, resource depletion, ozone depletion, etc. The results of the LCCA inventory can be divided, for example, into road owner costs and road user costs. In the case of SLCA, categories such as safety, driving comfort, stochastically stabilized flow, etc. can be used.

The "weight" or influence of each category is decisive in decision-making. It can be based, for example, on survey results, in which experts, engineers, and/or other groups have to answer specific questions, including the importance of categories.

4.1.4 EVALUATION AND OPTIMIZATION

After creating the rating, conclusions are made about the sustainability analysis results and whether the potentially most sustainable solution agrees with the aim of the analysis or other conditions. If this is not the case, then the analyst should return to Step 1 – pavement design and development of scenarios. Therefore, the development and search for the most sustainable scenario must start again.

5. TOOL PAVE/LCA/LCCA

The PAVE/LCA/LCCA tool was developed to conduct a sustainability assessment of different materials, technologies and/or strategies according to the described methodology in the previous chapter. With it, it is possible to evaluate environmental (CO_2 eq., consumed energy) and economic (road owner costs) parameters for a designed scenario. More about it can be found in the full text of the Thesis. The tool was developed in MS Office Excel and supplemented with a written Visual Basic script. The tool was created to be applied to a road of reconstruction and preventive maintenance technologies. The developed tool was given the name PAVE/LCA/LCCA. The name of the tool contains information about the purpose and application. PAVE is an abbreviation for PAVEMENT. LCA and LCCA mean that environmental and economic analysis can be performed with it. The tool is developed in English.

For a limited period, PAVE/LCA/LCCA is available here.

The potential application of the developed tool is for scientific purposes and for the road owner's decision-making process to perform a sustainability analysis (see. Fig. 5.1). PAVE/LCA/LCCA is not protected, therefore, if necessary, the person who performs the calculation can make adjustments, supplement the materials section, change equipment productivity, fuel consumption, etc. Thus, it is possible to further develop and improve the tool.

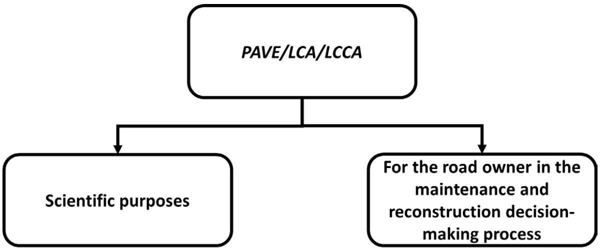

Fig. 5.1. Potential application of PAVE/LCA/LCCA.

Without performing additional calculations, the PAVE/LCA/LCCA tool is capable of the following impact assessments:

- impact of transportation distance;
- impact of recycled asphalt (RA) and recycled asphalt pavement (RAP) content;
- impact of bitumen, cement, and fly ash content;
- impact of local and imported materials;
- impact of pavement layer thickness, asphalt type, maintenance strategy;
- impact of a discount rate on life cycle costs;
- impact of the type of fuel used;
- impact of technical units (productivity, fuel consumption).

To evaluate the environmental and cost impact of specific, for example, rubber-modified asphalt, additional calculations must be made.

6. VALIDATION OF THE PAVE/LCA/LCCA

To make sure that the PAVE/LCA/LCCA calculation tool and the data entered into it give reliable LCA and LCCA values, three tasks were set: (1) compare the greenhouse gas (GHG) and energy consumption of the asphalt overlay from Scenario A (see Chapter 7) with values mentioned in literature sources; (2) compare GHG and energy consumption for the entire life cycle from Scenario A (see Chapter 7) with the tool ECORCE M; and (3) compare the costs of layers of road pavement from Scenarios A and B (see Chapter 7) with the LVC road construction price catalogue. More on validation can be found in the following subsections; see the full version of the Thesis for more detailed information.

6.1. Validation of GHG values for asphalt-wearing course

The GHG values obtained in Scenario A were compared with values mentioned in the literature (see Table 6.1). The results show that, on average, the GHG emission value obtained in this analysis per 1 ton of wearing course material AC11 is comparable to the results of other studies. With researchers Rathore and Hammond, and Jones, values are very close and differ within a range of 0.5–1.1 %. In contrast, compared to Giani and Miliutenko, 63.7 is up to 13 % higher. Nevertheless, it can be considered that the overall GHG value obtained is very close to the values calculated by other researchers.

Table 6.1

Comparison of GHG per ton of asphalt with PAVE/LCA/LCCA and information in literature

	PAVE/LCA/LCCA	Rathore	Giani	Miliutenko	Hammond and Jones
GHG, kg CO_2 eq per ton	63.7	63.0	52.0–60.2	57.0	64.0

6.2. Validation of GHG and energy values for Scenario A using ECORCE M

The GHG values obtained in Scenario A were compared with the ECORCE M values (see Table 6.2). The ECORCE M tool was chosen because it has been developed in Europe (France) and is free of charge.

The entire life cycle of Scenario A from initial construction to the end of life, was compared. The functional units as described in Chapter 7.1.

Overall, the results show a high difference between GHG emissions, which for the particular example is 45.6 %. At the same time, the difference between the values of consumed energy is significantly smaller and is just 12.0 %.

After a more detailed analysis of the results, it can be seen that the most significant GHG differences between tools are shown in the aggregate positions (sand, crushed stones). For example, in the sand material position in the ECORCE M, the total CO_2 eq. is 27.4 t, while in the PAVE/LCA/LCCA, this amount is several times higher – 128.9 t. The same is true for other mineral material types. In contrast, the results of the other categories (deconstruction, construction, transportation, asphalt production and bitumen) show only a 3.2 % difference. In this study, several sources were used to ensure that obtained data were precise. Therefore, the values used in the ECORCE M database for mineral materials may be too low, which is the main reason for such a difference.

Table 6.2

Comparison of GHG and energy of pavement with PAVE/LCCA/LCA and ECORCE M

	PAVE/LCA/LLCA	ECORCE M	Difference, %
GHG, t	982.7	675.0	45.6
Energy, MJ	10759748	9607000	12.0

The results are positive because they confirm that the LCA values obtained with PAVE/LCA/LCCA are similar, although they differ from the ECORCE-M. *Santos* has already emphasized that it is recommended to use only one tool to calculate the environmental impacts between various alternatives, otherwise, the conclusions can be misleading.

6.3. Validation of costs for road pavement layers

The costs of the road pavement layers of Scenarios A and B were compared with those obtained using the PAVE/LCA/LCCA tool and those mentioned in the recent LVC construction price catalogue. The costs in this catalogue are based on actual contracts concluded in the given year. The comparison can be seen in Table 6.3.

The results show that in all layers, the costs obtained with the PAVE/LCA/LCCA are lower than those mentioned in the SLLC "Latvian State Roads" price catalogue. The difference is in the range of 2.7 % to 20.4 %.

The costs may be affected by competition and the availability of materials in a particular region, which cannot always be accurately estimated. The results obtained are satisfactory, considering that the profit section is not evaluated in the analysis. Therefore, from the standpoint of cost validation, it can be argued that the planned LCCA results will have a high degree of confidence for drawing conclusions.

Table 6.3

Comparison of costs obtained by PAVE/LCA/LCCA and in LVC price catalogue.

Layer	PAVE/LCA/LCCA	LVC price catalogue 2022	Difference, %
Wearing course, €/t	86.6	105.1	–17.6
Base course, €/t	63.2	79.4	–20.4
Crushed stone base 0/45 mm, €/t	14.4	14.8	–2.7
CBGM (cement bound granular mixture), €/t	20.8	21.8	–4.6
Recycled pavement, €/t	3	3.6*	–16.7
Frost-resistant material, €/t	11.8	10.7	–10.3

* interpolated 2021 price.

7. ASSESSMENT OF THE SUSTAINABILITY OF MATERIALS AND TECHNOLOGIES USING THE DEVELOPED METHODOLOGY AND TOOL

To verify the operation of the methodology and the tool, economic and environmental parameters were evaluated for the following materials and technologies within the framework of the Doctoral Thesis:

- BBTM wearing course;
- EOC bitumen modifier;
- crumb rubber modified asphalt by wet process-high viscosity;
- red mud as a bitumen modifier;
- fly ash for road base stabilization;
- full-depth reconstruction and recycling of an old pavement.

7.1. Methodology

A flow chart with the steps planned can be seen in Fig. 7.1. First, the aim and the scope of the analysis were defined. According to the aim and scope of the analysis, seven scenarios were developed, which were marked: A, B, C, D, E, F, and G. A and B are reference scenarios which will be compared with the results obtained in other scenarios. Among all scenarios, three different pavement designs are possible (No. 1, No. 2, and No. 3). After defining the constructive layers of the scenarios, reconstruction and maintenance strategies were developed. At first, input data were collected. After that, with the PAVE/LCA/LCCA tool, LCA, and LCCA analyses were performed, supplemented by individual calculations for the inclusion of specific processes in the final output. After obtaining the results, their processing, rating creation, evaluation and optimization are planned.

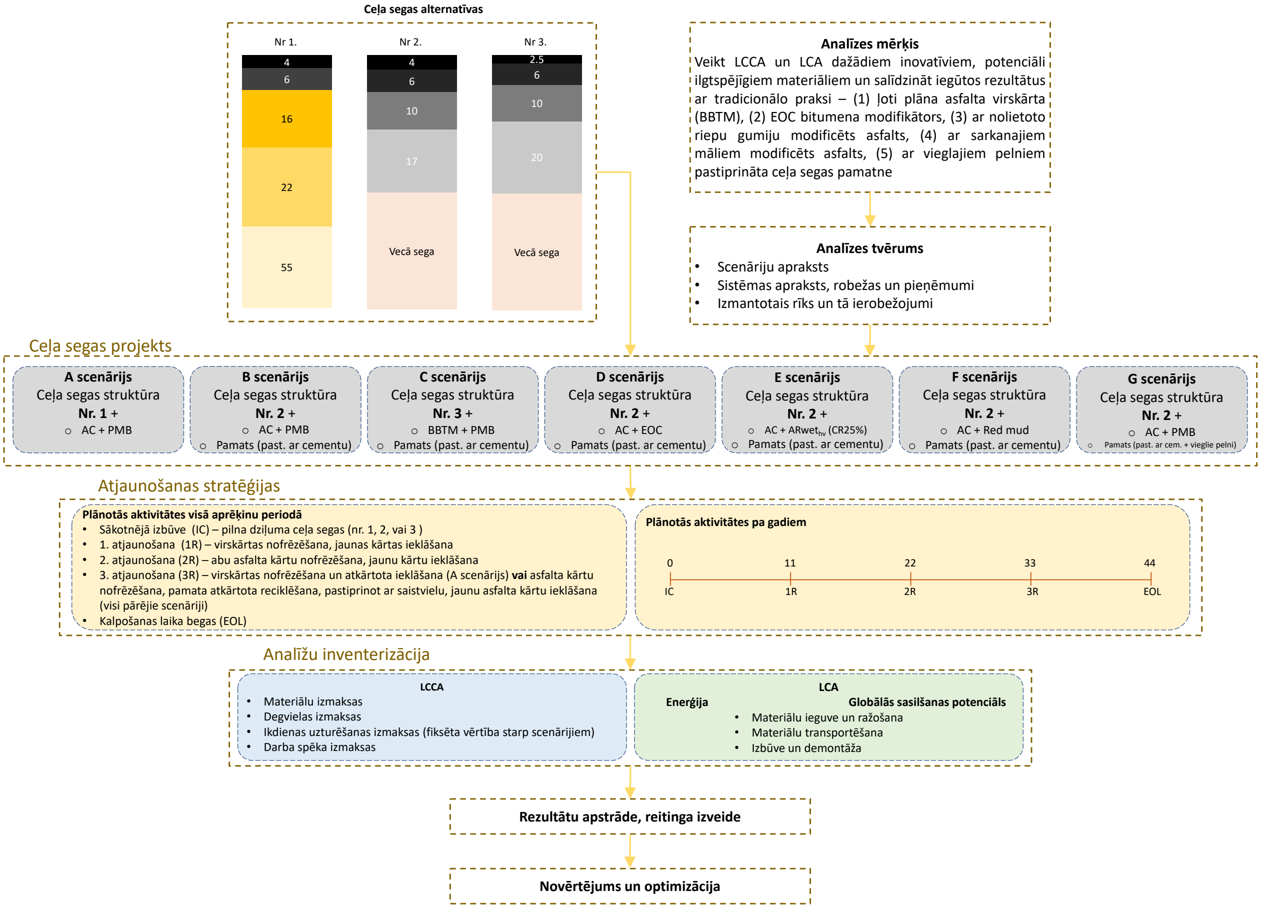

Fig. 7.1. Flowchart of the analysis.

7.1.1 AIM OF THE ANALYSIS

The aim of the analysis is to evaluate the environmental and economic parameters of various currently rarely used or innovative materials for road construction and compare them with traditional practice using the self-developed methodology and tool PAVE/LCA/LCCA. The analysed materials/technologies were (1) very thin asphalt concrete (BBTM), (2) EOC bitumen modifier, (3) crumb rubber modified asphalt, (4) red mud modified asphalt, (5) fly ash recycled road base.

7.1.2 SCOPE OF THE ANALYSIS

To perform the calculation, the system used, its boundaries and the most critical assumptions were defined. All processes are considered according to the tool PAVE/LCA/LCCA, about which more information can be found in Chapter 5. The impact assessment indicators in this study are:

- costs, €;
- GHG, t;
- energy consumption, MJ;
- quantities, t.

7.1.2.1 FUNCTIONAL UNIT

The functional unit for this study is a 1 km long, two-way (single lane in each direction) road, with the road width 7.5 m. Shoulders are not taken into the calculation. The analysis period consists of 4 cycles (starting from initial construction). The load-bearing capacity of the various pavements is as close as possible, so design structures can be assumed to be equivalent. Existing and predicted traffic volumes are constant in all scenarios.

7.1.2.2 SYSTEM DESCRIPTION

According to the calculation tool's capabilities, the limits of the calculation system were determined. The analysis was carried out according to the cradle-to-cradle approach. This means that the environmental impact is counted starting from acquiring materials (oil and mineral materials in quarries) to reusing materials. For reused materials, only deconstruction and transport are included, if necessary.

The road pavement life cycle consists of several stages. Various classifications exist, but this study used a four-stage road pavement life cycle approach. The breakdown of these stages can be seen in Table 7.1

Table 7.1

The stages, activities and processes of a pavement life cycle that were included in the analysis

Stage of the pavement life cycle	The processes that were evaluated at each of the pavement life cycle stages
Stage 1: Raw material acquisition, extraction, and production	Indicators which were included: costs, energy, CO_2 eq, material quantities. *LCA:* Includes energy demand and CO_2 eq, which are produced to obtain raw materials. Transportation of materials from a deconstructed site to an asphalt plant. Transportation of raw materials to an asphalt plant and an emulsion production plant. Production of asphalt, emulsion, and cement. *LCCA:* Prices of materials, total costs, labour costs, fuel costs.
Stage 2: Construction	Indicators which were included: costs, energy, CO_2 eq, material quantities. *LCA:* Transportation of raw materials from quarries to the site. Transportation of materials from plants to the site. Construction processes, emulsion spraying, laying, compaction, etc. Deconstruction processes, milling, excavation. Old material transportation to stockpiles. *LCCA:* Prices of materials, total costs, labour costs, fuel costs.
Stage 3: Use	Indicators which were included: costs, energy, CO_2 eq, material quantities. Includes all *Environmental* and *Economic* processes from Stage 1 – the raw material acquisition, extraction, and production, and Stage 2 – construction process. In addition, constant maintenance costs are assessed after the end of the warranty period until the next reconstruction of the road (repair of cracks and potholes).
Stage 4: End-of-life	Indicators which were counted – quantities.

7.1.3 PAVEMENT SCENARIOS

In accordance with the aim, seven different road pavement structures were designed (see visualization Fig. 7.2). Pavements were designed according to the "Latvian State Roads" mechanistic-empirical pavement design methodology. Scenario A is a full-depth road pavement construction in which the existing pavement is fully deconstructed and replaced by a new one. Scenario A consists of the following layers: a frost-resistant layer with a thickness of 55 cm; a sub-base layer with a thickness of 22 cm; a top-base layer with a thickness of 16 cm; a bituminous base layer AC22 with a thickness of 6 cm; and bituminous upper layer AC11 with a thickness of 4 cm. For AC11, a styrene-butadiene-styrene (SBS) bitumen modifier is used. The designed pavement is 103 cm thick. The construction of such a pavement does not pose substantial service life risks if design and construction are properly done. Nevertheless, this technology requires a large amount of new materials to be quarried, transported, and built.
On the other hand, in Scenarios B, C, D, E, F, and G, an old pavement is used and reinforced. The following layers are designed for those scenarios: a recycled old pavement layer with a thickness of 17 cm (for Scenario C – 20 cm); a cement bound granular mixture (CBGM) layer with a thickness of 10 cm; bituminous base layer AC22 with a thickness of 6 cm; and a

bituminous upper layer with the thickness of 4 cm (for Scenario C – 2.5 cm). Dolomite is expected to be used in all newly constructed layers in all scenarios. The chosen road reconstruction technology is the only difference between Scenarios A and B. Scenarios A and B are reference scenarios, and the other scenarios in the study are compared to them.

For Scenario C, a BBTM wearing course was used, therefore, a slightly different pavement structure was obtained. The wearing course thickness for Scenario C is 2.5 cm, which is 32.5 % thinner than for Scenarios B, C, D, E, F, and G. It was compensated by a 17.6 % thicker recycled pavement layer.

In Scenarios D, E, and F, the asphalt-wearing courses differ by the bitumen modifier used. In Scenario D bitumen modifier EOC is used. The added content of the EOC modifier is 4 % of the total binder mass. The same content has the SBS modifier in scenarios A, B, D, F, and G. For Scenario E, crumb rubber modified asphalt wearing course ($ARwet_{hv}$) is used. The content of the added crumb rubber (rubber from end-of-life tyres) is 15 % of the total binder weight. In Scenario F, a combination of SBS and red mud (RM) is used. The content of the red mud added is 7 % of the total binder weight (bitumen and SBS).

In Scenario G, unlike the others, a cement and fly ash combination is used for base reinforcement. In this analysis, the use of fly ash reduces the quantity of cement by 50 %. Fly ash is not as efficient a binder as cement, therefore, it must be used in larger quantities to achieve a similar result.

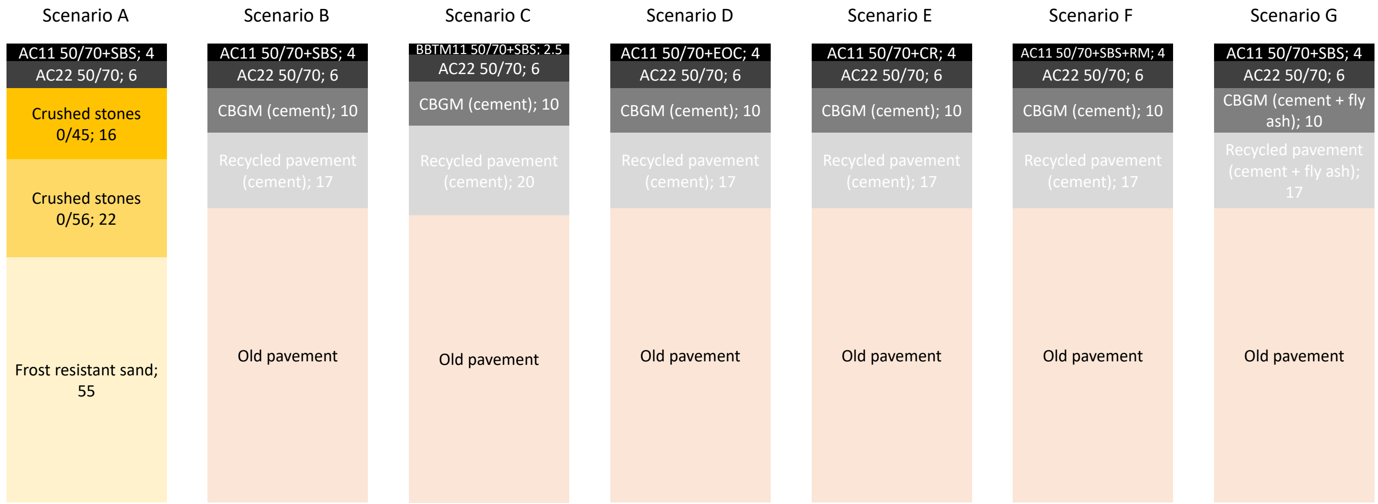

Fig. 7.2. Comparison of planned pavement constructions.

Road bitumen 50/70 is used for the wearing courses in all scenarios. No reliable data is available from polymer-modified bitumen producers on the presence of polymers and the impact of the modification process on the environment and energy consumption. Therefore, the modification of bitumen (with SBS, EOC, crumb rubber, red mud) is done by the contractor next to the asphalt plant. With this approach, it is possible to compare differences equally.

The total binder content (including modifier) for AC asphalt type is 5.2 %, for BBTM asphalt type 5.0 %, and for $ARwet_{hv}$ asphalt type 6.2 %. In the case of $ARwet_{hv}$, it should be noted that the actual content of neat bitumen is 5.27 %.

A warm mix asphalt (WMA) additive is added to the $ARwet_{hv}$ binder to reduce the asphalt manufacturing temperature by 20 °C. Thus, the manufacturing temperature of the wearing courses is the same in all scenarios – 160 °C.

The bituminous base layer used in all scenarios is identical. The type of bitumen used in it is 50/70, the binder content is 3.8 %, and the asphalt mixture production temperature is 160 °C. All mixtures were assumed to have the same volumetric properties.

7.1.4 RECONSTRUCTION AND MAINTENANCE PLANS

A detailed reconstruction and maintenance plan was developed for all scenarios (see Fig. 7.3). For Scenario A, the first reconstruction and maintenance strategy was adopted (column 4), while for other scenarios (B, C, D, E, F, G), the second strategy was adopted (column 5).

Year	Reconstruction plan	Acronym of mayor construction	Scenario A	Scenarios B, C, D, E , F, G
0	2023	IC	Initial construction	Initial construction
1	2024		Warranty	Warranty
2	2025		Warranty	Warranty
3	2026		Warranty	Warranty
4	2027		Warranty	Warranty
5	2028		Warranty	Warranty
6	2029		Maintenance	Maintenance
7	2030		Maintenance	Maintenance
8	2031		Maintenance	Maintenance
9	2032		Maintenance	Maintenance
10	2033		Maintenance	Maintenance
11	2034	1R	Surface Relaying (SR)	Surface Relaying (SR)
12	2035		Warranty	Warranty
13	2036		Warranty	Warranty
14	2037		Warranty	Warranty
15	2038		Maintenance	Maintenance
16	2039		Maintenance	Maintenance
17	2040		Maintenance	Maintenance
18	2041		Maintenance	Maintenance
19	2042		Maintenance	Maintenance
20	2043		Maintenance	Maintenance
21	2044		Maintenance	Maintenance
22	2045	2R	Surface-Binder- Relaying (SBR)	Surface-Binder- Relaying (SBR)
23	2046		Warranty	Warranty
24	2047		Warranty	Warranty
25	2048		Warranty	Warranty
26	2049		Maintenance	Maintenance
27	2050		Maintenance	Maintenance
28	2051		Maintenance	Maintenance
29	2052		Maintenance	Maintenance
30	2053		Maintenance	Maintenance
31	2054		Maintenance	Maintenance
32	2055		Maintenance	Maintenance
33	2056	3R	Surface Relaying (SR)	Recyling (R) and laying of asphalt courses
34	2057		Warranty	Warranty
35	2058		Warranty	Warranty
36	2059		Warranty	Warranty
37	2060		Maintenance	Warranty
38	2061		Maintenance	Warranty
39	2062		Maintenance	Maintenance
40	2063		Maintenance	Maintenance
41	2064		Maintenance	Maintenance
42	2065		Maintenance	Maintenance
43	2066		Maintenance	Maintenance
44	2067	EOL	-	-

Fig. 7.3. Reconstruction and maintenance plans for scenarios (excerpt from the PAVE/LCA/LCCA).

For the purpose of the analysis, it was assumed that the service life of the asphalt layers is identical in all scenarios. The reason for this approach is the lack of reliable data on the service life of the materials and technologies selected. Such an approach makes it possible to evaluate the basic impacts equally without favouring one of the materials or technologies. The average service life for one cycle in all scenarios is assumed to be 11 years. Such length of the cycle was determined in consultation with the road construction experts at LVC and Riga Technical University. All reconstructions are assumed to take exactly one year to simplify the calculation. The analysis period begins with the construction of the initial structure in 2023. The warranty is five years in the case of major reconstruction and three years in the case of replacing the asphalt layer(s).

7.1.5 FACTORS AND PROCESSES NOT INCLUDED IN THE ANALYSIS

Factors and processes that are not taken into account in this study:

- manufacturing and maintenance of equipment, production plants, offices, etc.;
- horizontal and vertical road signs, barriers, traffic lights, etc.;
- transportation of labour and equipment to and from the construction site;
- administrative costs of the road network manager and contractor and their impact on the environment;
- salaries of employees not directly related to the construction process;
- waste, by-products that are resulting from the extraction of raw materials, production of materials;
- rRoad user costs.

7.1.6 ASSUMPTIONS

The following assumptions were made for this analysis:

- There is no quality difference between different scenarios throughout the entire period of use.
- Manufacturing, laying, and compaction processes in scenarios do not differ.
- Rehabilitation takes one full year.
- Regardless of the pavement structure and the wearing course type, the annual average daily maintenance costs (crack filling, pothole patching) are identical for all types. Longer service life increases total routine maintenance costs.
- During the warranty period, the owner of the road does not invest in road maintenance.
- GWP and energy use that are made during the warranty period and daily maintenance period by crack filling and pothole patching are not taken into account.
- Asphalt plant productivity does not differ except for crumb rubber-modified asphalt.
- The bitumen modification plant is located next to the asphalt plant.
- The operator of the equipment does not influence its productivity.
- Fly ash as a material is for free, except the transportation process.
- The use of fly ash in the base of the pavement for reinforcement does not reduce its service life.
- Old pavement materials are for free as a material, except for recycling and/or the transportation process.
- Red mud is for free as a material, except for the transportation process.

7.2. Results and discussion

7.2.1 SUMMARY OF THE RESULTS OF THE DETERMINISTIC APPROACH

The summary of costs can be seen in Fig. 7.4. The LCCA results obtained show that Scenario A, for which full-depth reconstruction is planned, has significantly higher life cycle costs in the analysis period than other scenarios where old pavement reinforcement technology is used. The main reason is the higher costs in deconstruction and new materials positions. The cost increase for Scenario A compared to the second reference scenario B is 72.2 %. Such an increase is quite significant. At the same time, it should be noted that reinforcement of the old pavement does not guarantee that its service life will be equivalent to the service life of a completely new construction. Thus, the road owner must evaluate which technology applies to the chosen road, justifying the choice with calculations.

The second highest cost is for Scenario E due to higher bitumen modification costs, use of WMA, slightly higher bitumen content, and reduced plant efficiency. As a result, these components lead to a cost increase of 4.6 % over 44 years. From all the components mentioned above, the most significant cost increase comes from the reduction of asphalt plant efficiency. It is due to the higher binder viscosity, which makes it difficult for asphalt plants to transport it through the system and inject it into the mixing chamber. Potentially, this con may vary among asphalt plants. Nevertheless, it is possible to solve this con by making full or partial improvements to the asphalt plant equipment.

An increase in costs is also shown in Scenarios D and F. The increase in these scenarios is minimal, not even 0.1 %. Therefore, the life cycle costs of Scenarios D and F for the calculation period are considered identical to the reference Scenario B.

Scenarios C and G show a cost reduction compared to reference Scenario B. Scenario G shows 2.3 % lower life cycle costs than reference Scenario B. The cost reduction for Scenario G is related to the use of fly ash. In the specific analyses, fly ash reduces the consumption of cement by 50 %, as well as the consumption of new aggregates by 8.8 %. Scenario C shows the lowest life cycle costs, being 13.6 % lower than in Scenario B. The main reason for the cost reduction is the BBTM wearing course. It is 37.5 % thinner than wearing courses in every other scenario. It should be noted that the thinner wearing course for Scenario C was compensated by a 3 cm thicker base layer.

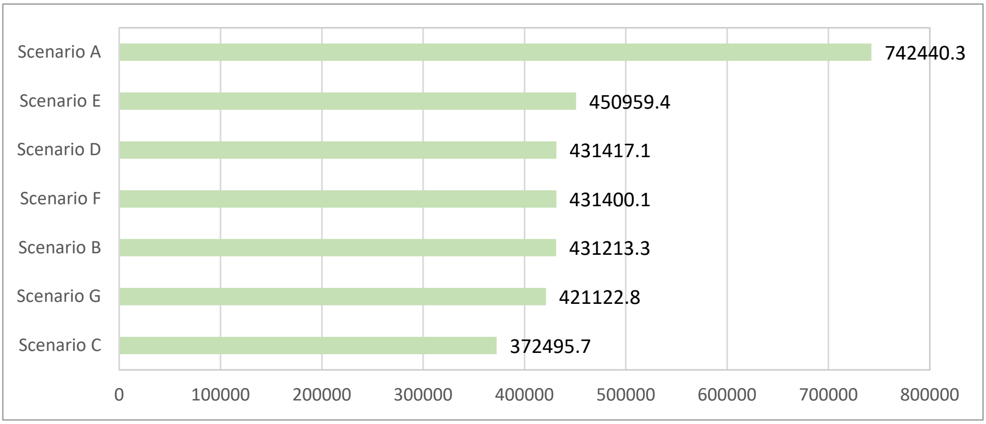

Fig. 7.4. Summary of the deterministic approach results of costs for each scenario.

The LCA results obtained show that Scenario A, has by 24.2 % higher value of CO_2 eq. in the analysis period than in other scenarios. It is noticeable that, Scenario A has 14.5 % lower GHG in the raw material position as in Scenario B. The reason for that is the reinforcement process, which is carried out twice through the analysis period for Scenario B. Nevertheless, Scenario A produces significantly higher emissions in material transportation (204 % more than B) and in deconstruction (152 % more than B) positions, resulting in higher GHG emissions throughout the period.

Higher GHGs are also shown in Scenario E. In Scenario E, these emissions are 0.98 % higher throughout the analysis period. The increase in emissions is caused by the bitumen modification process, WMA chemical additive, and slightly higher base bitumen content.

Scenario F shows an increase in GHG emissions by 0.16 % compared to reference Scenario B. This increase is related to higher emissions in the bitumen modification process. Such an increase is negligible in the 44-year calculation period if it opens the possibility of using the by-product – red mud, and reduces the required amount of traditional filler.

Scenario D shows equivalent GHG emissions compared to Scenario B due to the fact that CO_2 eq values do not differ between the different bitumen modifiers – EOC and SBS.

Scenarios C and G show a reduction of GHG compared to Scenario B. Scenario C has the second lowest CO_2 eq mainly due to thinner wearing course. Scenario G has the lowest CO_2 eq among all Scenarios, and the reason for that is reduced cement content by 50 % in base layers. Fly ash has considerable potential to reduce GHG emissions if it can fulfil the function of reinforcement and does not cause other harm to the environment. Scenario C has the lowest CO_2 eq value among all scenarios. Results show that Scenario C produces 12.2 % less CO_2 eq in the analysis period than reference Scenario B.

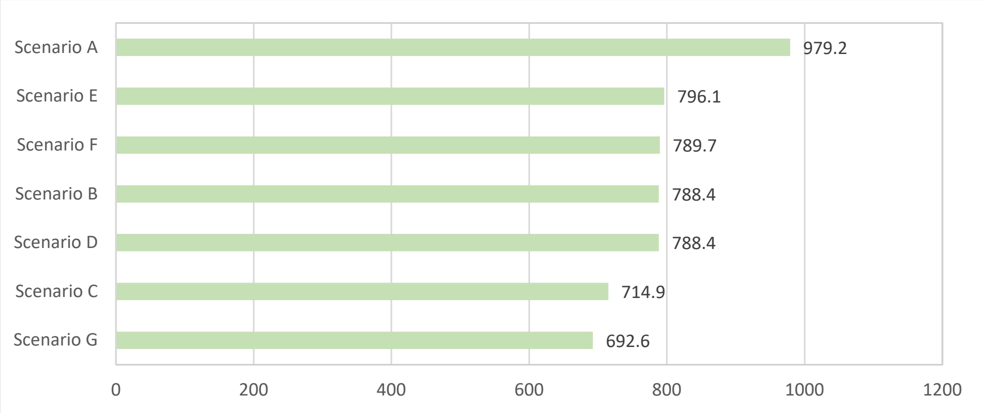

Fig. 7.5. Summary of the deterministic approach results of GHG for each scenario.

The summary of the deterministic approach results of energy demand for each scenario can be seen in Fig. 7.6. Similar to costs and GHG emissions, Scenario A has the highest value in the energy demand position. Overall, Scenario A shows 38.3 % higher energy consumption than the second reference Scenario B.

Scenarios E and F also show an increase in energy consumption compared to Scenario B, by 0.30 % and 0.24 %, respectively. The total energy increase of Scenarios E and F is related to higher energy consumption in the bitumen modification process. Nevertheless, the increase is relatively small.

The other scenarios (C, D, and G) show a reduction in energy consumption compared to the reference Scenario B. Scenario C demonstrates the highest energy demand reduction by 14.6 %, which is associated with a thinner asphalt wearing course. A high amount of energy is consumed in the production of bitumen. Thus, reducing the total thickness of the asphalt layers makes it possible to reduce the total energy consumption values significantly. Scenario G, where cement is partially replaced by fly ash, has a reasonable reduction in total energy consumption compared to Scenario B – by 2.4 %. The most negligible reduction is shown in Scenario D – 0.21 %. This reduction is due to the use of the EOC bitumen modifier. The EOC environmental product declaration data show that less energy is required to produce the EOC modifier compared to the traditional SBS modifier.

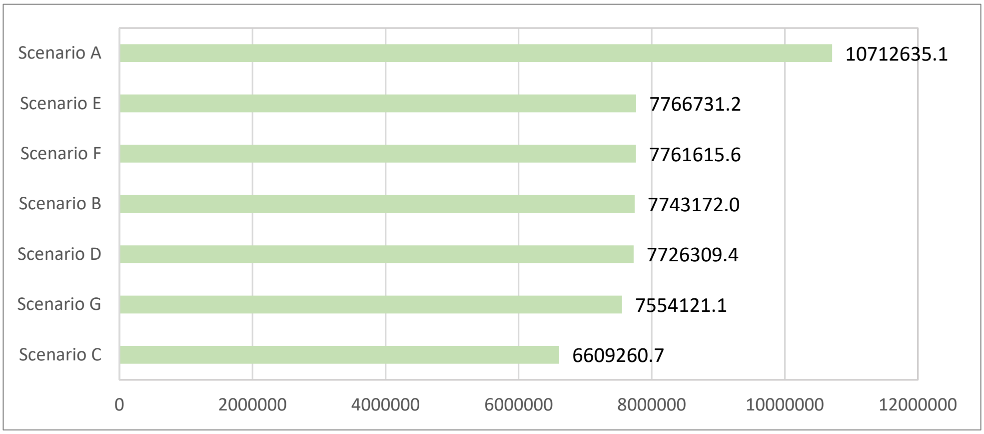

Fig. 7.6. Summary of the deterministic approach results of energy demand for each scenario.

7.2.2 SUMMARY OF THE RESULTS OF THE PROBABILITY APPROACH

A Monte Carlo simulation was used to generate the results of the probabilistic approach. For each scenario, 2000 values or iterations were generated. The following parameters were used in creating the probability distributions:

- the cost generation step is 10000 €;
- GHG generation step is 2 t;
- the energy consumption generation step is 20000 MJ;
- standard deviation – 3 years;
- min and max values of the average predicted service life – 5 years.

The summary of the results of the cost probabilistic analysis can be seen in Fig. 7.7. All distributions show a symmetrical normal distribution. Besides, all probability distributions of scenarios overlap, except for Scenario A. The results convincingly show that Scenario A has the highest costs. Even with the longest service life for Scenario A and the shortest for any other scenario, it cannot have lower total costs. The reason for that is much higher initial construction costs. As previously mentioned, the high costs associated with full-depth reconstruction involve a large amount of deconstruction material and the use of new material. Since, for this scenario, a large part of the cost is the construction of the initial structure, it is possible to predict the costs throughout the life cycle with a relatively high degree of confidence, which is close to 25 %.

The second potentially highest cost is predicted for Scenario E, which has a crumb rubber-modified asphalt wearing course. The fact that the cost of rubber-modified asphalt is higher was also confirmed in the author's previous publication, where it was concluded that this type of pavement should last longer to have lower annual life cycle costs.

The probability distributions of Scenarios B, D, and F are very close. A slight difference in the probability of execution can be observed, which is within 1.05 %. It can be concluded that using EOC or red mud does not increase the total costs compared to the traditional practice where only SBS is used as a bitumen modifier (Scenario B). In Scenario F, the red mud is an additional modifier to SBS, so this wearing course could potentially have higher performance properties.

The second lowest cost is for Scenario G, where cement is used 50 % less than in the other scenarios, replacing it with fly ash.

The lowest costs among all scenarios are shown in Scenario C, where BBTM asphalt wearing course is used in combination with a 3 cm thicker base. Scenario C also has the highest probability of execution of the most likely value (above 20 %). The reason for that is lower future costs, as replacement of thinner wearing course costs less.

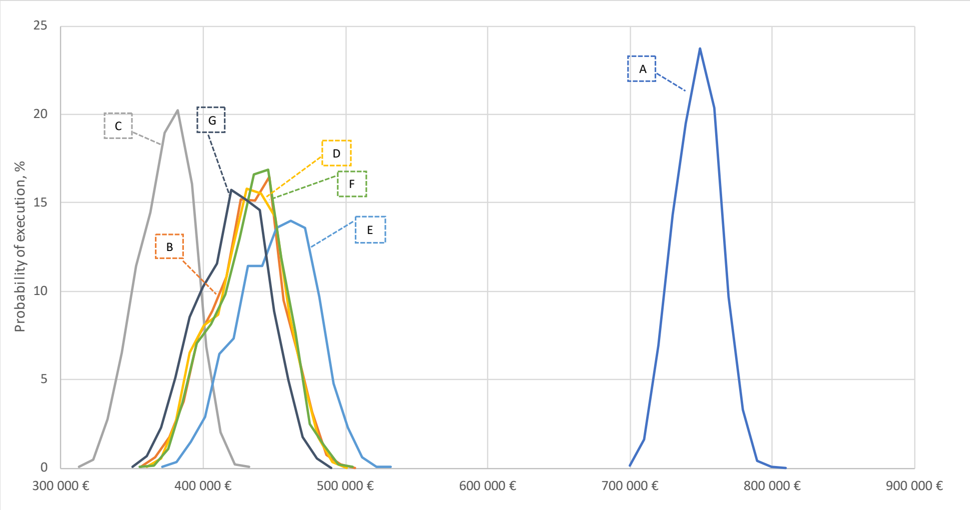

Fig. 7.7. Summary of the probabilistic approach results of costs for each scenario.

The summary of the results of the SEG probabilistic analysis can be seen in Fig. 7.8. All distributions overlap. Also in this position, the largest CO_2 eq. values are for Scenario A. However, in contrast to the probabilistic distribution of costs, Scenario A may even have lower annual CO_2 eq if longer service life compared to other scenarios is accomplished.

Similar to the distribution of costs, Scenarios B, D, and F show quite similar nature probability distribution in the GHG position. The main difference between these scenarios is the probability of execution for the most likely intervals. It is within the limits of 0.65 %. Therefore, it can be said that the EOC modifier and red clay do not have a negative (higher) GHG emission impact on the road pavement compared to the traditional practice with the SBS bitumen modifier.

Scenario E, in which bitumen in the wearing course is modified with crumb rubber, has a flatter probability distribution of CO_2 eq compared to Scenarios B, D, and F. At the same time, the difference between the most likely intervals is slight: 0.3–2.1 %.

The second lowest CO_2 eq is in Scenario C, where BBTM asphalt type is used as the wearing course. The BBTM wearing course is 37.5 % thinner compared to the wearing courses of other scenarios. A thinner wearing course reduces the required quantities of virgin bitumen and mineral materials, thus also reducing the annual CO_2 eq.

The lowest CO_2 eq is in Scenario G, where cement consumption is reduced by 50 %, partially replacing it with fly ash. In this scenario, the probability distribution does not show only one distinctly more likely CO_2 eq interval but two with a high probability of execution. Interestingly, the probability of execution of the two most likely intervals is 68.6 %. Although the use of fly ash has a positive effect on the reduction of CO_2 eq, its use should be carefully evaluated due to the high variability of quality, which can negatively affect the overall service life of the structure.

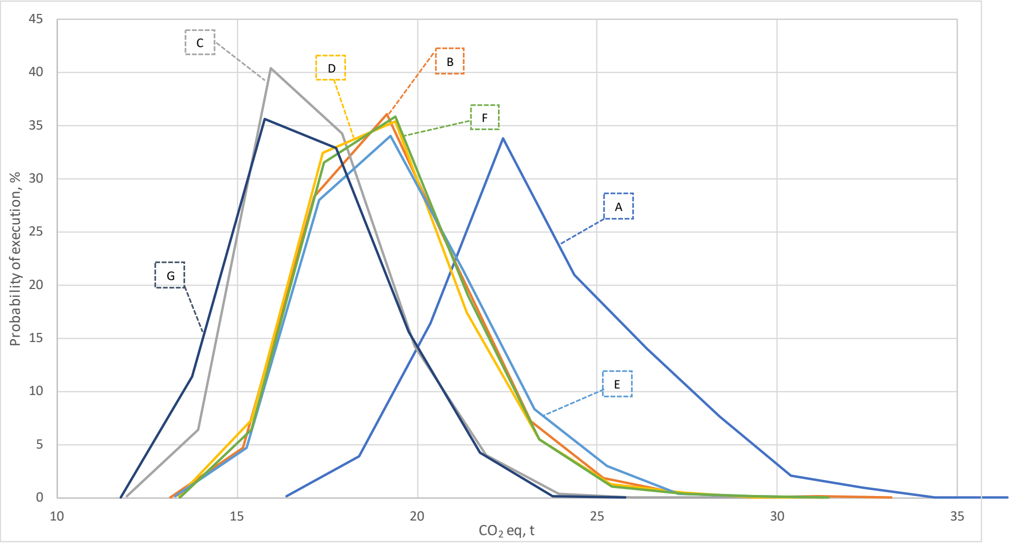

Fig. 7.8. Summary of the probabilistic approach results of GHG for each scenario.

The summary of the results of the energy demand can be seen in Fig. 7.9. As with costs and GHG emissions, Scenario A also has the highest energy consumption values. However, all distributions overlap. Therefore, there is a chance that Scenario A could have lower annual energy demand (in comparison to B, D, E, F, G), and the probability of that is approximately 20 %. The probability distribution in Scenario A has a lower but broader range of possible values.

Scenarios B, D, and E demonstrate quite similar probability distribution in the energy demand position. The main difference between these scenarios is the probability of execution for the most likely interval. It is within the limits of 0.35 %. Therefore, it can be said that the EOC modifier and red mud have a low energy consumption on the total road pavement compared to the traditional pavement practice with a wearing course modified by only the SBS modifier.

In Scenario E, in which the bitumen is modified with crumb rubber, the energy consumption is slightly lower than in scenarios B, D, and F. The difference between the most probable values is in the range of 1.7 %.

The second lowest energy consumption is in Scenario G, where cement consumption is reduced by 50 %, partially replacing it with fly ash. The most likely value in Scenario G is almost identical to the most likely value in Scenario C. However, the distribution in Scenario G is more broadly oriented towards higher energy consumption than in Scenario C.

The lowest energy consumption is in Scenario C, where the BBTM asphalt-wearing course is used. Similar to Scenarios B, D, E, and F, Scenario C does not show a distinct single most likely interval but rather two values with a high probability of execution. Since the production of bitumen consumes a lot of energy, using a thinner wearing course can significantly reduce energy consumption. As a result, the use of the BBTM allows a reduction of energy consumption and the use of non-renewable resources.

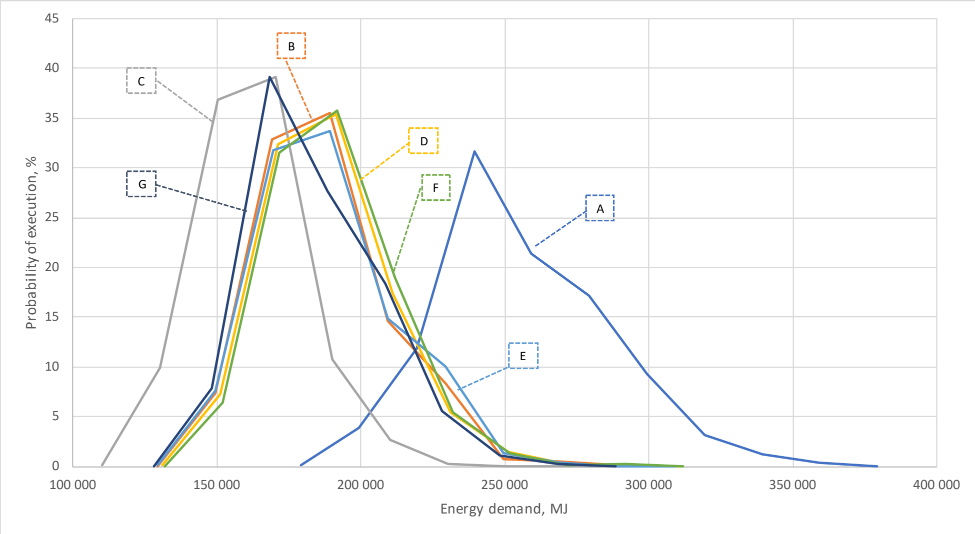

Fig. 7.9. Summary of the probabilistic approach results of energy demand for each scenario.

7.2.3 AMOUNT OF MATERIALS USED

For all scenarios, the volume of materials used was calculated (see Table 7.2). For more information see the full-text Thesis. Reference Scenario A has 17.6 % less aggregates consumed in asphalt layers than the other reference Scenario B. In terms of mineral filler and bitumen, Scenario A also shows a reduction of 11.4 % and 16.6 %, respectively. Also, Scenario A does not use cement, unlike the other scenarios. In Scenario A, a large amount of new aggregate materials is used in the base – sand 12893.9 t, crushed stone mixture 9810.2 t.

Compared to Scenario B, the total reduction of aggregates in the wearing course for Scenario C is 17.3 %. A thinner wearing course reduces the amount of aggregates and bitumen required by 37.5 % and 40 %, respectively. Also, Scenario C uses 12.2 % more material from the old pavement compared to Scenarios B, D, E, F, and G.

There is no material volume difference between Scenarios B and D. The only difference between them is the bitumen modifier (SBS or EOC) used, which does not affect the material volumes.

The use of crumb rubber in bitumen modification eliminates the need for an industrial bitumen modifier. Using such a modifier contributes to the circular economy and gives the opportunity to dispose of 26.93 t of tire rubber, which is more than 50 t of tires per 1 km.

Scenario F, unlike the others, uses two bitumen modifiers – SBS and red mud. The use of red mud in bitumen modification allows the disposal of 10.53 t of this by-product per 1 km.

In Scenario G, the use of fly ash reduces the required amount of cement by 50 % or 142.4 t. To achieve an equivalent reinforcing effect, fly ash is used significantly more than cement, making it possible to dispose of 949.6 t of this product in a 1 km long road section. The use of fly ash reduces the need for new aggregate material by 8.8 %.

Table 7.2

Amount of materials used throughout the life cycle

Material position	Scenario A	Scenario B	Scenario C	Scenario D	Scenario E	Scenario F	Scenario G
Virgin aggregates in asphalt layers, t	4725.2	5732.3	4737.5	5732.3	5730.3	5730.3	5732.3
Virgin filler in asphalt layers, t	160.9	181.7	137.9	181.7	181.7	171.2	181.7
Virgin aggregates in base, t	9810.2	2441.9	2435.17	2441.9	2441.9	2441.9	2228.0
Virgin aggregates in subbase, t	12893.9	0	0	0	0	0	0
Aggregates from old pavement, t	0	6768.9	7597.1	6768.9	6768.9	6768.9	6175.7
Virgin bitumen (without modificators), t	224.9	269.72	211.4	269.72	277.8	269.72	269.72
Industrially produced bitumen modifier, t	6.08	6.08	3.61	6.08	0	6.08	6.08
Crumb rubber, t	0	0	0	0	26.93	0	0
Red mud, t	0	0	0	0	0	10.53	0
Cement, t	0	284.9	307.92	284.9	284.9	284.9	142.4
Fly ash, t	0	0	0	0	0	0	949.6

7.3. Rating creation

The described results can be grouped and the scenarios can be ranked (see Table 7.3). In the framework of this study, rating creation was done based only on the results of the deterministic approach. The Thesis does not contain information on interpreting the probabilistic analysis results to create a rating of scenarios.

All scenarios were ranked in the following four categories: (1) annual costs, (2) annual energy consumption disaggregated, (3) annual GHGs, and (4) quantities of materials used. Annual results are obtained by dividing the total value of the life cycle by the analysis period. Positions in the ranking are from 1 (highest) to 7 (lowest). Scenario C has the highest position in the category of annual costs, followed by Scenarios G and B. In terms of annual energy consumption, Scenario G has the highest position, followed by Scenarios C and D. In terms of annual GHG, Scenario C has the highest position, followed by Scenarios G and D. Ranking by the amount of materials used category is not as straightforward because each scenario gives a particular benefit. Therefore, to create this ranking, it was evaluated from the positions of Latvia, for example, which local materials/by-products/waste have a high need to be used. Consequently, Scenario G was rated the highest in this position, followed by Scenarios C and E.

Among all scenarios, Scenarios C and G have the highest positions in the ranking. Scenario C ranks first in annual costs and GHG and second in annual energy consumption and material use. On the other hand, Scenario G takes the first position in annual energy consumption and material use and the second position in yearly costs and GHG. Scenario A has the lowest position in all categories in which full-depth reconstruction is planned. It can be concluded that the use of this technology should be critically evaluated, as it is not only expensive but also environmentally unfriendly. If, however, this technology needs to be selected, then it is suggested to improve the sustainability of this scenario by including some of the by-products or industrial waste in the production of asphalt layers.

Table 7.3

Scenario ranking

Scenario	Annual costs	Annual energy demand	Annual CO_2 eq	Quantities of materials used
A	7	7	7	7
B	3	4	4	6
C	1	2	1	2
D	5	3	3	5
E	6	6	5	3
F	4	5	6	4
G	2	1	2	1

7.4. Evaluation and optimization

There are no restrictions between the materials and technologies used. Therefore, all scenarios could be realised in the functioning road network. However, the results indicate that potentially combining materials and technologies from various scenarios would be the most sustainable approach. The use of BBTM wearing course (Scenario C) in combination with crumb rubber modified bitumen (Scenario E) and partial replacement of cement with fly ash for the base reinforcement (Scenario G) would be potentially the most sustainable pavement solution with the lowest annual costs, GHG, and energy consumption and the highest use of by-products. This is under the condition that this combination of materials and technologies does not lead to a shortened service life of the road pavement.

8. CONCLUSIONS

The Doctoral Thesis is an original research project in which a methodology and a tool have been developed for assessing the sustainability of road construction materials, technologies and strategies using life cycle techniques. The Doctoral Thesis includes the evaluation of various potentially sustainable materials and technologies according to the methodology developed and the PAVE/LCA/LCCA tool. Based on the results of the Doctoral Thesis, the following conclusions were drawn:

- The developed method makes it possible to quantitatively evaluate road reconstruction and maintenance approaches, giving the opportunity to improve decision-making policies. The practice of the lowest price policy as a primary criterion in tenders contains significant risks affecting sustainable development. Therefore, this Doctoral Thesis is an important step forward in raising awareness and promoting the implementation of sustainable development principles in the road construction industry.
- Currently, there is no single tool available in the road construction industry that combines LCA and LCCA with the possibility to develop a completely customized rehabilitation strategy. Taking into account that material flows and processes partially overlapped between the analyses combining them in one tool is logical, as operations are optimized, information is in one place and impact evaluation is more transparent.
- The developed PAVE/LCA/LCCA tool enables the calculation of environmental and economic parameters of materials, technologies and/or strategies used for road rehabilitation or construction in a single tool. In addition, it is possible to make calculations for the full-depth pavement with the scope from the acquisition of raw materials to the end of the service life. Also, with this tool, the results can be expressed both deterministically and probabilistically.
- For simplified understanding, the deterministic approach of expressing results can be used. However, the probabilistic approach is also recommended because it contains such an important parameter as the probability of execution. Therefore, to obtain more information about the results of different scenarios, obtaining of probabilistic results is recommended.
- The full-depth reconstruction of the road pavement is 72.2 % more expensive, 38.3 % more energy-consuming and 24.2 % more GHG-emitting in 44 years than the reconstruction in which reinforcement of the old pavement is done. However, the results of the probabilistic approach show that with longer service life, the first technology can have even lower annual energy and GHG.
- A road pavement with a BBTM asphalt wearing course is 13.6 % cheaper, 14.6 % less energy-consuming and 9.3 % less GHG-emitting in 44 years than a road pavement with a traditional wearing course. Taking into account that bitumen and high-quality mineral material need to be imported into Latvia, the use of BBTM is sustainable.

- A road pavement in which 50 % of cement is replaced with fly ash in the reinforcement of base has the potential to reduce life cycle costs by 2.3 %, energy consumption by 2.4 % and GHGs by 12.2 %. Cement production is an energy-consuming and environmentally unfriendly process. At the same time, cogeneration plants produce fly ash as a by-product daily, which has limited applications. Despite the high potential, the use of fly ash must be responsible (individual tests must be carried out), as it may contain various heavy metals harmful to the environment and humans.
- Using crumb rubber-modified bitumen (wet process-high viscosity) in the wearing course of the road pavement increases pavement life cycle costs by 4.6 % in 44 years. Still, its impact on the GHG and energy consumption is minor (1.0 % and 0.3 %). A study conducted by the author found that rubber-modified bitumen can have increased service life compared to traditional materials, thereby reducing annual costs, energy consumption and GHGs. In addition, tire recycling contributes to circular economy principles and decreases the quantity of end-of-life tyres in stockpiles.
- The use of red mud in the bitumen modification process does not increase costs, GHG or energy consumption compared to traditional practices. At the same time, the use of red mud reduces the need for conventional asphalt fillers by 16 %, thus reducing the use of non-renewable resources and promoting circular economy principles, which is particularly relevant in countries where industrial aluminium extraction is carried out.
- The use of EOC as a bitumen modifier does not increase costs, GHG or energy consumption compared to the traditional practice with the SBS bitumen modifier in the wearing course. This elastomer has not been industrially used to modify bitumen, so its use has potential risks. The laboratory performance tests carried out so far show that with the existing approach, EOC is not better than SBS, which means that its use in bitumen modification has no justification;
- The most sustainable scenarios are those using a pavement with a BBTM overlay and a pavement using a cement and fly ash combination in the base reinforcement. In contrast, the least sustainable approach is to perform a full-depth reconstruction. This technology would only be applicable in high-risk cases where longevity is hard to ensure with other technologies.
- The most sustainable approach would be a combination of materials and technologies from different scenarios. These combinations may vary between countries and regions. Taking into account the results of the rating and the conditions of Latvia, the most sustainable combination would be using a BBTM wearing course in combination with crumb rubber-modified bitumen and preserving the old pavement by reinforcing it with cement and fly ash.

Artūrs Riekstiņš was born in 1992 in Cesis. He received a professional Bachelor's degree in Transport Engineering and an engineering qualification in 2016 and a professional Master's degree in Transport Engineering in 2017 from Riga Technical University. Since 2014, he has been working at SLLC "Latvijas Valsts ceļi", and since 2017, he has been a research assistant with Riga Technical University. His scientific interests are related to sustainable and innovative road construction and maintenance.