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Sustainable Construction in Public and Private Works through IPP approach

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Report

Life Cycle Assessment of Road Pavement

Leading Partner: NTUA

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Versioning and contribution history

Version	Description	Comments
1	Life Cycle Assessment study of Road Pavement	1st Draft

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1 Introduction

This report is part of Task 3 “Life Cycle Assessment in two construction activities” of the research project “Sustainable Construction in Public and Private Works through IPP approach – SUSCON” project. After the environmental assessment of the life cycle of an office building, the object of this study was the environmental performance of a road located in Cyprus. This report presents the Life Cycle Assessment study of the road. The modelling of the system and the impact assessment has been done with the use of the “GaBi 4” software. The software system GaBi is a tool for the modelling of life-cycle-balances.

The life cycle of the road consists of three distinct phases; construction, use and end-of-life. The construction phase consists of the production of raw materials, site preparation activities, the transportation of raw materials to the site and their placement. The use phase encompasses all activities related to the use of the road over an assumed life of 50 years. These activities includes all material and energy consumed for maintenance purposes. The end-of-life phase deals with the eventual demolishing of the road, and includes the transportation of waste to recycling operations or landfills. The end of life stage of the road has not been included in this study.

The main responsibility for the implementation of this task lies on the **Unit of Environmental Science and Technology (UEST) of the National Technical University of Athens (NTUA).** The construction company **Cybarco Ltd.** that constructed the road in Cyprus, has provided all the data regarding the Life Cycle Inventory (LCI) of the system. The **Department of Civil and Environmental Engineering (CEE) of the School of Engineering at the University of Cyprus** had a major role, processing the data provided by Cybarco.

2 Life Cycle Assessment

2.1 About the methodology

Life Cycle Assessment (LCA) (or Analysis) is a method, which quantifies the environmental impacts associated with the delivery of a particular service or product. An accepted definition is:

‘*LCA is a systematic way of evaluating the environmental impact of products or activities by following a ‘cradle to grave’ approach. This approach implies the identification and quantification of emissions and material consumption which affects the environment at all stages of the entire product of life cycle*’.

Thus the analysis includes all processes connected to the delivery of this service or product, from the extraction of raw materials to the disposal of wastes. This network of processes forms the life cycle of the product or service. Using this method ensures that all processes, which contribute to the environmental impacts of the delivery of a particular service or product are included in the final result. This produces an unambiguous picture of the overall impacts in certain environmental categories of a particular system, allowing the comparison of different systems to be made on a consistent basis.

The life cycles of production systems will therefore include processes such as raw material extraction, transportation, intermediate processing and delivery.

For each process within the life cycle, detailed inventories of the material and energy inputs and outputs are produced. In this way a life cycle inventory (LCI) is produced which accounts for the total inputs and outputs of all energy and material flows attributable to the provision of a particular service or product.

These inventories consist of a large number of inflows and outflows, which in them are difficult to relate to individual environmental problems. To make the results intelligible and relevant these material and energy flows have to be translated into environmental impacts. This is the final assessment of the LCA. This relates the overall life cycle inventory to the effect on the environment of providing a certain service or product (Figure 2.1).

The contribution of each input or output flow in the life cycle inventory to the each of the environmental impact categories is calculated by multiplying by a relevant factor. Thus an output of CO_2 contributes a certain amount to global warming potential, CFC emissions to both greenhouse gas emissions and ozone depletion potential, and SO_2 and NO_x emissions to acidification potential. In each case the impact described is equal to the maximum impact on the environment that could be caused by the particular emission or consumption of resource.

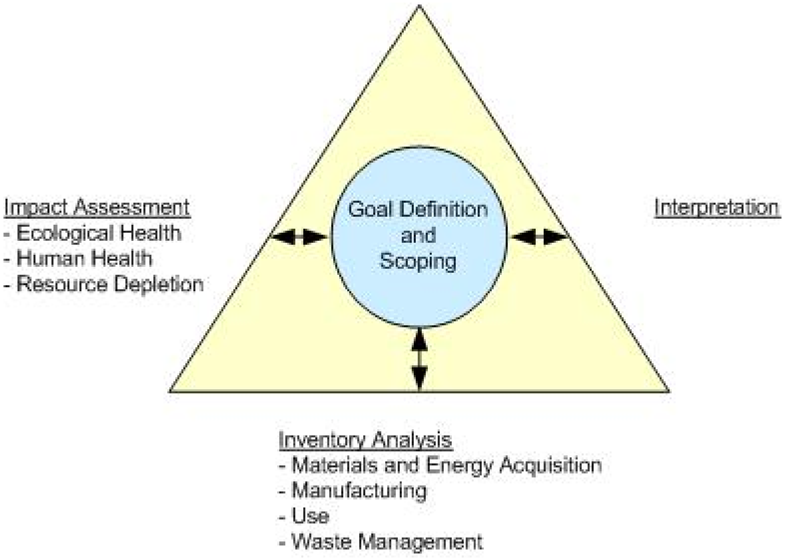


Figure 2.1: Technical framework for life cycle assessment studies

The end result of this procedure is to produce graphs of the environmental impacts in each category caused by the provision of the product or service. This information can be used in two ways. Firstly, when looking only at one life cycle, it can be used to assess which particular processes in the life cycle are responsible for the most significant environmental impacts. This allows improvements to the system to be targeted where they are likely to be most effective at reducing each category of environmental impact. Secondly, the results can be used to compare the environmental impacts of systems with the same functional units. This will provide answers to the questions of which production system contributes most to each environmental category.

Thus LCA will give a clear and unambiguous account of the environmental impacts of the product under study and will allow the system to be analysed on a clear and consistent basis.

2.2 Goal definition and scoping

The goal of the LCA study is to analyse the environmental impacts of a widely used construction product, as a road. The study will include the following components:

- Investigation of the production cycle of the materials including the construction phase of the road.
- Investigation of the impacts regarding the use phase of the road.
- Material and energy consumption, emissions to the environment and disposal problems will also be recorded.

The study will include all the material and components in the road from "cradle-to-grave". "Cradle-to-grave" begins with the gathering of raw materials from the earth to create the product, the use phase of the product (mainly energy consumption that is very much dependent on the design of the road and ends at the point when all materials are returned to the earth (end of life management). Based on the LCA study material, reduction opportunities, energy savings, recyclability, reusability and end of life management options will be determined.

2.3 The functional unit

The main purpose for a functional unit is to provide a reference to which the input and output data are normalised. This means that the data are transformed in units of an input or output flow per functional unit (ex. 2 g CO_2/kg cotton, 0.03 g CO/kg cotton etc.). The functional unit of this study is one (1) km of a typical urban (C) road constructed near the Germasogia dam in Limassol district in Cyprus. The road consists of two 3.5m wide lanes and two 2.5m wide shoulders. The time boundary of the analysis is 50 years during which maintenance is foreseen.

2.4 System boundaries

A system is a collection of operations that together perform some clearly defined function. A broad-based system begins with raw materials acquisition and continues through industrial or consumer use and final disposition.

In defining the system, the first step is to set the system boundaries (Figure 2.2). A complete life-cycle inventory will set the boundaries of the total system broadly to quantify resource and energy use and environmental releases throughout the entire life cycle of a product or process.

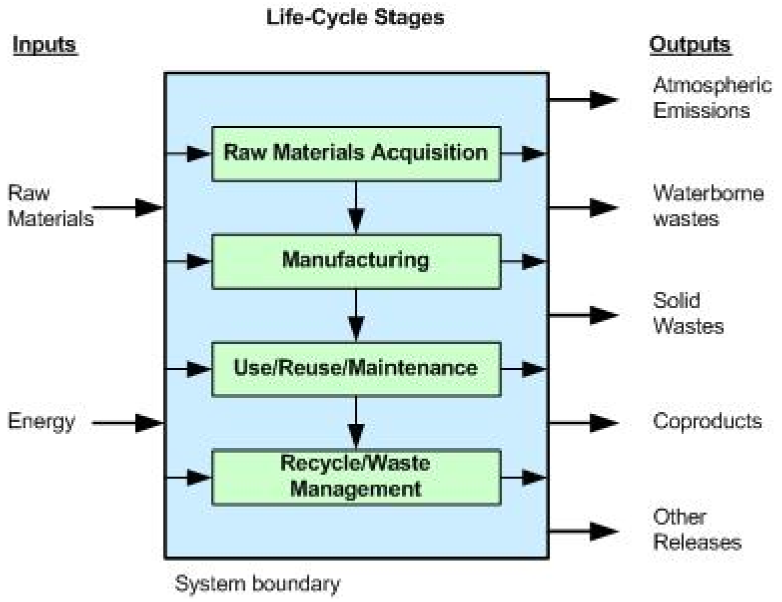


Figure 2.2: Defining system boundaries

The life cycle of the road shall be divided into 5 major subsystems, as shown in Figure 2.3:

1. **Raw material production:** The life cycle of the road starts with the extraction of the raw materials. The road consists mainly of inert rock and bitumen. This phase includes both the production of raw material and the use of these raw materials to produce other materials as asphalt. The environmental aspects and impacts from this phase arise from the mining operations and manufacturing of secondary materials.
2. **Raw material transportation:** Materials are delivered to the construction site by road transport. The environmental impacts in this phase mainly arise from energy consumption of the carriers.

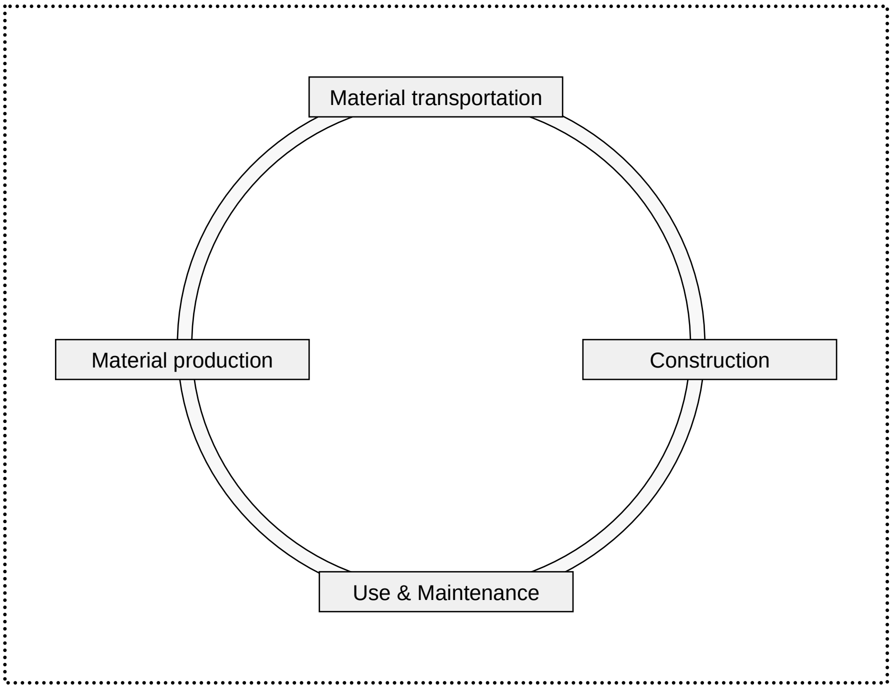


Figure 2.3: Road LCA system

3. **Construction of the road:** This phase covers the construction of the road. This phase includes excavation processes, material placement and road pavement processes. The main environmental aspect from this phase is the energy consumption and solid waste production.
4. **Use and Maintenance stage:** This stage includes the use phase of the road and all maintenance activities during its useful life.
5. **Demolition - Final Disposal/Recycle/Waste Management stage:** Begins after the road has served its intended purpose and includes the demolition process and the solid waste management system (recycling and final disposal of inert materials). An end-of-life subsystem is not included in the system since the practice in the last decades is not to demolish roads but continuously expand the existing road network or leave the road materials in place even when the road is withdrawn from service.

3 Life Cycle Inventory

3.1 About the LCI

The life cycle inventory (LCI) analysis component is a technical, data-based process of quantifying energy and raw material requirements, atmospheric emissions, waterborne emissions, solid wastes and other releases for the entire life cycle of a product, package, process, material or activity.

Qualitative aspects are best captured in the impact analysis, although it is useful during the inventory to identify these issues. In the broadest sense, inventory analysis begins with raw material extraction and continues through final product consumption and disposal.

The LCI provides a quantitative catalogue of energy and other resource requirements, atmospheric emissions, waterborne emissions and solid wastes for a specific product, process, package, material or activity. Once the inventory has been performed and is deemed as accurate as possible within the defined scope and boundaries of the system, the results can be used directly to identify areas of greater or lesser environmental burden, to support a subsequent life-cycle impact analysis and as part of a preliminary improvement analysis. Life cycle impact assessment can be applied to quantify the human and ecological health consequences associated with specific pollutants identified by the inventory.

3.1.1 Data origin

The data used for the purpose of this study comes from the following sources:

- Raw data provided by the construction company **Cybarco**. This data included the mass of materials or components and energy consumption required for the construction of 1km of the road.
- The GaBi software construction materials database that consists of life cycle data of generic construction materials and components.
- Literature data when it was necessary.

3.1.2 Data quality

Data quality is the degree of confidence in individual input data. The ISO standard sets some minimum standards for data quality: ‘Data quality requirements shall be defined to enable the goals and scope of the Life Cycle Assessment study to be met. The data quality requirements address issues such as:

- the precision, completeness and representativeness of the data and the data sources;
- the consistency and reproducibility of the methods used throughout the LCA;
- the sources of the data;
- the variability and uncertainty of the information and methods.’

The quality of the data used for this study is considered to be adequate for the goal of the LCA of the road in Cyprus.

3.1.3 Cut-off rules

During data collection, flows that are very small in the total mass of the product may have been disregarded. This rule does not apply where the flow, although below the cut-off level, cause significant environmental burdens, for example where the flow is classed as hazardous.

3.2 Life Cycle Inventory Data

The study shall include the main material and energy flows from the various activities of these subsystems as identified in the following sections. However, the environmental loadings caused by the manufacture and maintenance of capital equipment (machinery, vehicles etc) shall be excluded from the system boundary.

The typical section of the road is shown in Figure 3.1. The road consists of two 3.5m wide lanes and two 2.5m wide shoulders.

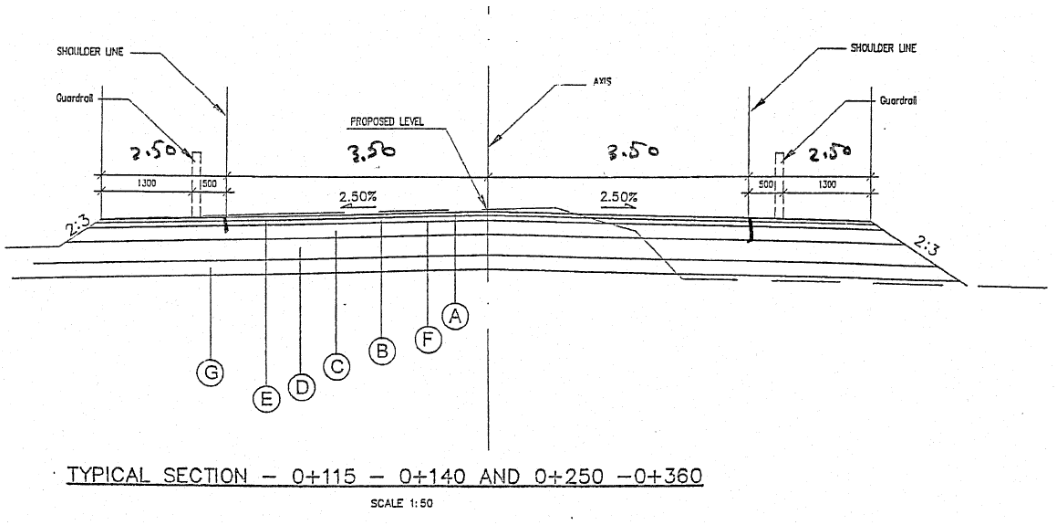


Figure 3.1: Typical road section

3.2.1 Material Production

The road structure consists of four main layers and two coating layers as shown in Figure 3.2.

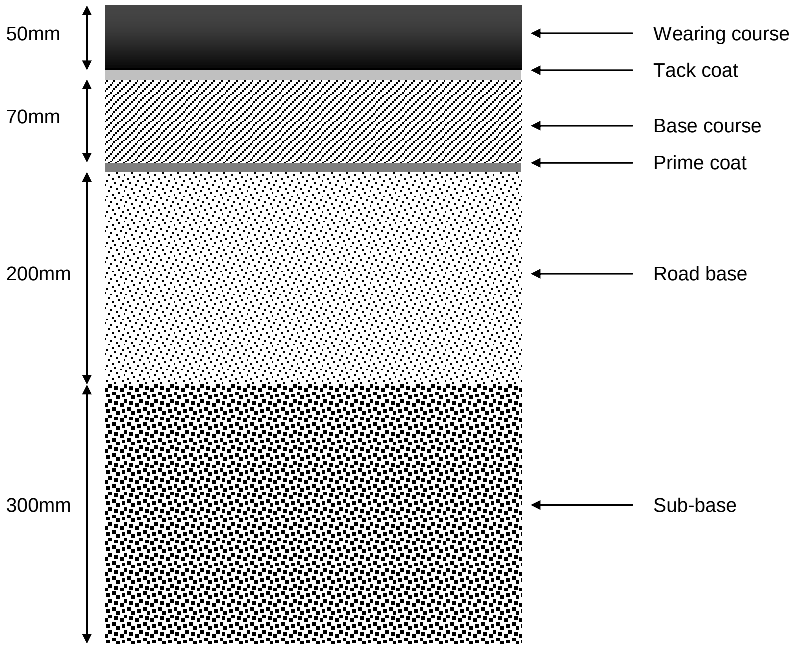


Figure 3.2: Structure of the road

The material quantities required for the construction of the pavement of 1 km of the road are shown in Table 3.1. In addition to the paving materials, secondary road equipment is produced.

Table 3.1: Pavement material quantities

Layer	Aggregates (tonnes)	Binder (tonnes)	Tack coat (litres)	Prime coat (litres)
Wearing course	1,326	84		
Tack coat			4,200	
Base course	1,875	99		
Prime coat				12,000
Road base	5,400			
Sub-base	7,200			
TOTAL	**15,801**	**183**	**4,200**	**12,000**

(1) In accordance with the Public Works Department Specifications

(2) Bitumen in accordance with a penetration of 40/50 at 25C in compliance with Table 5/2A of the Public Works Department Specifications

(3) Tack coat: Bittumen emulsion to BS 434, Anionic Class A1-40 or cationic Class K1-40

(4) Prime coat: 80/100 penetration bitumen or cut back bitumen type S-125, blended with solvent to render it equivalent to MC30 to ASTM D2027-76

The material production phase includes the activities shown in Table 3.2.

Table 3.2: Activities considered in life cycle for material production

No	Description	Unit	Quantity
1	Production of aggregates at quarry	Tonnes	15.801
2	Production of bitumen binder at refinery (incl.	Tonnes	183

	extraction and transportation of crude oil)		
3	Production of tack coat at refinery (incl. extraction and transportation of crude oil)	Litres	4.200
4	Production of prime coat at refinery (incl. extraction and transportation of crude oil)	Litres	12.000
5	Mixing of base course asphalt at asphalt plant*	Tonnes	1.974
6	Mixing of wearing course asphalt at asphalt plant*	Tonnes	1.410

The asphalt plant produces on average 240 tonnes/hour of asphalt (base and wearing courses)

3.2.2 Material Transportation

Both the quarry and the asphalt plant are located outside the community of Parekklisia (Figure 3.4). The distance between the quarry and the asphalt plant is 1km. The distance of the quarry from the construction site is 20km and the distance of the asphalt plant from the construction site is 19km.

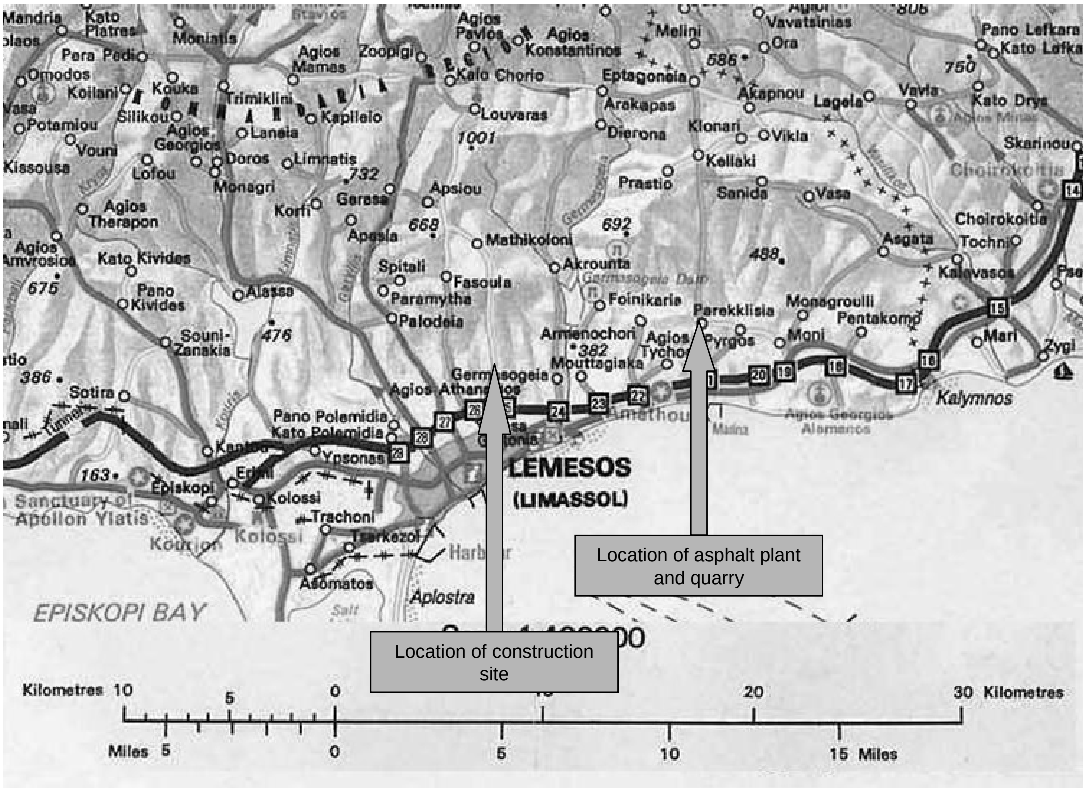


Figure 3.4: Location of asphalt plant, quarry and construction site

The transportation activities for the main construction materials, that are included in the inventory, are listed in Table 3.3.

Table 3.3: Transportation of construction materials

No	Material	Trip	Mass (tonnes)	Distance (km)	Transportation (tonnes*km)	Mode
1	Aggregates for sub-base and road base	Quarry to construction site	12,600	20	252,000	27-tonne trailer
2	Prime coat	Larnaca refinery to asphalt plant	12	70	840	Tanker
3	Prime coat	Asphalt plant to construction site	12	19	228	Truck
4	Bitumen	Larnaca refinery to asphalt plant	83	70	5,810	Tanker truck
5	Tack coat	Larnaca refinery to asphalt plant	4	70	294	Tanker truck
6	Tack coat	Asphalt plant to construction site	4	19	80	Truck
7	Aggregates for base and wearing courses	Quarry to asphalt plant	3,201	1	3,201	27-tonne trailer
8	Base course asphalt	Asphalt plant to construction site	1,974	19	37,506	27-tonne trailer
9	Wearing course asphalt	Asphalt plant to construction site	1410	19	26,790	27-tonne trailer

3.2.3 Construction stage data

The construction stage consists of three sub-phases that describe the activities related to the establishment of a new construction in a terrain. These are: (i) site clearance and earthworks, (ii) construction of pavement and (iii) additional works.

In site clearance and earthworks, the terrain of the road alignment is firstly prepared in terms of removal of vegetation, topsoil and unqualified soil (soft soil) and then soil is moved within the road area, removed from the road area, added to the road area and constructed to reach the required alignment of the road construction. This process includes the construction of embankments and cuttings. Consumption of material and energy as well as disposal of waste and emissions from operations shall be included in the inventory. The extent of earthwork processes can vary considerably among different road projects due to disparities in the terrain. For this case study the actual earthwork operations in the Germasogeia project are considered. The activities, which are included in the study, are shown in Table 3.4.

Table 3.4: Activities considered in life cycle for construction (site clearance and earthworks)

No	Description
1	Removal of vegetation, topsoil and unqualified soil
2	Excavation from site and removal to site
3	Excavation from site and removal to other sites
4	Excavation from other sites and removal to site
5	Construction of cuttings and embankments, soil compaction

During the pavement construction the various road layers are paved and subsequently compacted. The activities, listed in Table 3.5, are included in the study.

Table 3.5: Activities considered in life cycle for construction (pavement construction)

No	Description	Unit	Quantity
1	Compaction of soil foundation	m^2	15.000
2	Paving of sub-base by grader machine (in 2 layers)	Tonnes	7.200
3	Compaction of sub-base by roller compactor	m^2	30.000
4	Paving of road base by grader machine (1 layer)	Tonnes	5.400
5	Compaction of road base by roller compactor	m^2	15.000
6	Spraying the prime coat by hot bitumen distributor	Litres	12.000
7	Paving the base course by finisher machine (1 layer)	Tonnes	1.974
8	Compaction of base course by roller compactor	m^2	15.000
9	Spraying the tack coat	Litres	4.200
10	Paving the wearing course by finisher machine (1 layer)	Tonnes	1.410

11	Compaction of wearing course by roller compactor	m^2	15.000

The additional works sub-phase includes the installation of various road equipment such as safety barriers, road markings etc. The activities that are shown in Table 3.6, are considered not to have major environmental impacts and are excluded from the model.

Table 3.6: Activities considered in life cycle for construction (additional works)

No	Description	Unit	Quantity
1	Installation of safety barriers and railings	m	1.000
2	Painting of road markings	m	?
3	Installation of road signs	No	?
4	Installation of reflectors	No	?

3.2.4 Use & Maintenance stage data

No material or energy consumption has been identified in the use phase of the road as this particular road has no road lighting, no traffic lights and no sweeping is undertaken.

The maintenance stage includes different activities that all serve the purpose of keeping the road in safe and acceptable condition during its service life. It consists of two types of maintenance activities: (i) regular maintenance and (ii) pavement maintenance. Regular maintenance implies maintenance of the road equipment (safety barriers, road markings etc.), cutting vegetation near the road and garbage collection. Pavement maintenance includes the removal of the wearing course, which takes place every 8.5 years (average) and its substitution with a new wearing course. The asphalt removed is typically used in other projects for foundation of temporary roads, private roads etc. Assuming that the same materials are used in the same thickness throughout the 50-year lifetime of the road under study, the activities of Table 3.7 are accounted.

Table 3.7: Activities considered in life cycle for pavement maintenance

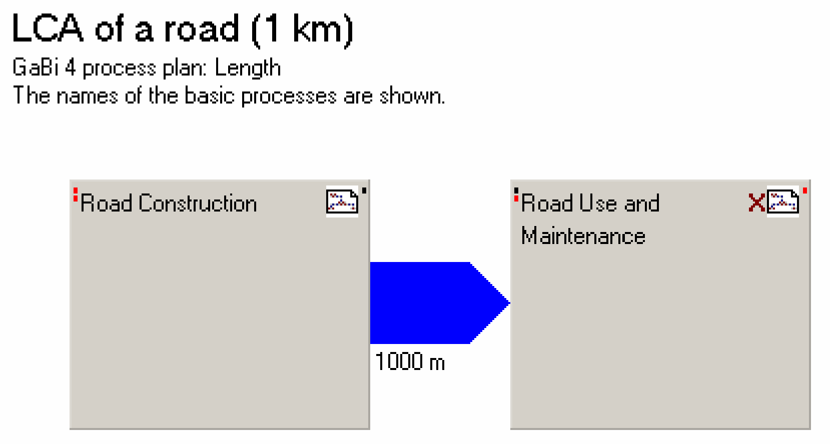
No	Description	Unit	Quantity
1	Removal of asphalt by milling machine	Tonnes	8.294
2	Paving the wearing course by finisher machine (in 1 layer)	Tonnes	8.294
3	Compaction of wearing course by roller compactor	m^2	88.235
4	Open loop recycling of removed asphalt (-ve consumption of virgin materials)	Tonnes	8.294
5	Transportation of asphalt from asphalt plant to site by	Tonnes*km	157.586

	27t-trailer		
6	Mixing of wearing course asphalt at asphalt plant	Tonnes	8.294
7	Transportation of bitumen from refinery to asphalt plant by tanker truck	Tonnes*km	34.580
8	Production of bitumen at refinery	Tonnes	494
9	Transportation of aggregates from quarry to asphalt plant by 24t-trailer	Tonnes*km	7.800
10	Production of aggregates at quarry	Tonnes	7800

3.3 The LCI modelling

The modelling of the system has been done with the help of the GaBi Software. The software system GaBi is a tool for the build up of life-cycle-balances.

The modelling of the road life cycle included the construction phase and the use phase of the road (Figure 3.5). The construction phase includes the material production processes, the transportation processes and road construction processes as excavation of the site and material placement. As mentioned before, the demolition and disposal phase has not been included in the model.



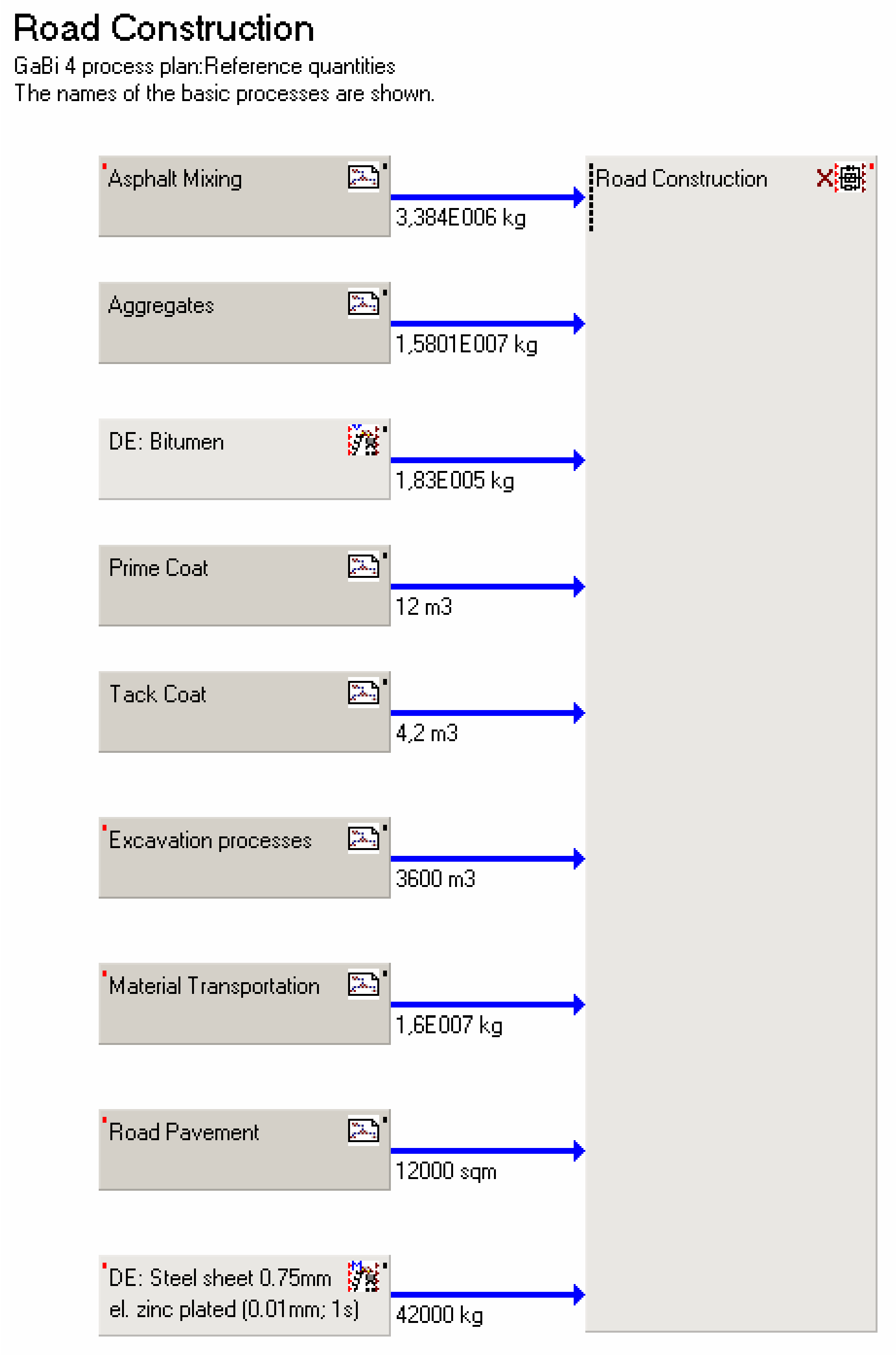
LCA of a road (1 km)

GaBi 4 process plan: Length

The names of the basic processes are shown.

Figure 3.5: The life cycle model of road pavement

The modelling of the construction phase of the road is presented into Figures 3.6. The modelling presents the amount of the most important materials that were used for the construction of the road. The materials that were used for the construction of the road included aggregates, bitumen and steel. Asphalt consists of aggregates and bitumen that are mixed in the asphalt production plant. For the production of one ton of asphalt, 8lt of liquid fuel is consumed (Figure 3.7).



Road Construction

GaBi 4 process plan:Reference quantities
The names of the basic processes are shown.

Figure 3.6: The construction phase modelling of the road

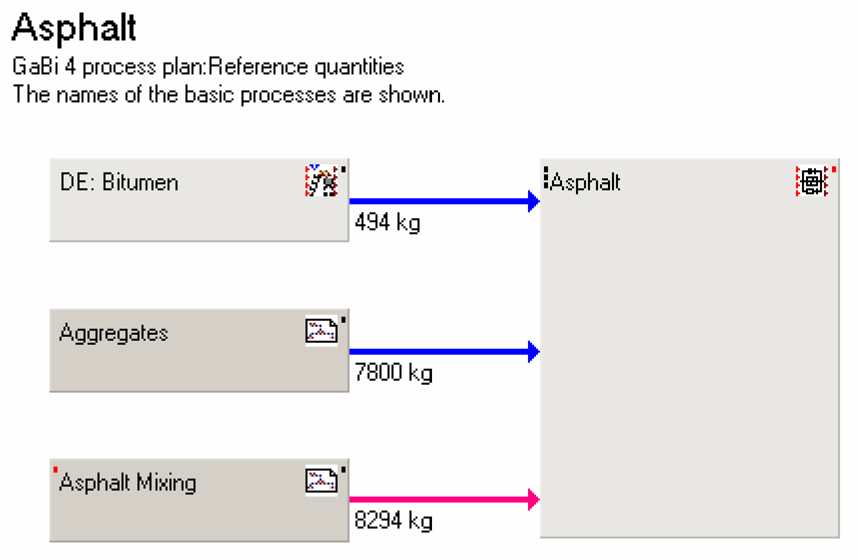

Asphalt
GaBi 4 process plan:Reference quantities
The names of the basic processes are shown.

Figure 3.7: The modelling of asphalt production

The use phase of the road includes all material and energy consumed during road maintenance. The life span of the road is modelled to be 50 years (Figure 3.8).

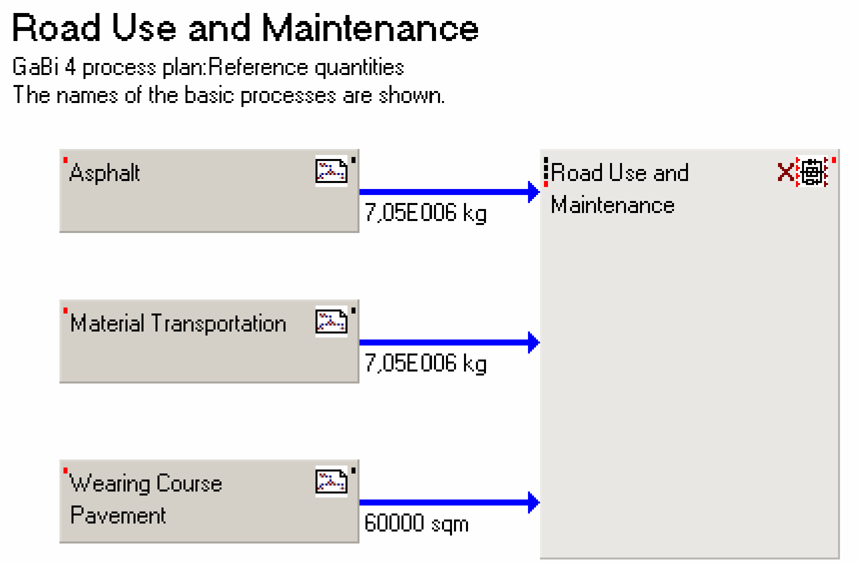

Road Use and Maintenance
GaBi 4 process plan:Reference quantities
The names of the basic processes are shown.

Figure 3.8: The modelling of the use phase of the road

4 Impact Assessment

4.1 Procedure

The impact assessment step analyzes and evaluates the magnitude and significance of the potential environmental impacts of the life cycle of the road. The results of the Inventory analysis are translated into contributions to relevant impact categories. Impact assessment consists of three steps:

- classification
- characterisation
- normalisation and
- evaluation

The classification assigns data identified in the inventory stage to various impact categories such as global warming, acidification, eutrophication, ozone layer depletion, and photochemical ozone creation.

The characterisation step aims at quantifying and aggregating the potential effects, normalized to the functional unit of the product system studied. In the characterisation step of Impact assessment the environmental interventions assigned qualitatively to a particular impact category in classification are quantified in terms of a common unit for that category, allowing aggregation into a single score: the indicator result. The resulting figure for one particular impact category is referred to as a category indicator result, and the complete set of category indicator results as the environmental profile. Equivalence factors are used for the different environmental effects.

Normalization is defined as an optional element relating all impact scores of a functional unit to the impact scores of a reference situation. This reference situation may be so-called actual flows of a certain region, but also variations in space or time of these. The main aim of normalization is therefore to relate the environmental burden of a product to the burden in its surroundings.

Normalization only reveals which effects are large, and which effects are small, in relative terms. It says nothing of the relative importance of these effects. Evaluation factors are used for this purpose. The evaluation step is the process where the impact scores of the different impact categories are compared and weighted for the comparison of the alternative products/processes. The relative importance of the impact scores is brought into perspective by normalization. In this way, impact scores are related to the total magnitude of the given impact category from all sources in a given area/period.

4.2 The CML2001 impact assessment weighting factors

Table 4.1 presents the normalization factors and Table 4.2 the evaluation factors used for the purpose of this study. The CML factors are used that were developed by the Institute of Environmental Sciences of the Leiden University[1].

Table 4.1: CML2001 Normalization factors (Europe)

Quantity	**Unit**	**Weights**
CML2001, Abiotic Depletion (ADP)	kg Sb-Equiv.	4,94E-11
CML2001, Acidification Potential (AP)	kg SO2-Equiv.	2,68E-11
CML2001, Eutrophication Potential (EP)	kg Phosphate-Equiv.	5,88E-11
CML2001, Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.)	kg DCB-Equiv.	1,45E-12
CML2001, Global Warming Potential (GWP 100 years)	kg CO2-Equiv.	1,55E-13

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[1] http://www.leidenuniv.nl/interfac/cml/ssp/index.html

CML2001, Human Toxicity Potential (HTP inf.)	kg DCB-Equiv.	9,69E-14
CML2001, Marine Aquatic Ecotoxicity Pot. (MAETP inf.)	kg DCB-Equiv.	6,46E-15
CML2001, Ozone Layer Depletion Potential (ODP, steady state)	kg R11-Equiv.	8,83E-09
CML2001, Photochem. Ozone Creation Potential (POCP)	kg Ethene-Equiv.	8,90E-11
CML2001, Radioactive Radiation (RAD)	DALY	1,51E-05
CML2001, Terrestric Ecotoxicity Potential (TETP inf.)	kg DCB-Equiv.	1,55E-11

Table 4.2: CML2001 Evaluation factors (Southern Europe)

Quantity	Unit	Weights
CML2001, Abiotic Depletion (ADP)	kg Sb-Equiv.	1,5
CML2001, Acidification Potential (AP)	kg SO2-Equiv.	1
CML2001, Eutrophication Potential (EP)	kg Phosphate-Equiv.	7
CML2001, Global Warming Potential (GWP 100 years)	kg CO2-Equiv.	10
CML2001, Ozone Layer Depletion Potential (ODP, steady state)	kg R11-Equiv.	2
CML2001, Photochem. Ozone Creation Potential (POCP)	kg Ethene-Equiv.	3
CML2001, Radioactive Radiation (RAD)	DALY	0,5

The environmental score of each effect is calculated based on the simple formula:

Environmental Score = Characterized Value x Normalization factor x Weighting factor

4.3 Impact assessment of the road life cycle

The total environmental score of the road life cycle is 2,85E-06 (Figure 4.1). The score value is dimensionless and its importance can be found by comparing it with the environmental scores of relative construction processes. The construction stage contributes by 51% to the total environmental score and the use phase by 49% (Figure 4.2).

The relative contribution of the environmental impacts to the total environmental score can be seen to Figure 4.3. The global warming potential is the environmental impact with the largest contribution to the overall score. The contribution of GWP to the total score is 52,19% (Figure 4.3). GWP contributes by 56,23% to the construction phase and by 48,05% to the use phase of the road (Figure 4.4 and 4.5).

Photochemical ozone creation (POC) contributes by 24,44% to the total environmental score. POC contributes by 19,87% to the environmental impact of the construction phase of the road. At the same time it contributes 29,11% to the overall impact of the use phase due to impacts of bitumen production processes.

The acidification potential contributes by 6,90% to the total life cycle (production and use phase). Acidification contributes by 7,23% to the environmental impact of the construction phase of the road. At the same time it contributes 6,58% to the overall impact of the use phase.

The eutrophication potential contributes by 15,74% to the total life cycle (production and use phase). Eutrophication contributes by 15,99% to the environmental impact of the construction phase of the road. It also contributes 15,49% to the overall impact of the use phase.

The ozone layer depletion potential contributes by only 0.60% to the total impact. Radioactive radiation is also contributing by only 0.13% due to energy consumption for galvanised steel production that is done in European countries where nuclear energy is part of the total electricity production.

The contribution of each construction material or process to the total environmental impact of the construction phase of the road is presented in Figures 4.6 and 4.7. The production and use of asphalt has the largest impact to the environmental score of the construction phase. The asphalt environmental impact is the summation of all impact related to bitumen and aggregates production and the energy consumed for the mixing process. The material transportation processes have also a large impact during the construction phase due to the consumption of diesel fuel. Bitumen that is used for asphalt production is the largest contributor to the ozone depletion potential and photochemical ozone creation effect. Diesel consumption for the transportation processes and site preparation contributes significantly to the acidification potential and the eutrophication potential (Figure 4.7).

The global warming potential is affected mostly from energy consumption processes, as material transportation, site preparation, asphalt mixing and galvanized steel production (Figure 4.8).

Asphalt consumption is the larger contributor to the environmental impacts of the use phase of the road life cycle (Figures 4.9 and 4.10). Its contribution is 79,36% to the total score of the use phase. Wearing course pavement contributes by 10,91% and material transportation processes by 9,73%. The environmental impact of asphalt is mostly affected by bitumen production and the asphalt mixing process (Figure 4.11).

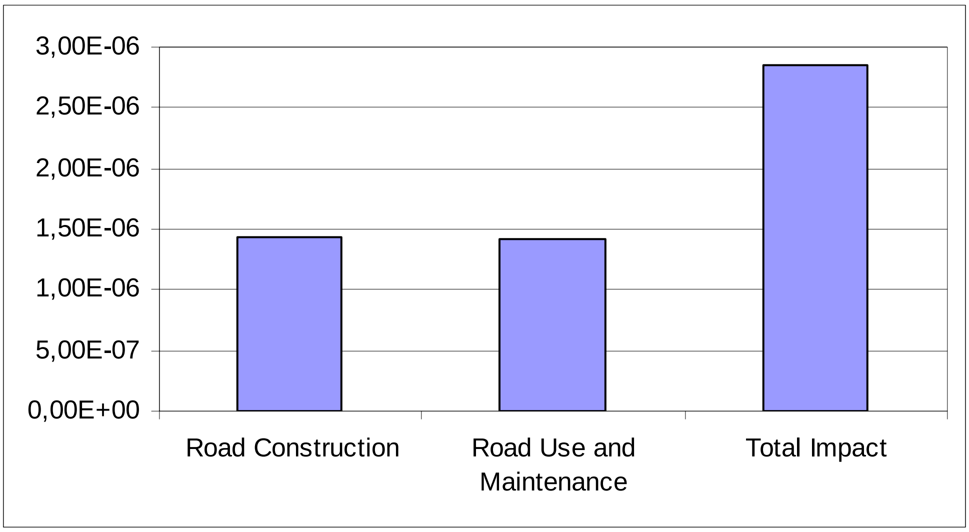

Figure 4.1: Total impact of the construction and use phase of the road

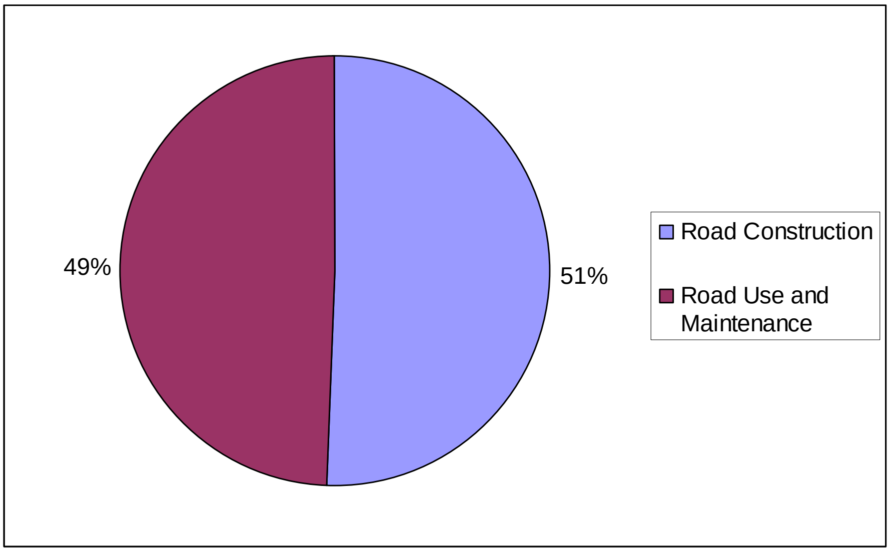

Figure 4.2: Percentage contribution to the total impact of the construction and use phase of the road

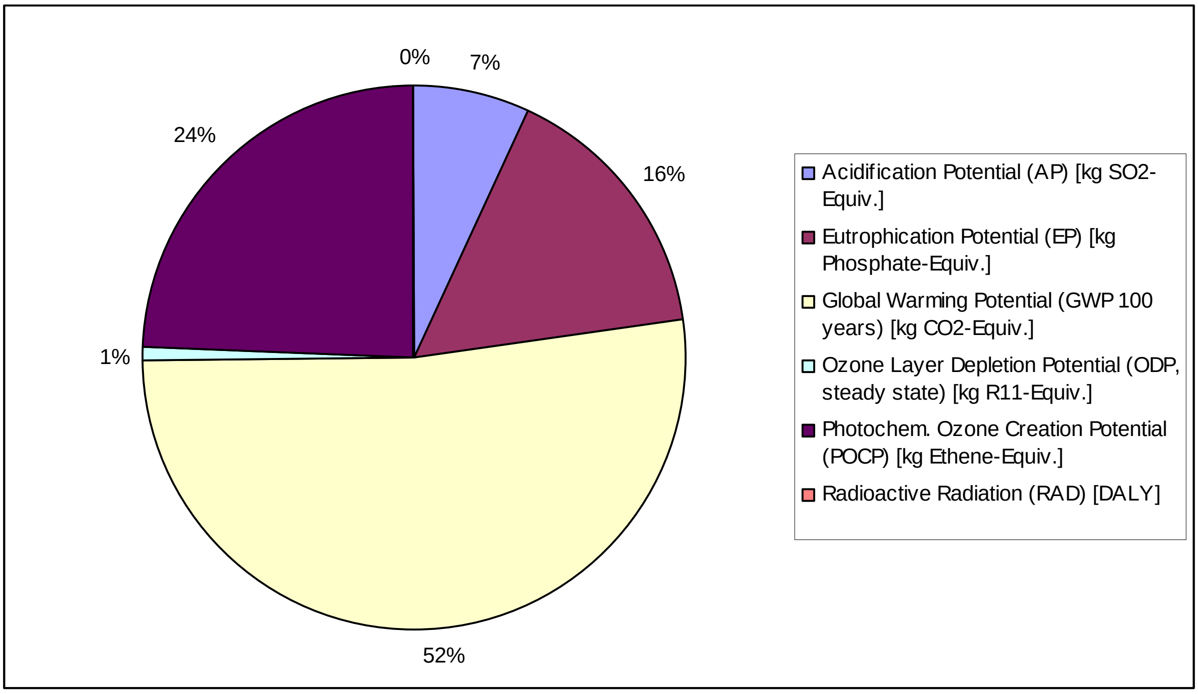

Figure 4.3: Percentage contribution of each impact category to the total environmental impact of the road

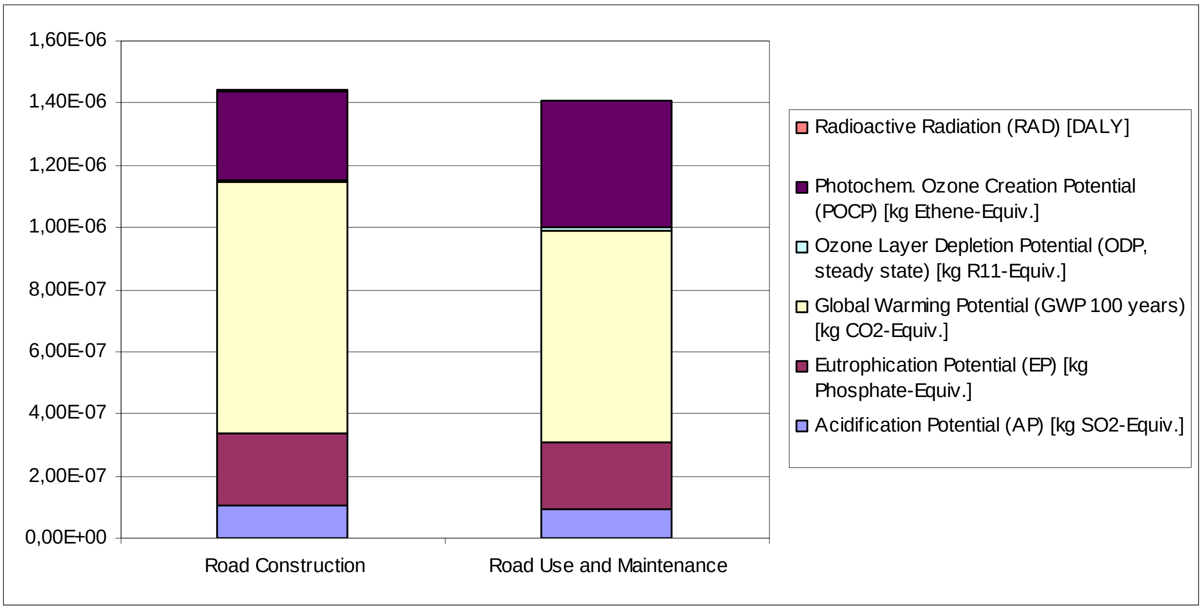

Figure 4.4: Percentage contribution of each impact category to the total impact of the construction and use phase of the road

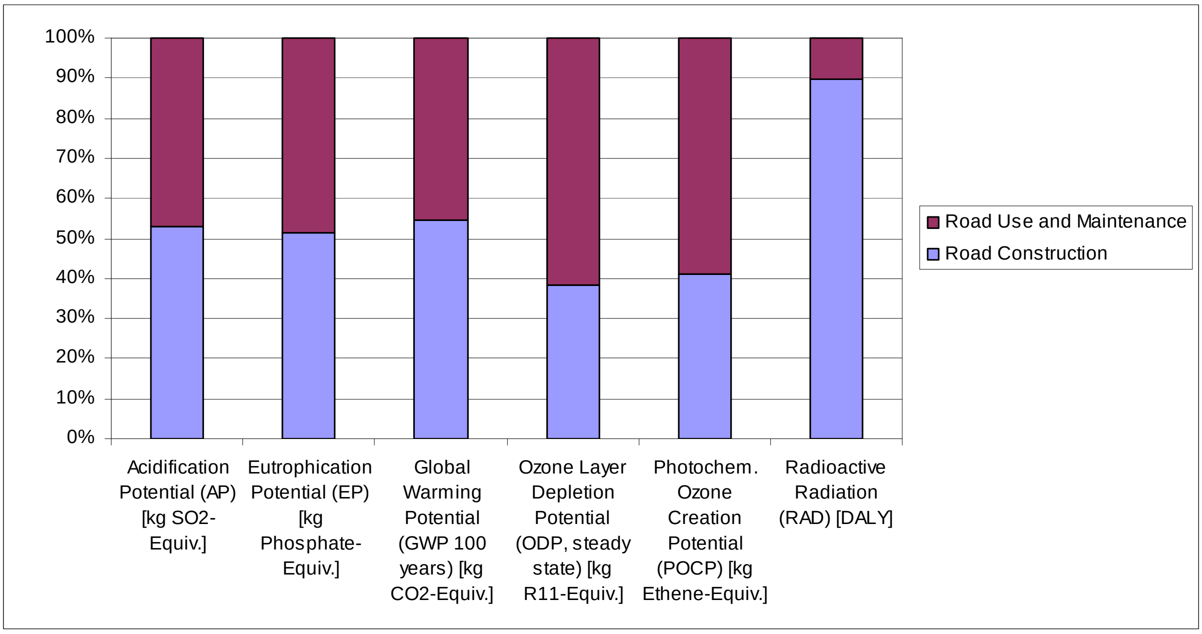

Figure 4.5: Percentage contribution of each life cycle phase to the total of each impact category

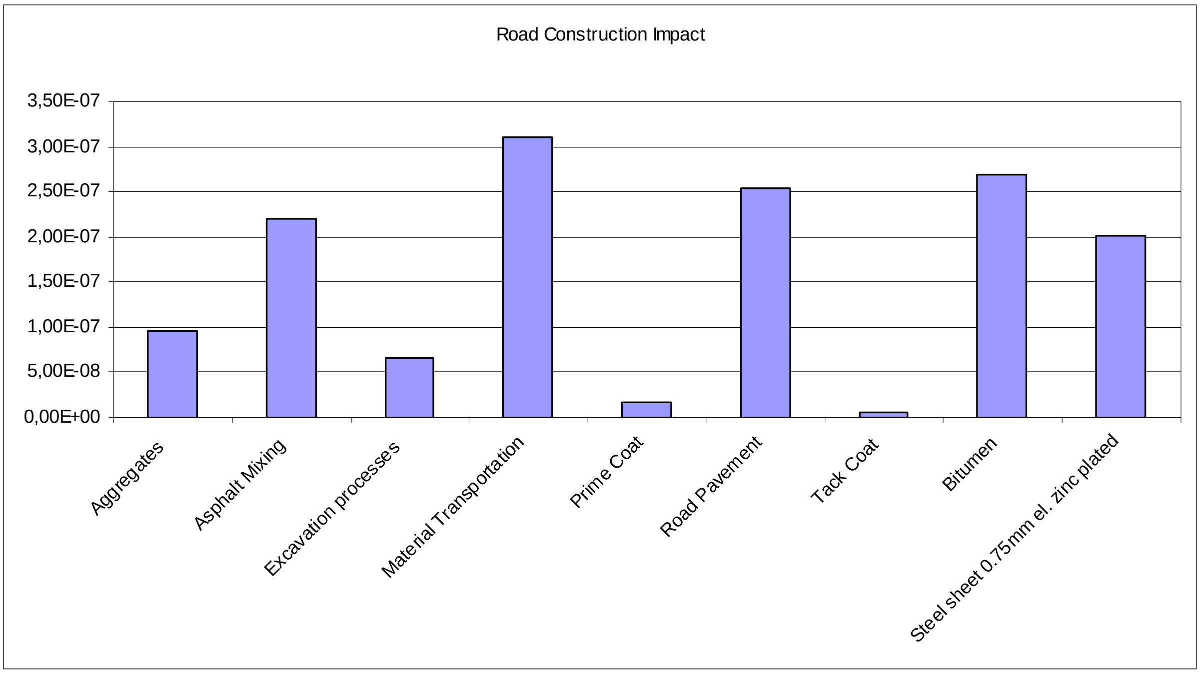

Figure 4.6: Contribution of each construction material - component to the total environmental impact of the construction phase of the road

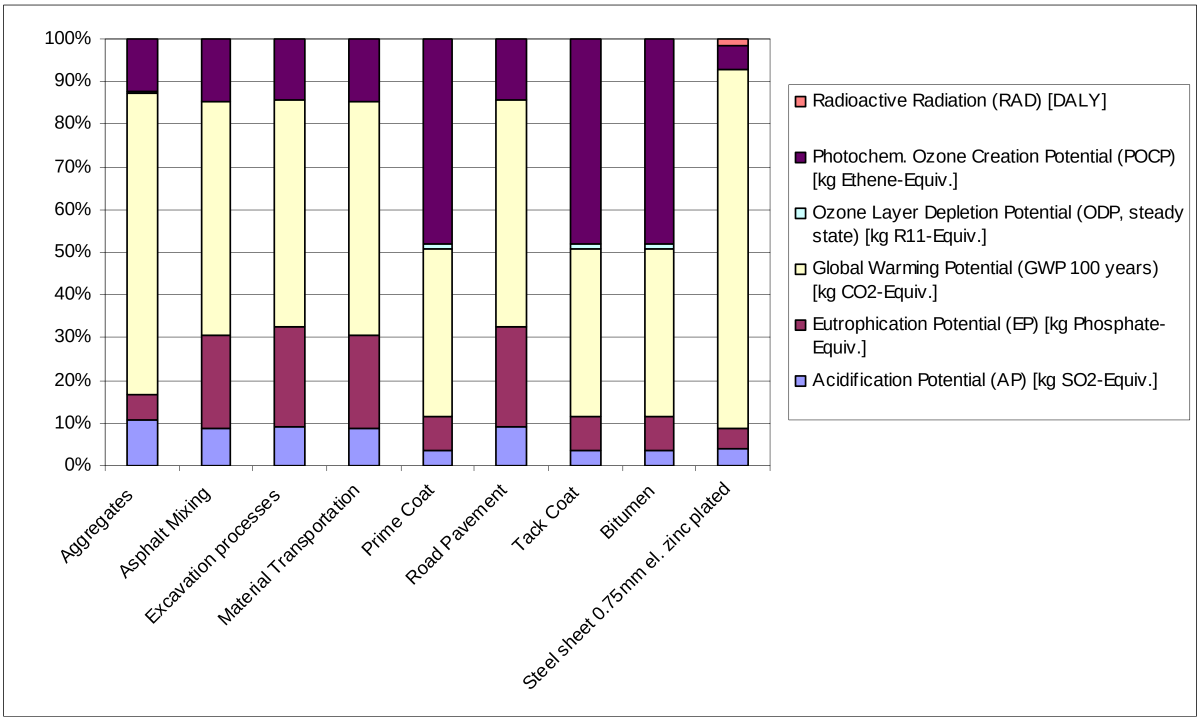

Figure 4.7: Contribution of each construction material - component to the total environmental impact of the construction phase of the road

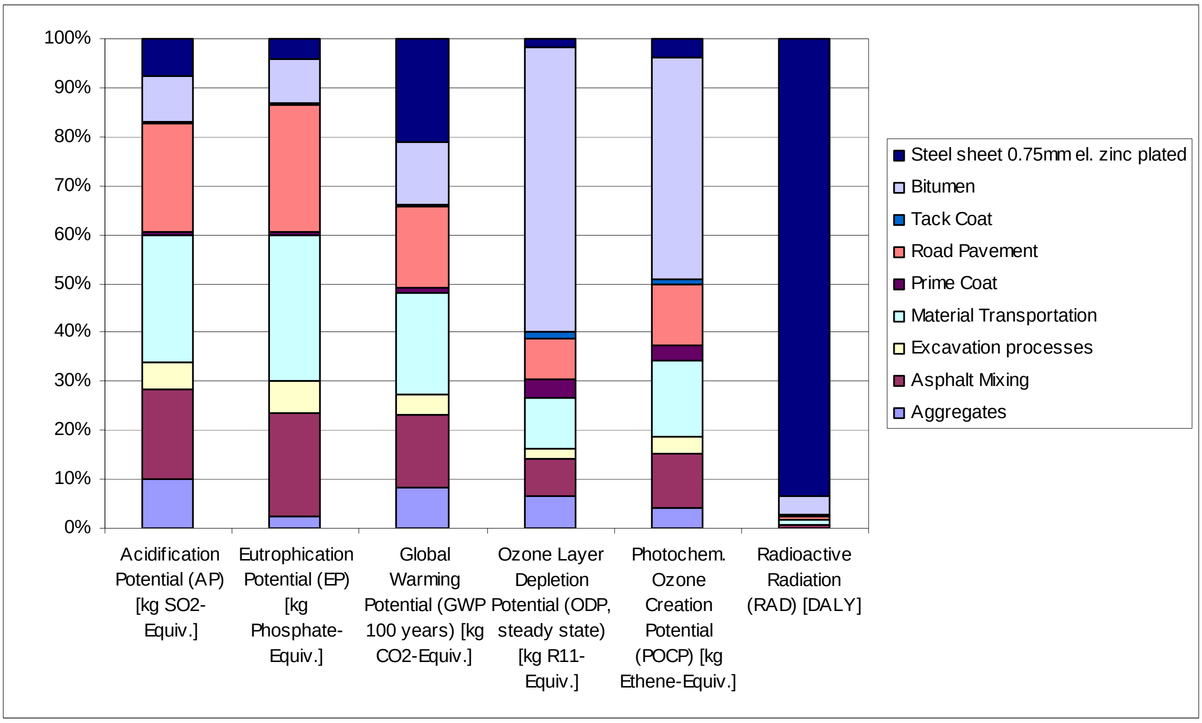

Figure 4.8: Contribution of each construction material - component to the total environmental impact of the construction phase of the road

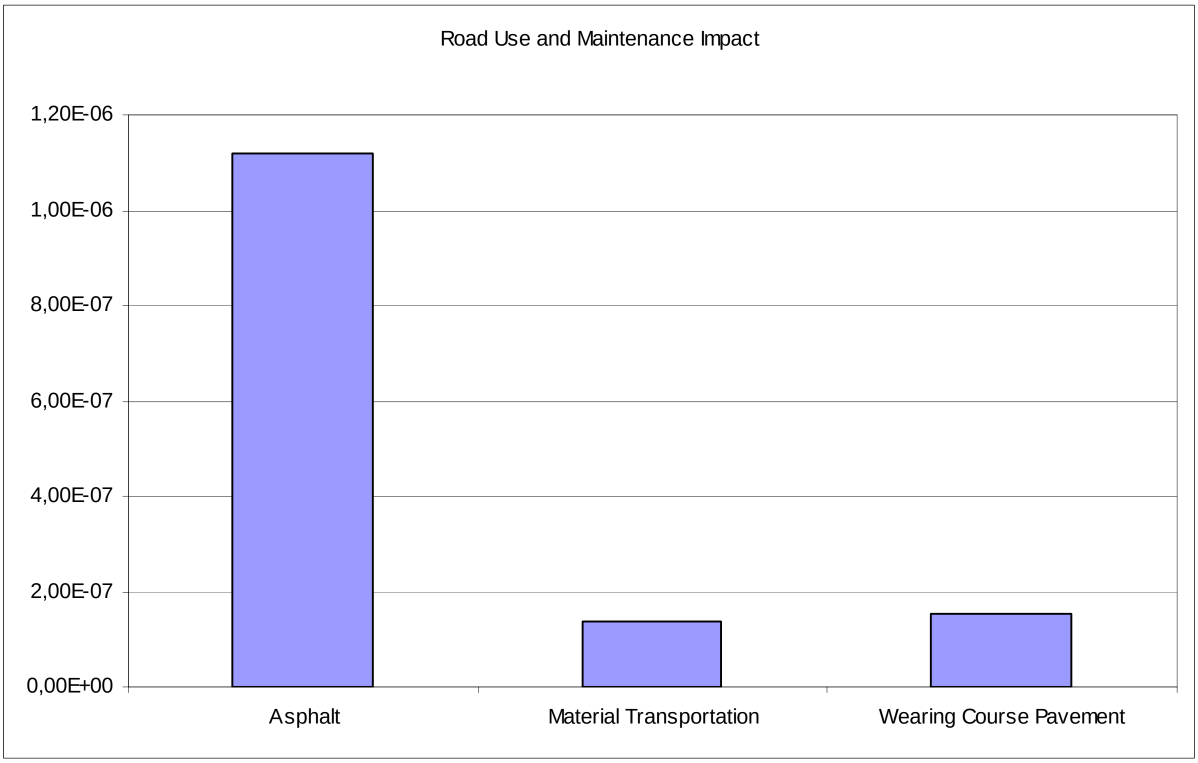

Figure 4.9: Contribution of each construction material - component to the total environmental impact of the use phase of the road

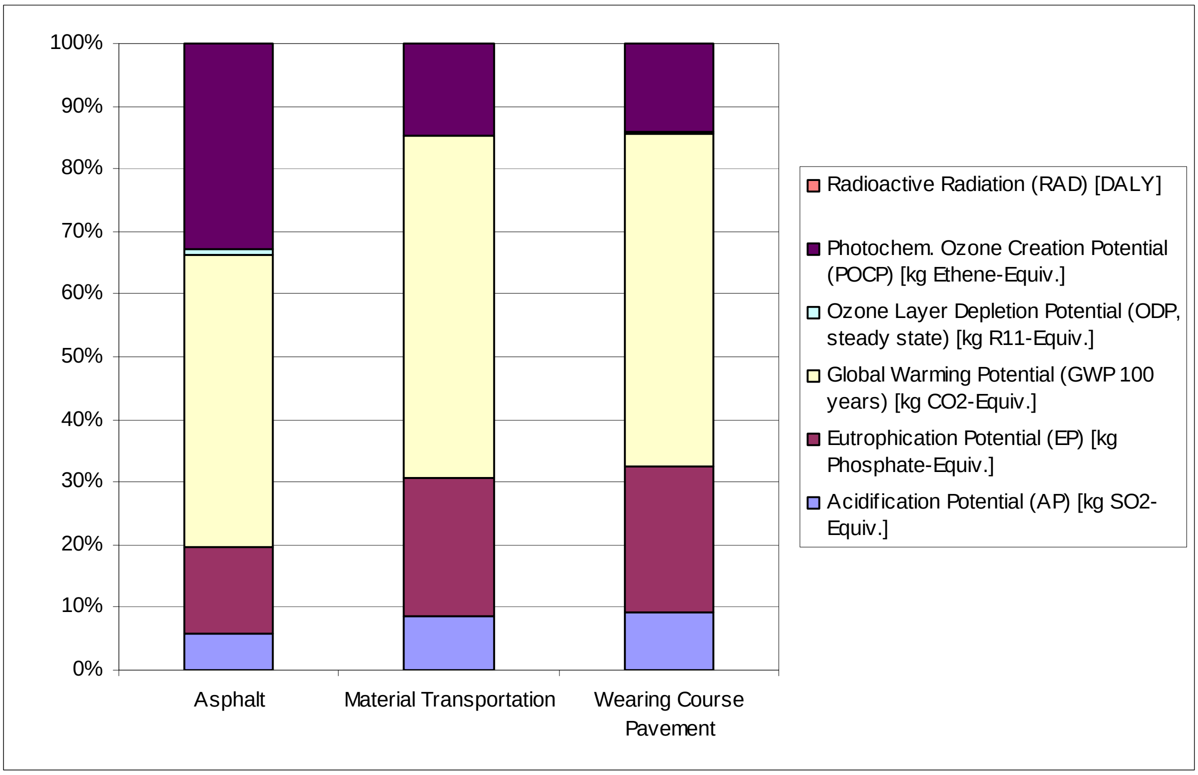

Figure 4.10: Contribution of each construction material - component to the total environmental impact of the use phase of the road

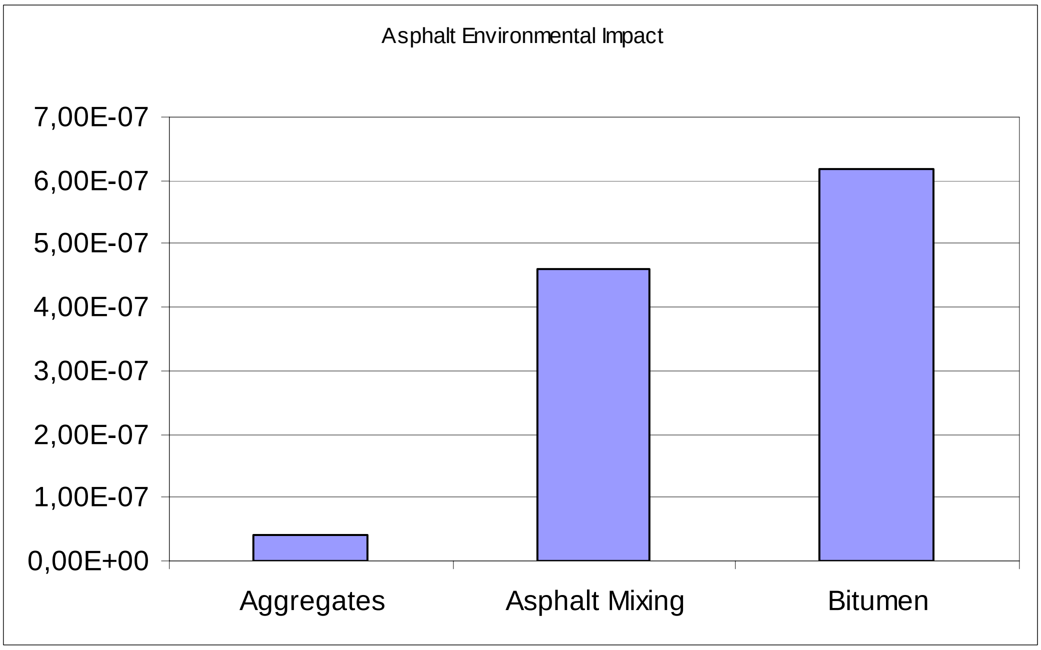

Figure 4.11: Contribution of each material - process to the total environmental impact of the asphalt production process

The number of safety bars used during road construction affects significantly the environmental profile of the road life cycle. If safety bars are used to both sides of each road lane then the total mass of galvanised steel is doubled (84 tons compared to 42 tons). In this case the construction phase contributes by 53,84% to the total environmental score and the use phase by 46,16%. Due to the energy intensiveness of the production process, it appears to have largest impact than bitumen during the construction process (Figures 4.13). It also raises its contribution to all environmental impact categories (Figure 4.14).

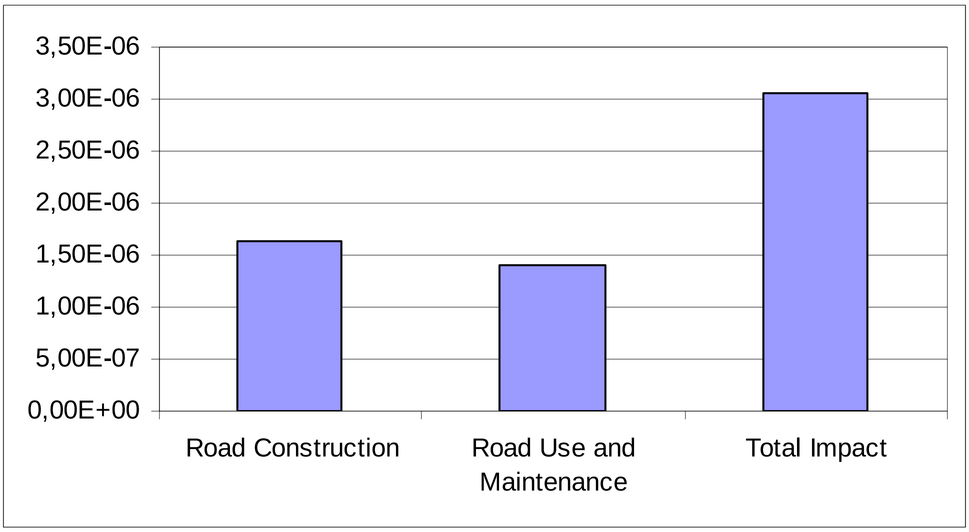

Figure 4.12: Total impact of the construction and use phase of the road in the case of double safety bars use for road construction

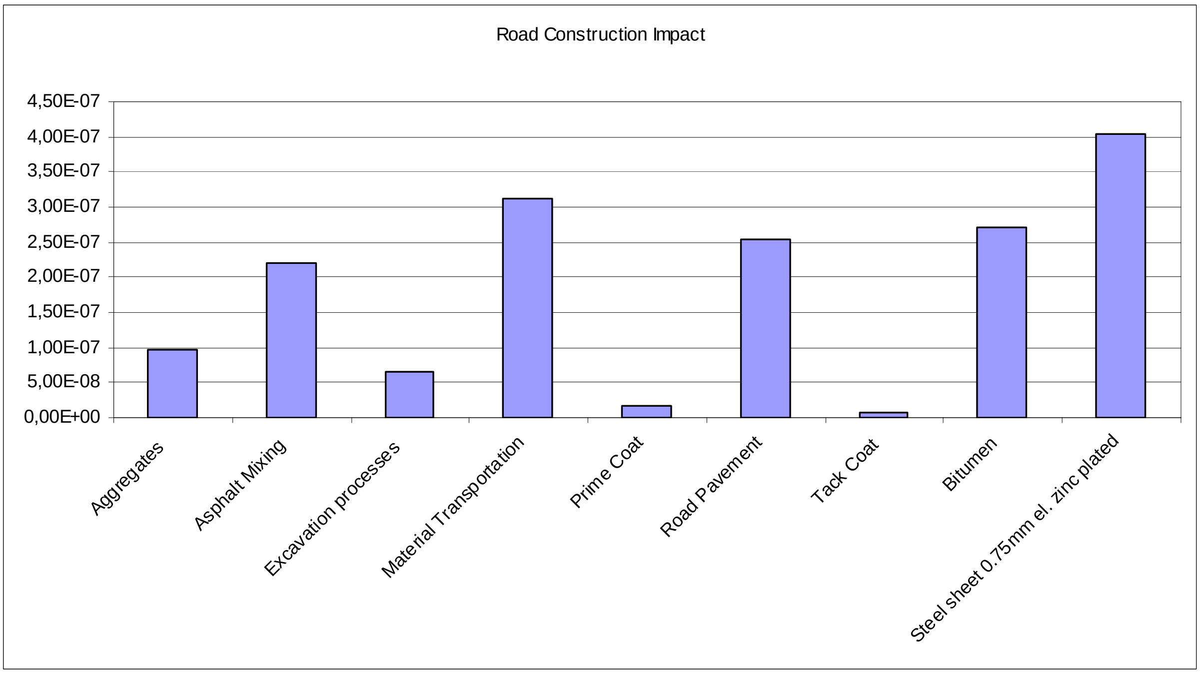

Figure 4.13: Contribution of each construction material - component to the total environmental impact of the construction phase of the road in the case of double safety bars use for road construction

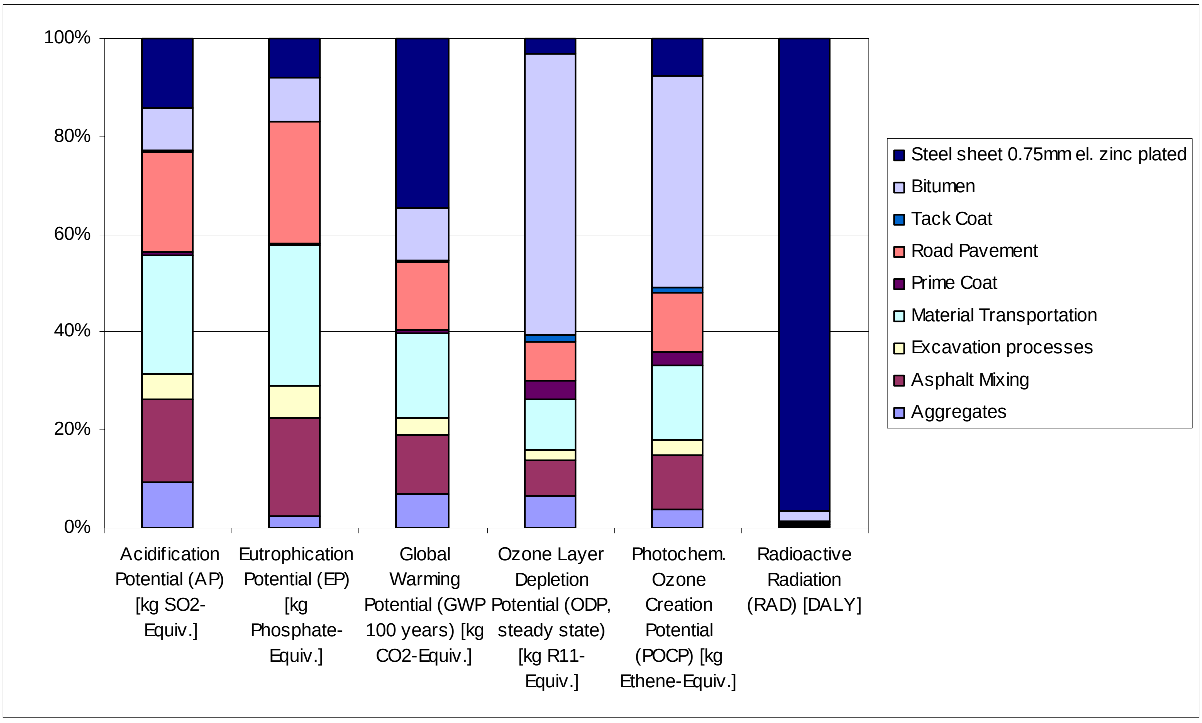

Figure 4.14: Contribution of each construction material - component to the total environmental impact of the construction phase of the road in the case of double safety bars use for road construction

5 Conclusions

The environmental impacts of the road life cycle are almost equally distributed among the construction and the use and maintenance phase of the road. The construction stage contributes by 51% to the total environmental score and the use phase by 49%.

The results showed that the construction phase environmental impacts are affected by the material production and transportation processes. Material selection can affect the environmental profile of the road life cycle. Bitumen, asphalt and steel production have large impact during construction. Fuel consumption during the transportation, excavation and pavement processes also contributes to the total impact during construction.

The use phase is mostly affected by the maintenance process. The wearing course is replaced every 8,5 years and asphalt is consumed for the construction of a new layer. The environmental impact of asphalt is mostly affected by bitumen production and the asphalt mixing process. Bitumen is the largest contributor to the ozone depletion potential and photochemical ozone creation effect.

Global warming potential is the environmental impact with the larger contribution to the total environmental score of the life cycle. Energy consumption during the material production processes and diesel consumption during the transportation processes are the reason of the production of large amounts of air emissions contributing to the GWP.

The environmental impact of the transportation processes is attributed to diesel consumption. The large amount of mass of the aggregates and asphalt transferred during the construction phase is the main reason of fuel consumption during the transportation phase.

6 References

[1] SETAC, “Guidelines for Life Cycle Assessment: A code of practice”, Society of Environmental Toxicology and Chemistry, Washington DC, 1993

[2] U.S. Environmental Protection Agency and Science Applications International Corporation, LCAccess - LCA 101, 2001

[3] ISO (1997a). Environmental management - Life cycle assessment - Principles and framework. ISO/FDIS 14 040

[4] Life cycle assessment: An operational guide to the ISO standards, 2001. Jeroen B. Guinée (final editor) – Marieke Gorrée – Reinout Heijungs - Gjalt Huppes – René Kleijn – Arjan de Koning – Lauran van Oers - Anneke Wegener Sleeswijk – Sangwon Suh – Helias A. Udo de Haes, Centre of Environmental Science – Leiden University (CML)

[5] Leiden University, C.f.E.S., Guide to LCA, Part 2b: Operational Annex, Leiden University, Centre for Environmental Science, Leiden, NL, 2000