POLITECNICO DI TORINO

College of Civil Engineering

Master of Science in Civil Engineering

Master of Science Thesis

Life Cycle Assessment of Pavements through PaLATE

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2019/2020

Declaration

I declare that this thesis has been composed solely by myself and that it has not been submitted, in whole or in part, in any previous application for a degree. Except where states otherwise by reference or acknowledgment, the work presented is entirely my own.

Tomás Tisberger

2020

Acknowledgments

The work presented in this thesis has been carried out at Politecnico di Torino, at the Department of Environment, Land and Infrastructure Engineering.

I would especially like to thank to my supervisor, Professor Ezio Santagata and co-supervisor, Professor Lucia Tsantilis, for their guidance during the process. I give my high regards to Prof. Tsantilis for being every day helping me, because what I have achieved, wouldn’t have been possible without her time and supervision.

I am very grateful to Ms. Arianna Vercelli from Sitalfa S.p.A. company, for her contribution to the thesis providing information. I would also like to acknowledge Ms. Angela Farina and Mr. Eldho Choorackal Avirachan for providing data for this work.

I am indebted and grateful with Universidad Nacional de Cordoba and all its members who made it possible to finish my Civil Engineer degree in Italy.

Special thanks to my mom, dad and brothers for being my principal support in life and their belief in me.

In the end, I want to thank my family, loved ones and friends in Argentina for their love and moral support.

Tomás Tisberger

Torino, March 2020

Abstract

Sustainability concepts are becoming more and more popular over the years. In the transportation field, pavement´s construction plays a leading role regarding environmental issues and impacts; hence, different tools and methodologies are arising to handle them. The aim of this work is to critically analyze the possibility of employing one of these tools called PaLATE (Pavement Life-cycle Assessment Tool for Environmental and Economic Effects) in Europe. This tool works within a "Life Cycle Assessment" (LCA) methodology, which takes into account the whole process of a pavement construction, making emphasis principally in sustainability and giving an estimation of environmental burdens (emissions and resources´ consumption) useful for decision-makers, companies, governmental and non-governmental organizations. To achieve the goal of this thesis two case studies were considered; the first one is the construction of the "Torre del Colle" viaduct located in the Piedmont region of Italy a few kilometers away from Turin in which the pavement is composed by two bituminous mixture layers. The second one, is that of an Italian extra-urban road also located in the Piedmont region and it is a traditional pavement composed by three bituminous mixture layers and one made of crushed granular material. Finally, with these cases, it was possible to highlight advantages, drawbacks and limitations of PaLATE.

Keywords: sustainability, pavement, environmental issues, PaLATE, Life Cycle Assessment, environmental burdens, emissions.

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List of Acronyms

LCA: Life Cycle Assessment

ISO: International Organization for Standardization

EOL: End-of-life

LCI: Life Cycle Inventory

LCIA: Life Cycle Impact Assessment

GWP: Global Warming Potential

EIA: Environmental Impact Assessment

PaLATE: Pavement Life-cycle Assessment Tool for Environmental and Economic Effects

IO-LCA: Input-Output Life Cycle Assessment

EIO-LCA: Economic Input-Output Life Cycle Assessment

EMF: Electromotive Force

SETAC: Society of Environmental Toxicology and Chemistry

EPA: Environmental Protection Agency

RAP: Recycled Asphalt Pavement

FRAP: Fractionated Reclaimed Asphalt Pavement

RAS: Recycled Asphalt Shingles

RCA: Recycled Concrete Aggregates

RCM: Reclaimed Concrete Material

HIPR: Hot In-Place Recycling

CIR: Cold In-Place Recycling

FDR: Full-depth Reclamation

CO_2: Carbon Dioxide

NOx: Nitric Oxide

PM_{10}: Particulate Matter 10 milimeters of diameter

SO_2: Sulfur Dioxide

CO: Carbon Monoxide

Hg: Mercury

Pb: Lead

RCRA: Resource Conservation and Recovery Act

HTTP: Human Toxicity Potential

DNA: Deoxyribonucleic damage

VOC: Volatile Organic Compounds

H_2S: Hydrogen Sulphide

USCU: United States Customary Units

SI: International System of Units

CDD/CDF: Chlorinated Dibenzodioxin/Chlorinated Dibenzofuran

PMB: Polymer Modified Bitumen

SMA: Stone Mastic Asphalt

JPCP: Jointed Plain Concrete Pavement

C&DW: Crushing and Demolition Waste

UK: United Kingdom

CH_4: Methane

N_2O: Nitrous Oxide

GHG: Greenhouse Gases

hp: Horsepower

FC: Fuel Consumption

BTZ: Basso Tenore di Zolfo

GER: Gross Energy Requirement

Nm^3: Normal cubic meter

DIV: Default Input Values

EIV: Estimated Input Values

1 Introduction

1.1 Problem Statement and Objective

Nowadays the planet is going through an era in which environmental issues are gaining ground. Global Warming Potential, Ozone Depletion and Climate Change topics are of utmost importance and governments around the world are wishing to reduce pollution and contribute to the globe. Not just these environmental concerns are of importance but also the consumption of natural resources, therefore, the life of future generations of humans is being threatened and sustainability concepts is a common pursuit of everybody today.

The engineering world is a starting point in this matter and several projects and ideas are being developed in order to save the planet. The construction industry and, more specifically, the road construction business should be aware of the situation due to the fact that *"transportation infrastructures represent key elements for characterizing the level of development and welfare of a given country"* (Celauro et al., 2015). Roads are leading components of transport infrastructures and one of the most used civil constructions in the whole world, making available the mobility of people and freights. Roads can be understood as links.

Fortunately, due to these environmental issues, transportation scenarios are turning towards greener futures and a large number of researches and studies devoted to evaluate the environmental impact of road infrastructures mainly based on Life Cycle Assessment (LCA) approaches, which are being incorporated in different tools created around the world to manage these issues in the pavement construction field. These tools are becoming really important because they provide environmental impacts generated through the whole life cycle of a pavement, and with this information agencies, companies, decision-makers, governmental and non-governmental organizations can take control of the situation, recognizing points to improve during road design, maintenance and management, for then, take final decisions in order to conclude the project as "greener" and "environmentally friendly" as possible.

With the aim of contributing towards a better future in Europe, the objective of this present work is to critically analyze the possibility of employing one of these tools called PaLATE in the named continent. To achieve this goal, two different case studies of real road constructions in Italy will be developed through this tool. As PaLATE was created in the University of California, Berkeley, every data that compounds it is from United States, so, for the aim of this thesis, an exhaustive research through a large variety of literature was done in order to modify the background default data into information representative of an European situation.

1.2 Thesis Structure

First of all, in chapter 2, a description of the LCA methodology will be done in order to make as clear as possible to the reader the basis of PaLATE. Then, in chapter 3, a general characterization of PaLATE will be exposed with the objective of giving an overview of the software. Further on, in chapter 4 (the central chapter of the thesis), a demonstration of how the default information was changed will be explained and the two case studies will be developed in order to, finally in chapter 5, make conclusions highlighting eventual criticisms or limitations related to the use of this tool.

2 Generalities of Life Cycle Assessment Methodology

2.1 Introduction to LCA

The environment is playing an important role in the last decades due to all the activities carried out by the human in every possible sector, efforts are being made to quantify environmental effects and to embrace them into the decision-making process in a more systematic and organized fashion. A great number of companies, institutes and governing bodies are adopting sustainability principles in managing their projects (Federal Highway Administration (FHWA), 2014). Thus, methods and instruments concerning these problems are emerging, "Life Cycle Assessment" (known as LCA) is one of them and it is a really interesting methodology where its principal objective is to estimate and understand the environmental impacts of a product, from material extraction to end-of-life disposition, each phase of the life cycle is ideally included in the assessment (Santero et al., 2010).

2.2 Origin, Principles and Purpose of LCA

2.2.1 Origin

Precursors to LCA were originally developed in the late 1960s and the principal worries were not as much as today´s. Environmental outputs analyzed were basically land, air and water emissions from solid wastes. Over the years some new outputs started being incorporated such as energy, resource use and chemical emissions, concentrating in product packaging and consumer products rather than complex infrastructure systems. Afterwards, in the late 90s, the development of new tools changed their way radically focusing in the creation of full-fledged impact assessment methods and the standardization of methods by the International Organization for Standardization (ISO). Regarding transportation, LCA topics have considered the assessment of asphalt binder and cement production and the examination of both: transportation networks and interaction between transportations infrastructures, vehicles and human behavior (Federal Highway Administration (FHWA), 2014). LCA is being more and more widespread in the International Field thanks to policies impulses in order to improve industrial production and services.

2.2.2 Principles and Purpose of LCA

In an LCA approach of a certain product, this, come evaluated in the whole process to obtain it, from raw material production till the end of the product´s life. During its life cycle different stages are under study, LCA examines inputs (energy and materials) and outputs (waste and pollution) generated in each of these, starting from raw material acquisition proceeding through other several phases as material processing, manufacturing, use and finishing at the end-of-life (EOL), furthermore, it is important to mention that transportation between stages is being considered (see Figure 1) (Federal Highway Administration (FHWA), 2014). Outputs like waste and pollution from the model can be translated into environmental and social impacts.

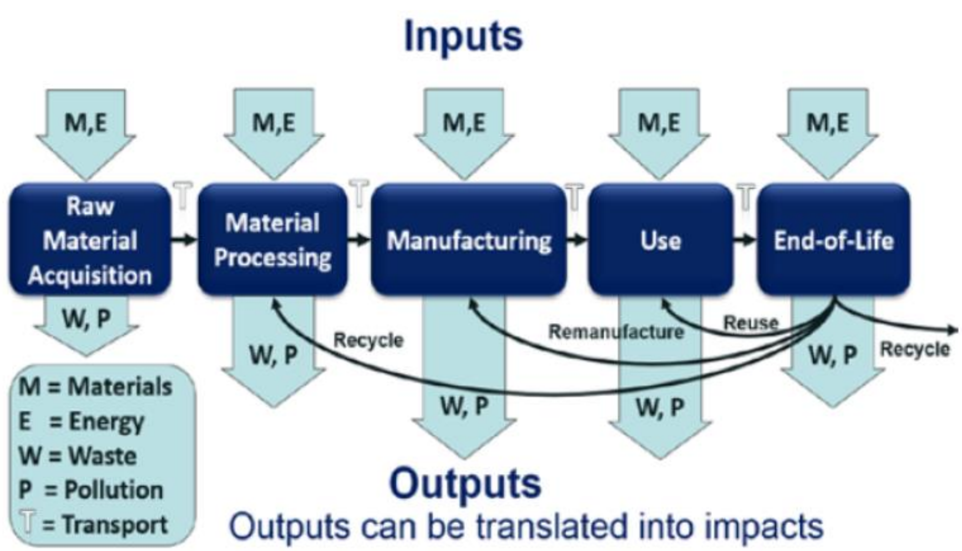

Figure 1. Generic life cycle of a production system for LCA (Federal Highway Administration (FHWA), 2014).

This figure shows a life cycle called "cradle to grave", besides, exists two other types of LCAs (see Figure 2):

i.) "Cradle-to-grave" LCA, is a complete pavement LCA from raw material extraction (cradle) to EOL disposal (grave).

ii.) "Cradle-to-gate" LCA, does not include the use or EOL stages, is a partial pavement LCA covering raw material extraction (cradle) and construction (gate) phases only.

iii.) "Cradle-to-cradle", is a close-loop LCA that the solid waste (pavement by-products) generated from construction and EOL phase is recycled or reused in material production (cradle) and has a secondary life cycle instead landfilled (Li et al., 2019) (see figure 2).

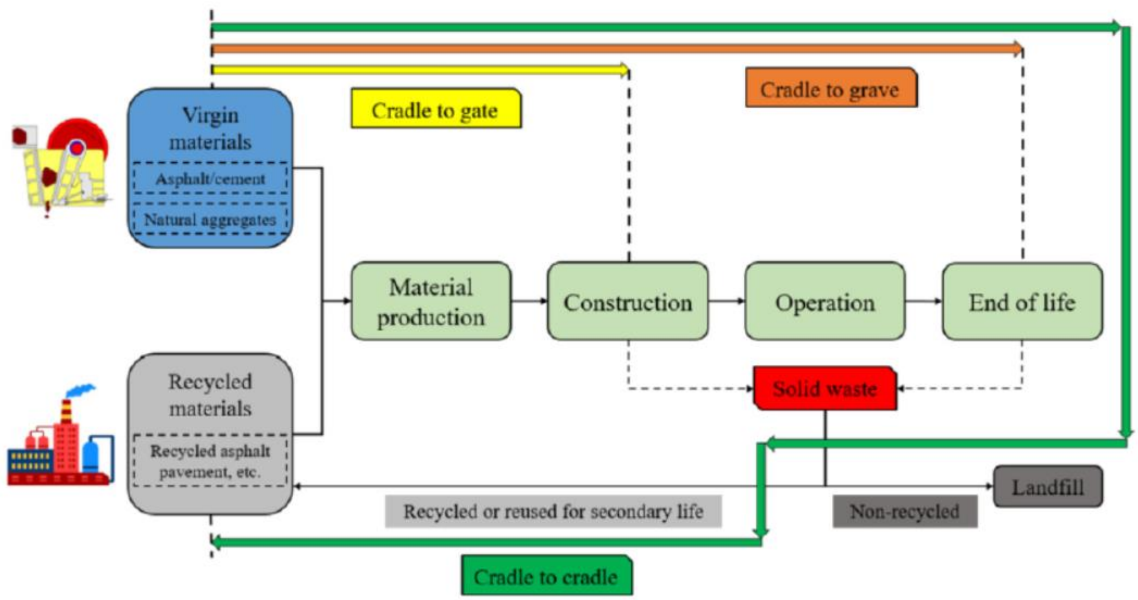

Figure 2. Diagram of three pavement LCAs (Li et al., 2019).

LCA can be utilized for a variety of important purposes to take into consideration in the modern world. Some of them can be listed as follows:

- Improve the environmental performance of products and production systems in different points of its life cycle.
- Guide decision-makers in companies, industries, government and non-governmental organizations.
- Develop relevant indicators of environmental performance of a product or production system (Federal Highway Administration (FHWA), 2014).
- Obtain a reduction of energy and depletion of resources.
- Health improvement.
- Environment saving (Pasetto et al., 2017).

When LCA methodology is properly applied it turns to be a really interesting tool due to the fact that is possible to investigate the consequences of changes that considers system-wide effects and the entire life cycle. The application of LCA to pavements is not completely developed yet, showing a number of uncertainties in the data and details, but it is believed to gain confidence as its use and application evolves.

2.3 LCA Standards. ISO 14040 and 14044.

2.3.1 Introduction

The LCA standards were created by the International Organization for Standardization (ISO) 14000 series, in order to ensure consistency in the process and provide guidelines for performing an LCA. The publication of the initial ISO standard was in 1997, ISO 14040 (prepared by Technical Committee ISO/TC 207, *Environmental management*, Subcommittee SC 5, *Life cycle assessment*) and resulted in an accepted method for LCA. The second edition of ISO 14040, together with ISO 14044:2006, cancels and replaces ISO 14040:1997, ISO 14041:1998, ISO 14042:2000 and ISO 14043:2000 (Iso, 2004). This normative defines the framework of an LCA.

2.3.2 Phases of an LCA

LCA framework is described in the ISO 14040:2006 and 14044:2006, these includes four basic phases as illustrated in Figure 3.

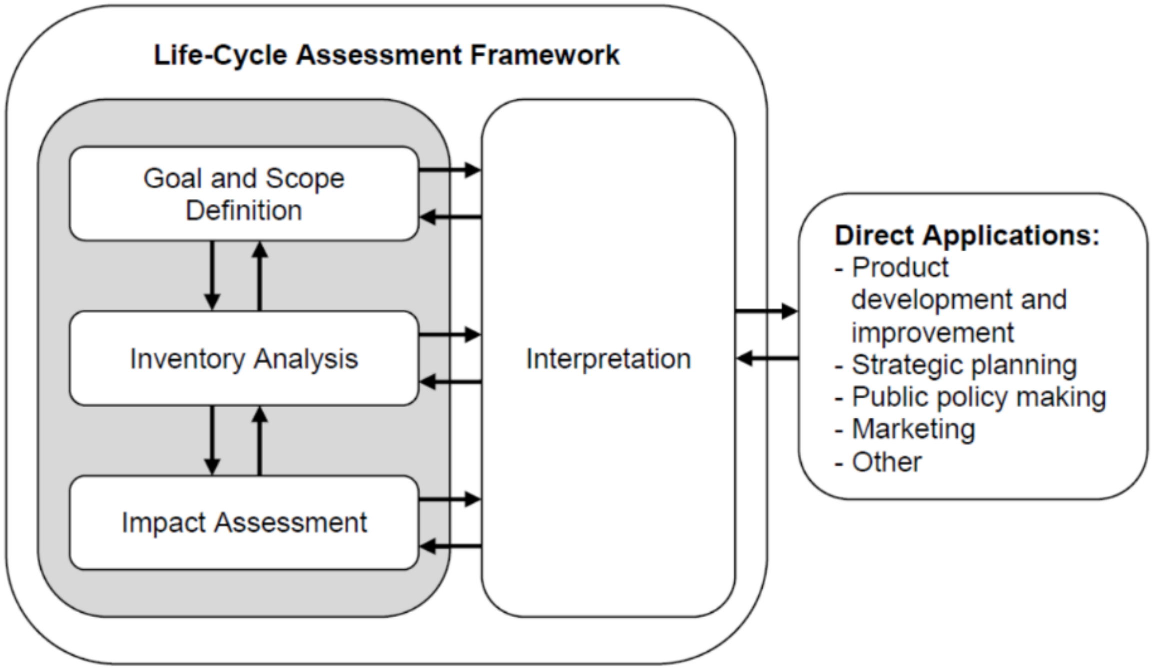

Figure 3. Basic LCA framework (Santero et al., 2010).

1. Goal and scope definition. Determines the guidelines to be followed during the rest of the study by specifying the reason for conducting the study, the intended use of the results, intended audience, the system boundaries, the functional unit, the data requirements and the study limitations (Celauro et al., 2015). The system boundary settle which process might be included in an LCA, an example can be seen in Figure 4. The functional unit is a reference to which inputs and outputs are related.

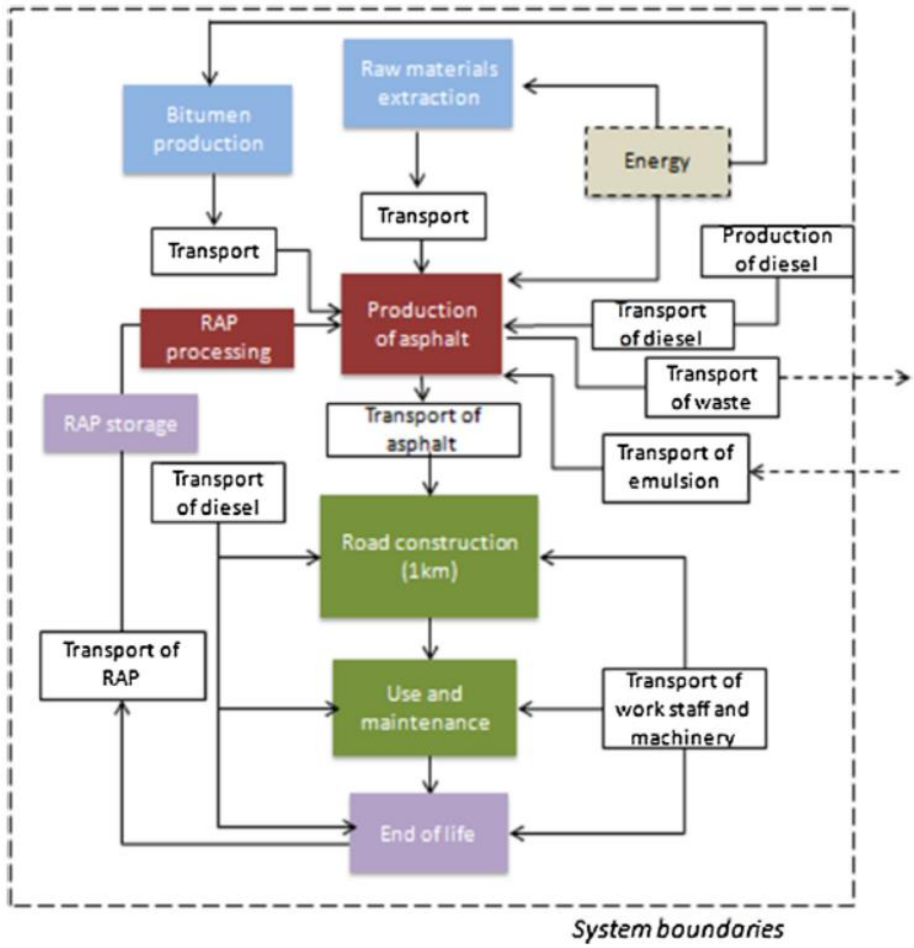

Figure 4. System boundaries (Giani et al., 2015).

2. Inventory Analysis. "Life Cycle Inventory" (LCI) phase focuses on the primary data collection, quantifies the consumption of resources, waste flows, and emissions per functional unit attributable to all processes within the life-cycle system boundaries.

3. Impact Assessment. Also called "Life Cycle Impact Assessment" (LCIA) phase aims to understand the environmental sense of LCI results, transforming its outputs into different impact categories (e.g. Global Warming Potential (GWP), acidification and primary energy use). LCIA adopts three mandatory elements: selection of impact categories, assignment of LCI results to the selected impact categories and modeling category indicators.

4. Interpretation. Uses the results from LCI or LCIA phase to summary, identify and evaluate them in order to draw some conclusions, make recommendations or otherwise aid in the decision-making process for the studied projects (Li et al., 2019).

2.3.2.1 The Use of LCA results

The LCA results can be used in several ways, most particularly in product development, environmental reporting or labelling. There are some applications in private and public organizations. ISO 14040 recommends that the LCA approach should be adapted to techniques, methods and tools such as:

a) Environmental Impact Assessment (EIA);
b) Assessment of policies (models for recycling, etc);
c) Hazard and risk assessment of chemicals;
d) Risk analysis and risk management of facilities and plants;
e) Product stewardship, supply chain management; among others.
(Gopalakrishnan et al., 2014).

An example of a product system for LCA given by the ISO can be seen in Figure 5.

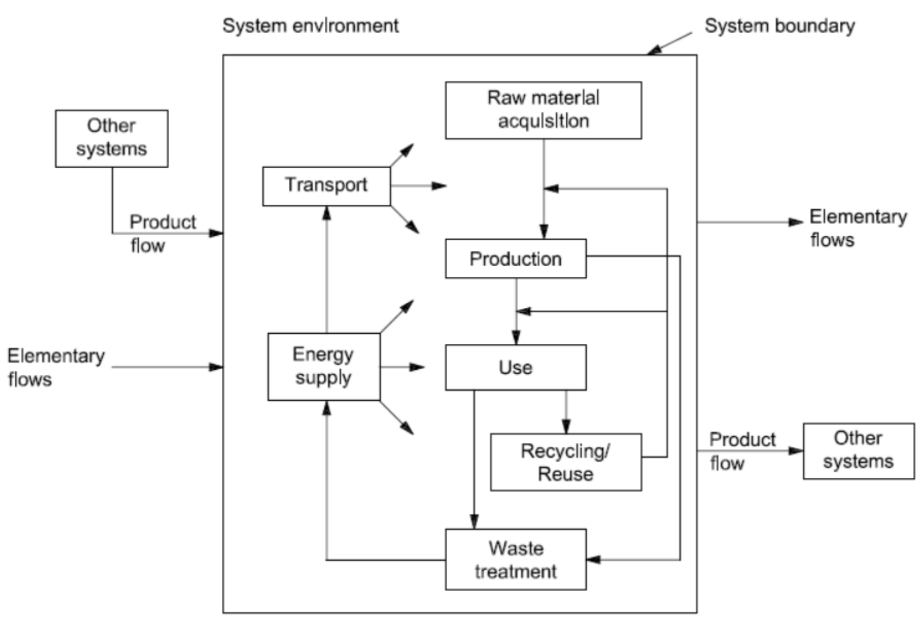

Figure 5. Example of a product system for LCA (Iso, 2004).

Where possible flows could be:

- Elementary flows entering the unit process: crude oil from the ground
- Elementary flows leaving the unit process: emissions to air, discharges to water or soil and radiation.
- Intermediate product flows: basic materials and subassemblies.
- Product flows entering or leaving the system: recycled materials and components for reuse. (Iso, 2004).

The ISO 14040 and 14044 does not describe specifically how to proceed in the case of a pavement construction and these normative could be used equally for any product.

2.4 LCA Approaches

There are three different approaches to conducting an LCA: process LCA, input-output LCA (IO-LCA) and hybrid LCA.

2.4.1 Process LCA

Process LCA is an approach that aims to quantify the inputs and emissions of each discrete process within a life-cycle system boundary. Total life-cycle inputs, emissions and impacts are then estimated by summing up the data across all discrete processes. Functionally, this serve as a bottom-up method to characterizing the environmental impacts of a product. Process LCA traces its roots to approaches supported and refined by the Society of Environmental Toxicology and Chemistry (SETAC) and the United States Environmental Protection Agency (EPA). For this reason, it is sometimes referred to as the SETAC-EPA approach.

2.4.2 Input-Output LCA

IO-LCA is a top-down approach that includes all sectors of an economy in the analysis. It is based on the economic input-output (IO) approach developed by Wassily Leontief in 1936. By identifying the flows of goods and services between distinct sectors of an economy, IO models can trace all direct and indirect economic inputs required to produce a unit of output from a given economic sector. IO-LCA methods couple such IO models with sector-level environmental data to generate estimates of the economy-wide environmental burdens associated with producing a given product (or service).

2.4.3 Hybrid LCA

Hybrid LCA is a method that combines process LCA and IO-LCA approaches in a manner that exploits their strengths and curtails their weaknesses. These strengths and weakness are summarized in Table 1. Strength and weaknesses of the LCA approaches *(Santero et al., 2010)*. (Santero et al., 2010).

	Process LCA	IO-LCA
Strengths	- Detailed process-specific analyses - Specific product comparisons - Process improvements, weak point analyses - Future product development assessments	- Economy-wide, comprehensive assessments (all direct and indirect environmental effects included) - System LCA: industries, products, services, national economy - Sensitivity analyses, scenario planning - Publically available data, reproducible results - Future product development assessments - Information on every commodity in the economy
Weaknesses	- System boundary setting subjective - Tend to be time intensive and costly - New process design difficult - Use of proprietary data - Cannot be replicated if confidential data are used - Uncertainty in data	- Many product assessments contain aggregated data - Process assessment difficult - Difficulty in linking dollar values to physical units - Economic and environmental data may reflect past practices - Imports treated as U.S. products - Difficult to apply to an open economy (with substantial non-comparable imports) - Non-U.S. data availability a problem - Uncertainty in data

Table 1. Strength and weaknesses of the LCA approaches (Santero et al., 2010).

The tool that was used for this study is called PaLATE and uses a hybrid LCA approach. An explanation of PaLATE will be done in the following chapter.

3 PaLATE

3.1 Definitions and Characteristics

PaLATE is the chosen tool to be analyzed in this work. As it was already said but it is fair to repeat it means: Pavement Life-cycle Assessment Tool for Environmental and Economic Effects.

<u>What is PaLATE?</u>

Figure 6. PaLATE logo.

"Is an Excel-based tool for life-cycle assessment (LCA) of environmental and economic effects of pavements and roads. The tool takes user input for the design. Initial construction, maintenance, equipment use, and costs for a roadway, and provides outputs for the life-cycle environmental effects and costs" [1]. Some of the environmental effects investigated by PaLATE are CO_2, NOx, CO, PM_{10}, SO_2, leachate information, etc.

<u>Who developed PaLATE?</u>

It was originally designed and developed in 2003 principally by a team lead by Professor Arpad Horvath from the Department of Environmental and Civil Engineering at the University of California, Berkeley.

Who should use PaLATE?

It was created fundamentally for pavement designers, transportation agency decision-makers, civil engineers and researchers. Users should have a working knowledge of pavements and a desire to learn more about the environmental and economic implications of their decisions [1].

How to get it?

To work with this tool a copy was downloaded from internet with an excel extension (.xls).

Principal characteristics

The principal characteristics are flexibility, transparency and its analytical structure. Flexibility allows to use it in different countries because users can make changes according to their needs regarding materials, different maintenance techniques and so on, in an easy way. Transparency in the sense that the user or a reviewer of the model know the origin of the data and assumptions made in the calculations. Analytical structure permits the user to study each phase (material production, maintenance, etc.) separately (Celauro et al., 2015).

Type of LCA approach

PaLATE combines Economic Input-Ouput Life Cycle Assessment (EIO-LCA) data with additional process-based information obtaining a hybrid LCA (Santero et al., 2010).

3.2 Program description

3.2.1 Introduction

PaLATE applies an LCA methodology to pavements for its entire life-cycle except for the use phase[1] (see Figure 7. Life cycle of a pavement considered by PaLATE.). The software works with United States customary units (USCU) that is to say in feet (ft), inches (in), yards (yd) and

[1]To analyze the use phase of the Life-cycle of a pavement other programs are recommended such as EPA´s MOBILE 6.2 (Excel file PaLATE).

gallons (gal). It provides environmental outputs as well as costs results, but, as a principal concern, the scope of this work is just focusing on environmental emissions, therefore, everything related with costs will be neglected. Is basically composed of eighteen worksheets (including those costs related) of which seven are the principals and it is where the user should add, modify, complete with information (input) and obtain results (output), whereas the remaining sheets are, let's say, "complementary" and it is where the program provides information (Data) in order to generate a connection between input and output data. The process followed by PaLATE can be summarized as shown in Figure 8. PaLATE process.

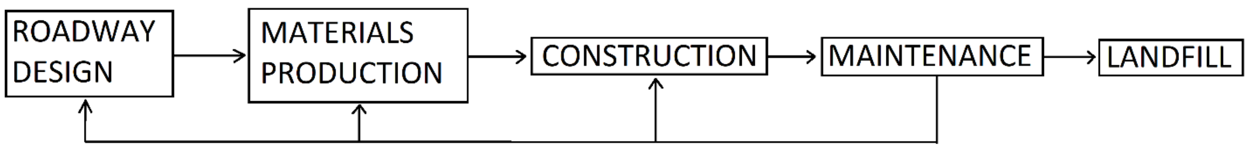

Figure 7. Life cycle of a pavement considered by PaLATE.

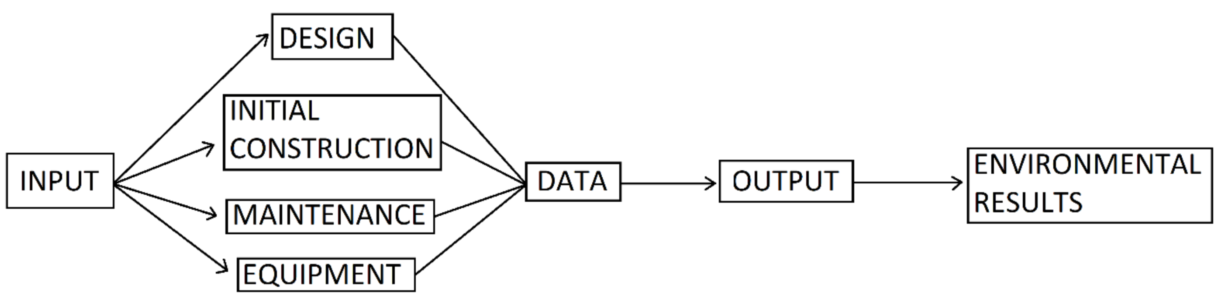

Figure 8. PaLATE process.

The eighteen worksheets that compose PaLATE are:

- Introduction

INPUT

- Design (*)
- Initial Construction (*)

- Maintenance (*)
- Equipment (*)
- Costs (*) (**)

OUTPUT

- Costs Results (*) (**)
- Environmental Results (*)

REFERENCES

- References

DATA

- Data (it is an empty sheet, is just making a division between user input-output sheets and data sheets)
- Densities
- Equipment Details
- Electromotive Force (EMF) Transport
- Fumes
- Leachate
- Cost Data (**)
- Conversions
- Diagrams

A brief description of every sheet will be done[2], but being more precise in those considered principals sheets.

[2] As it was already said everything referred to costs will be neglected, so the worksheets containing cost´s information won't be described.
(*) Principal sheets.
(**) Neglected sheets.

3.2.2 Worksheets Description

3.2.2.1 Introduction sheet

This first sheet makes a short introduction telling which are the rules of the program and where the user is supposed to input data (in which cells).

3.2.2.2 Design

In this sheet the user is available to input data referring to the geometric parameters of the pavement and designating which layers will compose the pavement.

The values to input are width, length and depth for each layer in feet, miles and inches respectively, and the program calculates the volume in yd^3. It is also possible to input data about the volume of the shoulder and embankment (in yd^3) in the case that a more detailed analysis might be done. Moreover, the period of analysis (years of life) of the pavement is also required to denote the number of years over which maintenance will be performed. Figure 9 shows what this sheet looks like.

Layer Specifications				
Layer	Width [ft]	Length [miles]	Depth [inches]	Volume [yd^3]
Wearing Course 1				0
Wearing Course 2				0
Wearing Course 3				0
Subbase 1				0
Subbase 2				0
Subbase 3				0
Subbase 4				0
Total			0	0

Embankment and Shoulder Volume [yd^3]:	

Period of Analysis [yrs] (40 yrs or less)	**40**

Figure 9. Design sheet.

In addition to what was already explained, this sheet also contains three different tables suggesting values of densities for different materials and a little graphic of the pavement as shown in Figure 10.

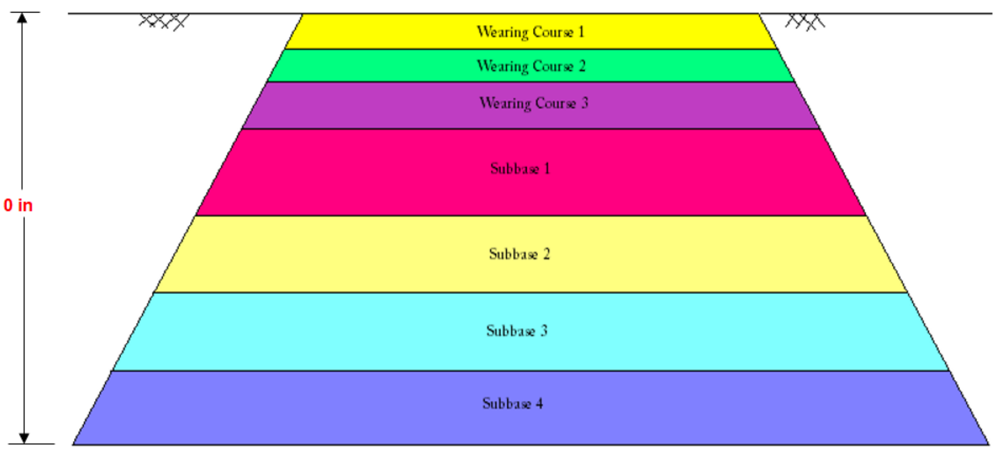

Figure 10. Pavement design.

3.2.2.3 Initial Construction

In this worksheet, the user should input everything referred to materials involved in the construction of the pavement. PaLATE gives the option to analyze both asphalt pavements and concrete pavements. Each wearing course[3] mix (asphalt or portland cement concrete) needs to be disaggregated into its basic materials in order to account for transportation emissions in the supply chain, hence, the user has the possibility to input the volume in yd^3 of each material composing a certain layer. The options of materials that consider PaLATE for wearing courses are: virgin aggregates, bitumen, cement, concrete additives, recycled asphalt pavement (RAP), fractionated reclaimed asphalt pavement (FRAP), recycled asphalt shingles (RAS), recycled concrete aggregates (RCA), coal fly ash, coal bottom ash, blast furnace slag, foundry sand, recycled tires/ crumb rubber, glass cullet, water and steel reinforcing bars. In addition to these materials there are three more rows where the user can input the volume of waste material going to landfill. If the

[3] PaLATE names wearing course to every layer representing the pavement itself (wearing, binder and base course).

pavement to be analyzed is a flexible pavement, then, the first column should be filled in, but in case that a rigid pavement is being analyzed, then, the second column should be completed.

Regarding transportation of materials there are two columns to be filled in. The first one is referred to transportation distance, where the user should input the one-way distance in miles of each material from material source to asphalt/concrete plant, except for the "Total" rows where the distance to input is that one from asphalt/concrete plant to the worksite. The second one is the transportation mode of each material till asphalt/concrete plant and worksite. The program allows the user to choose between five different modes of transportation: dump truck, cement truck, tanker truck, rail or barge, from which the user should select the most predominant one for each material. For more comprehension see Figure 11.

		Material	Density [tons/(yd^3)]	New Asphalt Pavement	New Concrete Pavement	New Subbase & Embankment Construction	Transportation	
				Volume [yd^3]	Volume [yd^3]	Volume [yd^3]	One-way transport distance [mi]	Transportation mode
Wearing Course 1	Materials	Virgin Aggregate	2.23	0	0		0	dump truck
		Bitumen	0.84	0			0	tanker truck
		Cement	1.27		0		0	barge
		Concrete Additives	0.84		0		0	tanker truck
		RAP	1.85	0	0		0	dump truck
		FRAP	1.85	0	0		0	dump truck
		RAS	1.12	0	0		0	dump truck
		RCA	1.88	0	0		0	dump truck
		Coal Fly Ash	2.20	0	0		0	cement truck
		Coal Bottom Ash	2.00	0	0		0	dump truck
		Blast Furnace Slag	1.72	0	0		0	dump truck
		Foundry Sand	1.50	0	0		0	dump truck
		Recycled Tires/ Crumb Rubber	1.92	0	0		0	dump truck
		Glass Cullet	1.93	0	0		0	dump truck
		Water	0.84		0			
		Steel Reinforcing Bars	0.24		0		0	dump truck
		Total: Asphalt mix to site	1.23	**0**			0	dump truck
		Total: Ready-mix concrete mix to site	2.03		**0**		0	mixing truck
	Waste material to landfill	RAP from site to landfill	1.85	0			0	dump truck
		RAS from site to landfill	1.12	0	0		0	dump truck
		RCM from site to landfill	1.88		0		0	dump truck

Figure 11. Initial construction - wearing course.

Now, in what respects to subbases[4] the columns to be filled in are the same as for wearing courses, but with the difference that some materials offered by the software are others and they are: RAP, RAS, reclaimed concrete material (RCM), cement, coal fly ash, coal bottom ash, blast furnace slag, foundry sand, recycled tires/ crumb rubber, glass cullet, rock, gravel, sand and soil.

[4] PaLATE names subbases to every layer that compose the foundation of the roadway (subbase and subgrade course).

For the subbase layers as well as embankments and shoulders, transportation distances are entered for each basic material. The "total" indicates the total volume of subbase materials in each subbase layer. The transportation mode stays the same as for wearing course. For more comprehension see Figure 12.

		Material	Density [tons/(yd^3)]	New Asphalt Pavement	New Concrete Pavement	New Subbase & Embankment Construction	Transportation	
				Volume [yd^3]	Volume [yd^3]	Volume [yd^3]	One-way transport distance [mi]	Transportation mode
Subbase 1	Materials	RAP to recycling plant	1.85			0	0	dump truck
		RAP from recycling plant to site	1.85			0	0	dump truck
		RAS to recycling plant	1.12			0	0	dump truck
		RAS from recycling plant to site	1.12			0	0	dump truck
		RCM to recycling plant	1.88			0	0	dump truck
		RCM from recycling plant to site	1.88			0	0	dump truck
		Cement	1.27			0	0	dump truck
		Coal Fly Ash	2.20			0	0	cement truck
		Coal Bottom Ash	2.00			0	0	dump truck
		Blast Furnace Slag	1.72			0	0	dump truck
		Foundry Sand	1.50			0	0	dump truck
		Recycled Tires/ Crumb Rubber	1.92			0	0	dump truck
		Glass Cullet	1.93			0	0	dump truck
		Rock	2.00			0	0	dump truck
		Gravel	1.35			0	0	dump truck
		Sand	1.25			0	0	dump truck
		Soil	1.63			0	0	dump truck
		Total: Subbase 1 materials to site	**0.00**			**0**		
	Waste mat'l sent to landfill	RAP from site to landfill	1.85			0	0	dump truck
		RAS from site to landfill	1.12			0	0	dump truck
		RCM from site to landfill	1.88			0	0	dump truck

Figure 12. Initial construction – subbase course.

3.2.2.4 Maintenance

In this worksheet everything is related to materials used for maintenance of the pavement. For each material the user is supposed to fill in the total quantity (yd^3) used during maintenance in the whole life cycle of the pavement. The volume in yd^3 of each material is the sum of every volume of this same material utilized during maintenance for different years. The available materials for maintenance are the same than for initial construction, in fact, the whole table is similar except for that in this case the software also provides the user a variety of maintenance processes that should be applied such as: Hot In-Place Recycing (HIPR), Cold In-Place Recycling (CIR), patching, microsurfacing, crack sealing, whitetopping, rubblization and full-depth reclamation (FDR). Moreover, in this sheet also the transportation distances and transportation modes are considered. Figure 13 illustrates maintenance sheet for wearing course.

		Material	Density [tons/(yd^3)]	Lifetime Asphalt Repaving Volume [yd^3]	Lifetime Concrete Repaving Volume [yd^3]	Lifetime Subbase Reconstruction Volume [yd^3]	Lifetime Embankment Reconstruction Volume [yd^3]	Transportation: One-way transport distance [mi]	Transportation: Transportation mode
Wearing Course 1	Materials	Virgin Aggregate	2.23	0	0			0	dump truck
		Bitumen	0.84	0				0	tanker truck
		Cement	1.27		0			0	cement truck
		Concrete Additives	0.84		0			0	tanker truck
		Asphalt Emulsion	0.84	0				0	tanker truck
		RAP	1.85	0	0			0	dump truck
		FRAP	1.85	0	0			0	dump truck
		RAS	1.12	0	0			0	dump truck
		RCA	1.88	0	0			0	dump truck
		Coal Fly Ash	2.20	0	0			0	tanker truck
		Coal Bottom Ash	2.00	0	0			0	dump truck
		Blast Furnace Slag	1.72	0	0			0	dump truck
		Foundry Sand	1.50	0	0			0	dump truck
		Recycled Tires/ Crumb Rubber	1.92	0	0			0	dump truck
		Glass Cullet	1.93	0	0			0	dump truck
		Water	0.84		0				
		Steel Reinforcing Bars	0.24		0			0	dump truck
		Total: Hot-mix Asphalt to site	1.23	**0**				0	dump truck
		Total: Ready-mix Concrete mix to site	2.03		**0**			0	mixing truck
	Processes	HIPR	1.83	0					
		CIR	1.83	0					
		Patching	1.23	0	0				
		Microsurfacing	1.23	0	0				
		Crack Sealing	0.84	0	0				
		Whitetopping	2.03		0				
		Rubblization	1.95		0				
		Full-depth Reclamation	1.83	0	0				
	Waste material to landfill	RAP from site to landfill	1.85	0				0	dump truck
		RAS from site to landfill	1.12	0				0	dump truck
		RCM from site to landfill	1.88		0			0	dump truck

Figure 13. Maintenance - wearing course.

Regarding foundation layer the table to be filled in is the same as for initial construction, with the exception that there is just one process available and it is full-depth reclamation (see Figure 14). So, the maintenance process in this case should be considered just in the case that an FDR comes implemented. Furthermore, embankment and shoulder can also be considered in the analysis just by adding values for materials and transportation, no maintenance process is considered.

		Material	Density [tons/(yd^3)]	Lifetime Asphalt Repaving	Lifetime Concrete Repaving	Lifetime Subbase Reconstruction	Lifetime Embankment Reconstruction	Transportation	
				Volume [yd^3]	Volume [yd^3]	Volume [yd^3]	Volume [yd^3]	One-way transport distance [mi]	Transportation mode
Subbase 1	Materials	RAP to recycling plant	1.85			0		0	dump truck
		RAP from recycling plant to site	1.85			0		0	dump truck
		RAS to recycling plant	1.12			0		0	dump truck
		RAS from recycling plant to site	1.12			0		0	dump truck
		RCM to recycling plant	1.88			0		0	dump truck
		RCM from recycling plant to site	1.88			0		0	dump truck
		Cement	1.27			0		0	dump truck
		Coal Fly Ash	2.20			0		0	cement truck
		Coal Bottom Ash	2.00			0		0	dump truck
		Blast Furnace Slag	1.72			0		0	dump truck
		Foundry Sand	1.50			0		0	tanker truck
		Recycled Tires/ Crumb Rubber	1.92			0		0	dump truck
		Glass Cullet	1.93			0		0	dump truck
		Rock	2.00			0		0	dump truck
		Gravel	1.35			0		0	dump truck
		Sand	1.25			0		0	dump truck
		Soil	1.63			0		0	dump truck
		Total: Subbase 1 materials to site	**0.00**			0			
	Process	Full-depth Reclamation	1.83			0			
	Waste material to landfill	RAP from site to landfill	1.85			0		0	dump truck
		RAS from site to landfill	1.12			0		0	dump truck
		RCM from site to landfill	1.88			0		0	dump truck

Figure 14. Maintenance - subbase course.

3.2.2.5 Equipment

This worksheet as its name indicates is referred to the equipment used all along the construction of the pavement. PaLATE divides the road construction in activities (considering initial construction and maintenance) and for each activity designates it corresponding equipment, at the same time, it offers a variety of models for each equipment with its characteristics (engine capacity, productivity, fuel consumption and fuel type), where the user is supposed to choose one. In the case that there is a certain model of an equipment that the user would like to apply and it is not offered by PaLATE, it exists an option that says “other”, where the user, addressing to another worksheet called “Equipment Details” (will be explained later), is available to add the characteristics of the desired model. Figure 15shows an illustration of the Equipment sheet. The software, thanks to the data chosen here, is able to calculate environmental burdens regarding equipment utilized.

ACTIVITY	Equipment	Brand/Model	Engine Capacity	Productivity	Fuel Consumption	Fuel Type
Concrete Paving	Slipform paver	Wirtgen SP 250	106 hp	564 tons/h	19.7 l/h	diesel
	Texture curing machine	Gomaco T/C 400	70 hp	187 tons/h	20.2 l/h	diesel
Asphalt Paving	Paver	Dynapac F30C	196 hp	2,400 tons/h	49.1 l/h	diesel
	Pneumatic roller	Dynapac CP132	100 hp	668 tons/h	26.1 l/h	diesel
	Tandem roller	Ingersol rand DD110	125 hp	285 tons/h	32.7 l/h	diesel
Cold in Place Recycling	CIR recycler	Wirtgen 2200 CR	800 hp	1,713 tons/h	150.00 l/h	diesel
	Pneumatic roller	Dynapac CP134	100 hp	884 tons/h	25.1 l/h	diesel
	Tandem roller	Ingersol rand DD110	125 hp	285 tons/h	32.7 l/h	diesel
Full Depth Reclamation	Asphalt road reclaimer	Wirtgen WR 2500 S	670 hp	4,800 tons/h	120.0 l/h	diesel
	Vibratory soil compactor	Dynapac CA 262D	150 hp	1,832 tons/h	37.6 l/h	diesel
Hot In Place Recycling	Heating machine	Wirtgen HM4500	49 hp	256 tons/h	9.1 l/h	diesel
	Asphalt remixer	Wirtgen 4500	295 hp	208 tons/h	55.0 l/h	diesel
	Pneumatic roller	Dynapac CP132	100 hp	668 tons/h	26.1 l/h	diesel
	Tandem roller	Ingersol rand DD110	125 hp	285 tons/h	32.7 l/h	diesel
Rubblization	Multi head breaker	Badger MHB Breaker	350 hp	520 tons/h	76.5 l/h	diesel
	Vibratory soil compactor	Dynapac CA 262D	150 hp	1,832 tons/h	37.6 l/h	diesel
Milling	Milling machine	Wirtgen W2200	875 hp	1,100 tons/h	156.2 l/h	diesel
Grinding	Grinding machine	CBI Magnum Force Shingle I	1050 hp	115 tons/h	161.1 l/h	diesel
Concrete Demolition	Multi head breaker	Badger MHB Breaker	350 hp	520 tons/h	76.5 l/h	diesel
	Wheel loader	John Deere 644E	160 hp	490 tons/h	40.1 l/h	diesel
Crushing Plant	Excavator	John Deere 690E	131 hp	225 tons/h	34.2 l/h	diesel
	Wheel loader	John Deere 624E	135 hp	225 tons/h	35.3 l/h	diesel
	Dozer	Caterpillar D8N	285 hp	225 tons/h	71.4 l/h	diesel
	Generator	Caterpillar 3406C TA	519 hp	225 tons/h	98.4 l/h	diesel
Excavation, placing and compaction	Excavator	John Deere 690E	131 hp	315 tons/h	34.2 l/h	diesel
	Vibratory soil compactor	Dynapac CA 262D	174 hp	1,832 tons/h	27.6 l/h	diesel
Tire Recycling	Shredder + Granulator + Classifier + Aspirator System	Wendt Corporation	630 hp	3.00 tons/h	104.73 kWh/ton	105 hp
Glass Recycling	Hopper + Conveyor + Shredder System	Andela GP-05 Pulverizer	10 hp	1.00 tons/h	7.46 kWh/ton	17 hp
HMA Production	asphalt mixer	Uncontrolled Batch-mix		226.80 tons/h		oil

Figure 15. Equipment worksheet.

3.2.2.6 Environmental Results

This worksheet is the most important one and it is where the user is allowed to see the environmental outputs (final results) from the whole roadway construction considering both initial construction and maintenance during the analysis period. The twelve measured outputs calculated from PaLATE are: energy consumption in megajoules (MJ), water consumption in kilograms (kg), carbon dioxide (CO_2) in megagrams (Mg), nitric oxide (NOx) in kg, particulate matter 10 micrometers diameter (PM_{10}) in kg, Sulphur dioxide (SO_2) in kg, carbon monoxide (CO) in kg, mercury (Hg) in grams (g), lead (Pb) in g, hazardous waste generated[5] in kg and human toxicity potential (HTP, both cancer and non-cancer) in g. Now a brief description of them will be done.

- Carbon Dioxide (CO_2): is a colorless gas that has a delicate, sharp odor and a sour taste, with a density about 60% higher than of dry air. It is composed by one atom of carbon bonded with two atoms of oxygen. Is a minor constituent of Earth´s atmosphere (around 0.0041%) and it is produced by combustion of coal, peat, petroleum and natural gas. CO_2 has a characteristic that keeps some of the radiant energy received by Earth from being rebound to space, thus producing the so-called **greenhouse effect** [3].
- Nitrogen Oxide (NOx): is a chemical compound of oxygen and nitrogen that is formed by reacting with each other during combustion at high temperatures, mainly combustion of fuel such as oil. This acronym (NOx) is a generic term for the nitrogen oxides that are more relevant to air pollution and includes different oxides such as nitric oxide (NO) and nitrogen dioxide (NO_2). NOx is harmful to humans causing serious respiratory diseases and is also responsible for smog covering cities and producing poor air quality [4].
- Particulate Matter (PM_{10}): are small particles with a diameter of 10 micrometers or less (approximately 1/7 the diameter of a single human hair). Their small size permits them to make their way deep into the lungs and result in adverse effects. PM_{10} can also cause visibility damage [5].
- Sulfur Dioxide (SO_2): is an invisible gas with a nasty sharp smell. The main source is industrial activity that processes materials containing sulfur such as the generation of electricity from coal or industrial activities that burn fossil fuels containing sulfur. SO_2 is present in motor vehicles and affects humans once breathed irritating throat, nose and airways [6].
- Carbon Monoxide (CO): is a colorless, poisonous, odorless and tasteless gas. It is an industrial hazard resulting from the incomplete burning of material that contains carbon such as natural gas, kerosene, oil, coal, gasoline or wood. It affects humans when breathed displacing oxygen in the blood and deprives vital organs of oxygen such as the heart and

[5] Hazardous wastes are defined under the Resource Conservation and Recovery Act (RCRA) which *"is the public law that creates the framework for the proper management of hazardous and non-hazardous solid waste. The law describes the waste management program mandated by Congress that gave EPA authority to develop the RCRA program. The term RCRA is often used interchangeably to refer to the law, regulations and EPA policy and guidance" [2].*

brain. A large amount of CO can overcame a person without warning causing loss of consciousness and suffocate (Harper & Croft-Baker, 2012).

- Mercury (Hg): is a heavy, silvery-white liquid metal. Is the only common metal which is liquid at ordinary temperatures. It can cause harmful effects on humans such as disruption of the nervous system, damage to brain functions, allergic reactions and DNA (Deoxyribonucleic acid) damage and chromosomal damage [7].
- Lead (Pb): is a soft, dense and malleable metal. Can be found in all parts of the environment and it is toxic to humans, causing health effects. The vast majority of the human exposure comes from human activities including the use of fossil fuels containing past use of leaded gasoline, past-use of lead-based paint in homes and some types of industrial facilities. It affects every organ in the human body, and it is more influenceable on children causing anemia, hearing problems and learning problems, among others [8].
- Hazardous waste generated: is waste that contains properties that make it dangerous and generates harmful effects in human health and environment. Hazardous wastes are generated from many sources, an example can be batteries or industrial manufacturing processes [9].
- Human Toxicity Potential (HTP): is a calculated index that reflects the potential harm of a unit of chemical released into the environment. It is used to weight emissions inventoried as part of an LCA and to aggregate emissions in terms of a reference compound. Total emissions can be evaluated in terms of benzene equivalence (carcinogens) and toluene equivalents (noncarcinogens) (Hertwich et al., 2001).

Results for environmental outputs are obtained after a series of calculous for initial construction, maintenance and the total, which is the sum of the two named before. At the same time, in order to adopt an organized structure, both initial construction and maintenance are divided into three groups: material production, material transportation and processes (equipment), hence, in this way it can be clearly seen the contributes to emissions for each operation (in chapter 4, section 4.3 a detailed procedure for environmental outputs will be demonstrated). This valuable worksheet is where decision-makers and users in general takes information from, to proceed to the interpretation step of an LCA and make some conclusions.

Environmental results come organized as shown in Figure 16 which is cut in two for a better comprehension.

GRAND TOTALS

		Energy [MJ]	Water Consumption [kg]	CO_2 [Mg] = GWP	NO_x [kg]	PM_{10} [kg]	SO_2 [kg]	CO [kg]	Hg [g]	Pb [g]	RCRA Hazardous Waste Generated [kg]	Human Toxicity Potential (Cancer) [g]	Human Toxicity Potential (Non-cancer) [g]
Initial Construction	Materials Production	0	0	0	0	0	0	0	0	0	0	0	0
	Materials Transportation	0	0	0	0	0	0	0	0	0	0	0	0
	Processes (Equipment)	0	0	0	0	0	0	0	0	0	0	0	0
Maintenance	Materials Production	0	0	0	0	0	0	0	0	0	0	0	0
	Materials Transportation	0	0	0	0	0	0	0	0	0	0	0	0
	Processes (Equipment)	0	0	0	0	0	0	0	0	0	0	0	0
Total	Materials Production	0	0	0	0	0	0	0	0	0	0	0	0
	Materials Transportation	0	0	0	0	0	0	0	0	0	0	0	0
	Processes (Equipment)	0	0	0	0	0	0	0	0	0	0	0	0
	Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

Figure 16. Environmental Results.

In addition, these environmental results also come evaluated through graphs for a better interpretation for every emission. In each graph the user is available to see results of a certain emission divided in initial construction, maintenance and total, and, at the same time, these, come divided into material production, material transportation and processes (equipment). An example is shown in Figure 17.

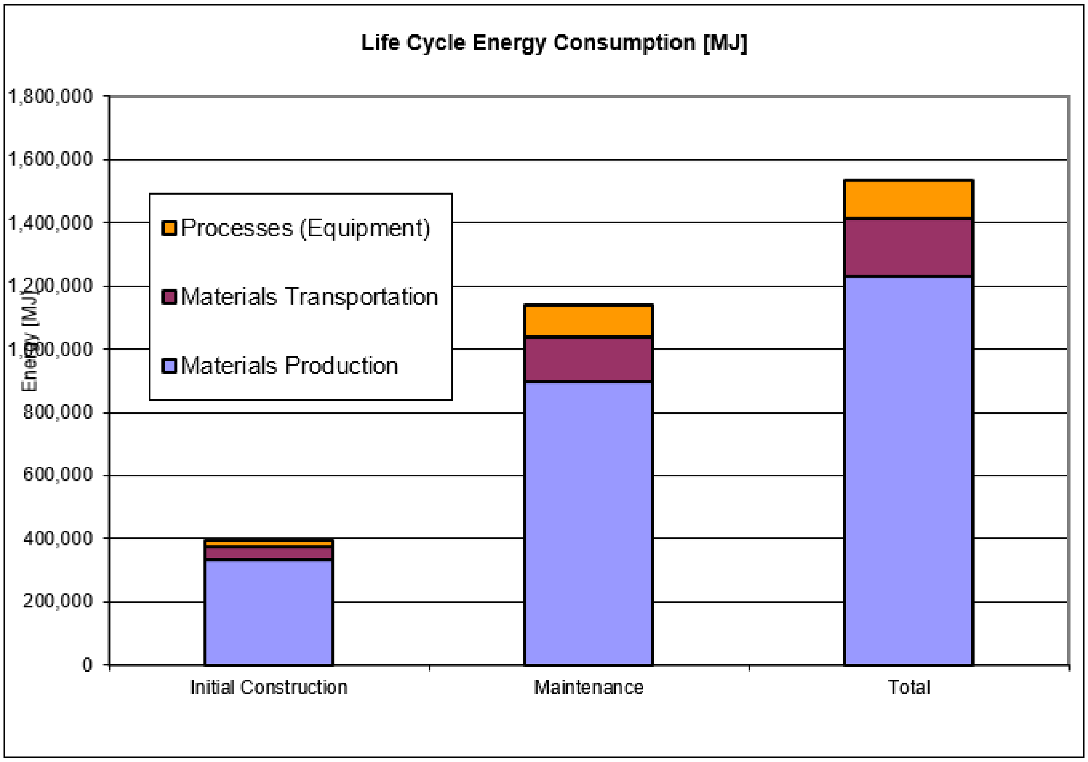

Figure 17. Example of graph showing energy consumption.

Finally, and as it was already said, thanks to these results the user can make valuable conclusions and proceed to changes in the pavement composition in case that values of emissions are undesirables being too harmful for the environment. Changes should be done in the corresponding INPUT worksheets.

3.2.2.7 References

In this sheet the user can see the source from where the creators of PaLATE took every information considered in the input and output worksheets. There are references for materials offered in the software, so, everything has an explanation, and nothing is leave as random. For example, in the case of byproducts offered for initial construction and maintenance, each of them was analyzed and studied so as to introduce it to PaLATE.

3.2.2.8 Data

As it was already said, this is an empty sheet colored in red to indicate a separation from input/output sheets and indicating the beginning of "Data" worksheets. These are backup sheets of the program, it is where PaLATE has its bases, and provides information about every data used in input/output worksheets.

3.2.2.9 Densities

In this worksheet the user can find every density used in the software for each material with its corresponding reference.

3.2.2.10 Equipment Details

It is the worksheet where the user can see the characteristics of every machine involved in PaLATE that participates in the activities already described in the "Equipment" sheet. It is a sheet that has every equipment with its corresponding models and a row that says "other" and, as it was explained, if the user wishes to choose another model of machine that is not offered by PaLATE, it is available to do it through this row by inserting the characteristics of the new equipment to be utilized, such as: brand/model, engine model, hp, productivity, fuel consumption and fuel type. An example for the asphalt paver is shown in Figure 18.

type	brand/model	engine model	hp	Productivity (non-standard units)	Conversion Factors	Productivity	fuel consumption	capacity	fuel type
Asphalt Paver	Blaw-knox PF-5510	Cummins 6BTA	184 hp			?	46.1 l/h		diesel
	Cedarapids CR451		172 hp			?	43.1 l/h		diesel
	Dynapac F25C	Cummins 6BTA 5,9	126 hp			1,700 tons/h	31.6 l/h		diesel
	Dynapac F30C	Cummins 6BTA 5,10	196 hp			2,400 tons/h	49.1 l/h		diesel
	none		0			1	0		
	other		1			1	1		

Figure 18. Example of an asphalt paver characteristics.

3.2.2.11 EMF transport

This sheet is important and, in chapter 4, section 4.2.1.1 will be explained in detail, because it contains information about the emissions of vehicles´ engines that are used in the processes of <u>material transportation</u> already described in the "Initial Construction" sheet. Information is provided form the US EPA and the Organization for Economic Co-operation and development (OECD[6]). These emissions are strongly correlated with transport distances and transportation mode chosen. The emissions of NOx produced by a cement truck are not the same than the ones generated by a barge for example.

Moreover, this worksheet contains information of emissions generated from every economic sector involved in PaLATE such as the bitumen or virgin aggregate sector, hence, final environmental burdens for material production in a pavement's construction can be calculated relating the quantity of a certain material used (e.g. yd^3 of virgin aggregates) with the emissions of the correspondent economic sector (e.g. emissions for the virgin aggregates sector). Every calculation carried out by PaLATE is automatically made in the "Environmental results" sheet. Further explanation of emissions generated from an economic sector will be given in the following chapter.

3.2.2.12 Fumes

In what respects to bitumen production, toxic fumes are generated during storage and handling of bitumen at high temperatures and are responsible for the typical odor of it. Bitumen fumes contain particulates, hydrocarbons (VOC) and hydrogen sulphide (H_2S) which are dangerous for human health [11]. PaLATE associates fumes with HTP. Therefore, this sheet contains information about the fumes generated in bitumen production.

3.2.2.13 Leachate

"Leachate is defined as any contaminated liquid that is generated from water percolating through a solid waste disposal site, accumulating contaminants, and moving into subsurface areas. A second source of leachate arises from the high moisture content of certain disposed wastes. As these wastes are compacted or chemically react, bound water is released as

[6] "*The Organisation for Economic Co-operation and Development (OECD) is a group of 34 member countries that discuss and develop economic and social policy. OECD members are democratic countries that support free-market economies"[10].*

"leachate"" (Cheremisinoff, 1997). This sheet contains information about leachate that release every material depending on the content of arsenic and lead that they have.

3.2.2.14 Conversions

As PaLATE is a software that was designed in United States a lot of information is required to be filled in with their system of measurement units that is called "United States Customary Units" (USCU), but, in the contrary, there is a lot of information going around the software which is expressed in the "International System of Units" (SI) (modern metric system), therefore, results need to be converted to this last system and there is exactly where this worksheet participates, because it has data about the unit´s conversion that are adopted all along the software.

3.2.2.15 Diagrams

It is an interactive and good sheet to look at from a functional point of view, in order to comprehend better how does PaLATE works and correlates every activity, because it contains diagrams showing the whole life-cycle for both asphalt and concrete pavement construction. An example for asphalt construction is shown in Figure 19. Example of asphalt construction life-cycle..

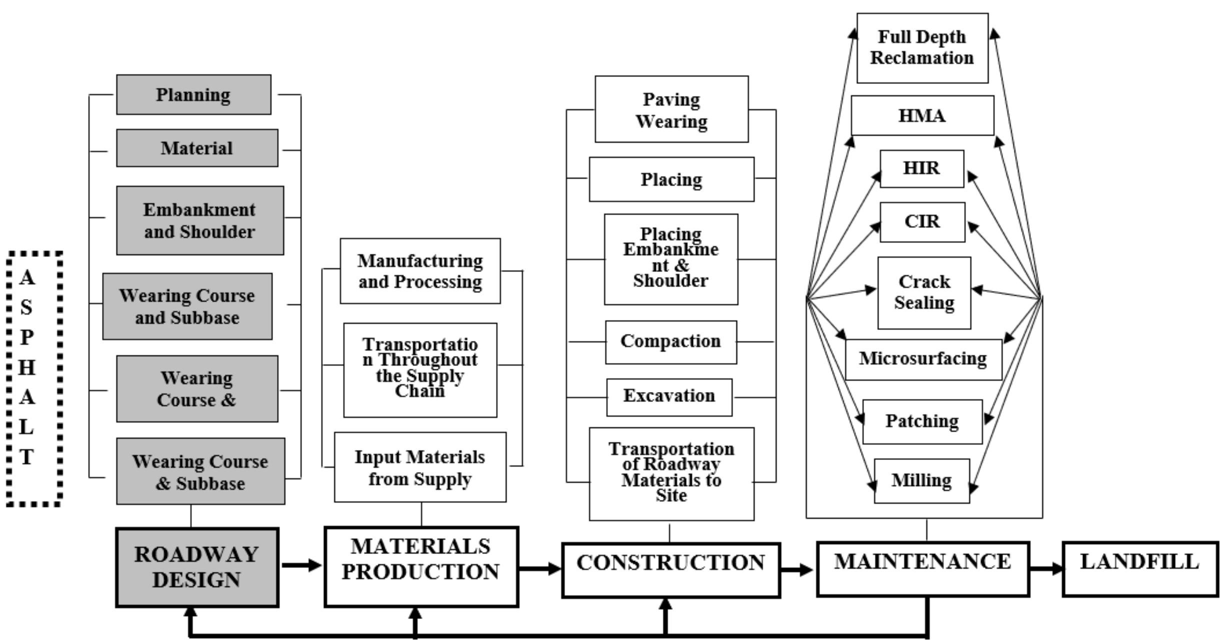

Figure 19. Example of asphalt construction life-cycle.

Having finished with the explanation of every sheet of this software, in the following chapter, two real case studies will be analyzed, and a practical demonstration of PaLATE will be done. Details of information and data inputted in the software will be clearly described.

3.3 Mistakes found in PaLATE

While using the software two main mistakes where found and of course, corrected.

1) When PaLATE calculates environmental impacts during HMA production, inside the calculous every equipment which participates is considered, hence, reference is done to the "Equipment" and "Equipment Details" sheets. The equipment consumes Energy, produces CO_2, CO, NO_2 (which is a gas that compounds NOx), PM_{10} and SO_2 emissions, and all these emissions are contained in those sheets. The problem is that when PaLATE makes reference to this information from another sheet, it does it through a function called INDEX and it is used in a wrong way. This function allows the user to choose a specific value from another sheet contained in a matrix by indicating row and column in which this value is located. But, in PaLATE, the selected matrix (B171: K176) is one with two empty columns (E and F) as shown in Figure 20 (which is cut in two for better comprehension), and when the program calls the desired value (for example PM_{10} for a Uncontrolled Batch-mix) it does it by calling the row number 1 (equal to row number 171) and column number 4 (equal to column letter E), when actually this column is empty, therefore, the result for PM_{10} emission will always be equal to 0, and this is not correct. The mistake is that PaLATE thinks that when applying the INDEX function, this, doesn't takes into account the empty columns when it does it indeed.

	A	B	C	D	E	F
170				energy		
171	HMA Production	Uncontrolled Batch-mix	214 tons/h	227 MJ/ton		
172		Fabric Filter-Controlled Batch-mix	214 tons/h	227 MJ/ton		
173		Uncontrolled Drum-mix	272 tons/h	202 MJ/ton		
174		Fabric Filter-controlled Drum-mix	272 tons/h	202 MJ/ton		
175		none	0	0		
176		other	0	0		

	G	H	I	J	K
170	**PM10**	**CO**	**CO_2**	**NOx**	**SO_2**
171	2.043 kg/ton	0.18 kg/ton	16.798 kg/ton	0.054 kg/ton	0.040 kg/ton
172	0.004 kg/ton	0.18 kg/ton	16.798 kg/ton	0.054 kg/ton	0.040 kg/ton
173	2.951 kg/ton	0.06 kg/ton	14.982 kg/ton	0.025 kg/ton	0.026 kg/ton
174	0.010 kg/ton	0.06 kg/ton	14.982 kg/ton	0.025 kg/ton	0.026 kg/ton
175	0	0	0	0	0
176	0	0	0	0	0

Figure 20. Emissions generated during HMA production mistake.

The solution adopted was to change the column number (letter) in the INDEX function, and for PM_{10} the selected column is no more the number 4 but number 6. The same was done for all emissions.

2) The second mistake found was that in the "EMF transport" sheet when PaLATE performs the EIO-LCA methodology in the sector table (with further explanation in the following chapter), in the case of Water Consumption, the program is multiplying a value expressed in gal/$ (gallon/dollar) by one expressed in $/ton and the final result obtained is expressed in g (grams)/ton, when it should be actually expressed in gal/ton. And the worst part is that when calculating Environmental impacts that involves the water consumption resource, PaLATE performs calculations with the value as it were expressed in g/ton, therefore, every value considering this resource gives a bad result. See Figure 21 for better comprehension.

As a mode of example, the result from row 125 and column M, is obtained by the multiplication of row 111, column M by row 111, column O. The number resulted is correct but not the measurement unit.

	M	N	O
109	gal/$		
110	**Water Consumption**	all prices from [Means 1995]	
111	3.79	28 $/Mg	25 $/ton
112	6.03	31 $/Mg	28 $/ton
113	66.26	300 $/Mg	272 $/ton
114	2.15	11 $/Mg	10 $/ton
115	9.14	1,000 $/Mg	907 $/ton
116	22.27		84 $/ton
117	18.71	2,114 $/Mg	1,918 $/ton
118	9.14	864 $/Mg	784 $/ton
119	2.01		0.00082 $/ton
120	0.81	0.10 $/kWh	
121			
122			
123	**Water Consumption**		
124	g/ton		
125	96		
126	169		
127	18,037		

Figure 21. Measurement unit mistake during water consumption.

The solution adopted was to transform gallons in grams in order to obtain “real grams”.

4 Practical application with PaLATE

This is the central and principal chapter of this thesis, where the focus was given to environmental impacts of the pavement construction and the background data used for its calculations, therefore, as a first step and before showing a practical application of the software, it is necessary to understand how PaLATE calculates every output with each step followed. Secondly, changes of default data of the software to estimated data found in European literature (reminding that is an USA software and every data used is correspondent to that country) will be demonstrated. Now, as a third step, it is possible to show the application of two different case studies that will be analyzed regarding environmental outputs with both default input values (DIV) and estimated input values (EIV) remarking differences, and finally, a brief comparison to another tool called SimaPro 7.3 will be done in order to find advantages and drawbacks.

4.1 PaLATE overview: steps for environmental outputs

PaLATE uses an LCA methodology to reach results and to get started it is useful to see Figure 22 that makes clear how it correlates the phases of an LCA with the pavement life-cycle and outputs.

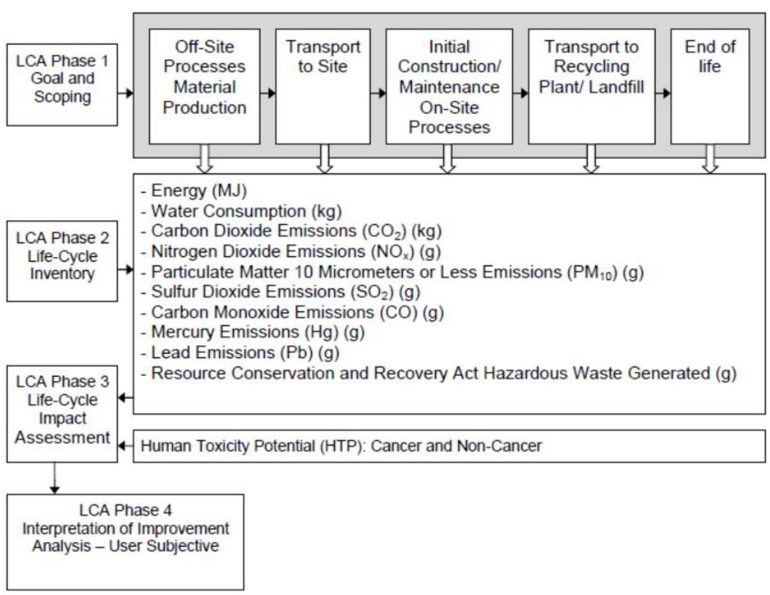

Figure 22. Overview of the PaLATE model (Santero et al., 2010).

PaLATE does complex relationships among pavement construction materials and processes and disaggregates the construction process into tasks that are then used to compute the twelve environmental impacts. These impacts are organized on the "Environmental Results" sheet as it was shown in Figure 16, but to arrive to a final result for the twelve outputs some calculations are done and for each pavement construction material or process twelve outputs are associated. In this way, each material has assigned to it 12 calculations for each material life-cycle stage. Figure 23 illustrates how PaLATE, in a brief way, organizes calculations and arrives to an output. The left side of this figure shows the steps that were used to arrive at the specific material-related disaggregate calculation, while the right side shows the disaggregated environmental calculations (Nathman et al., 2009). In order to give more details about results, the steps are explained as follows (in a top-down approach) and a demonstration will be done just with Initial Construction because Maintenance is analogous.

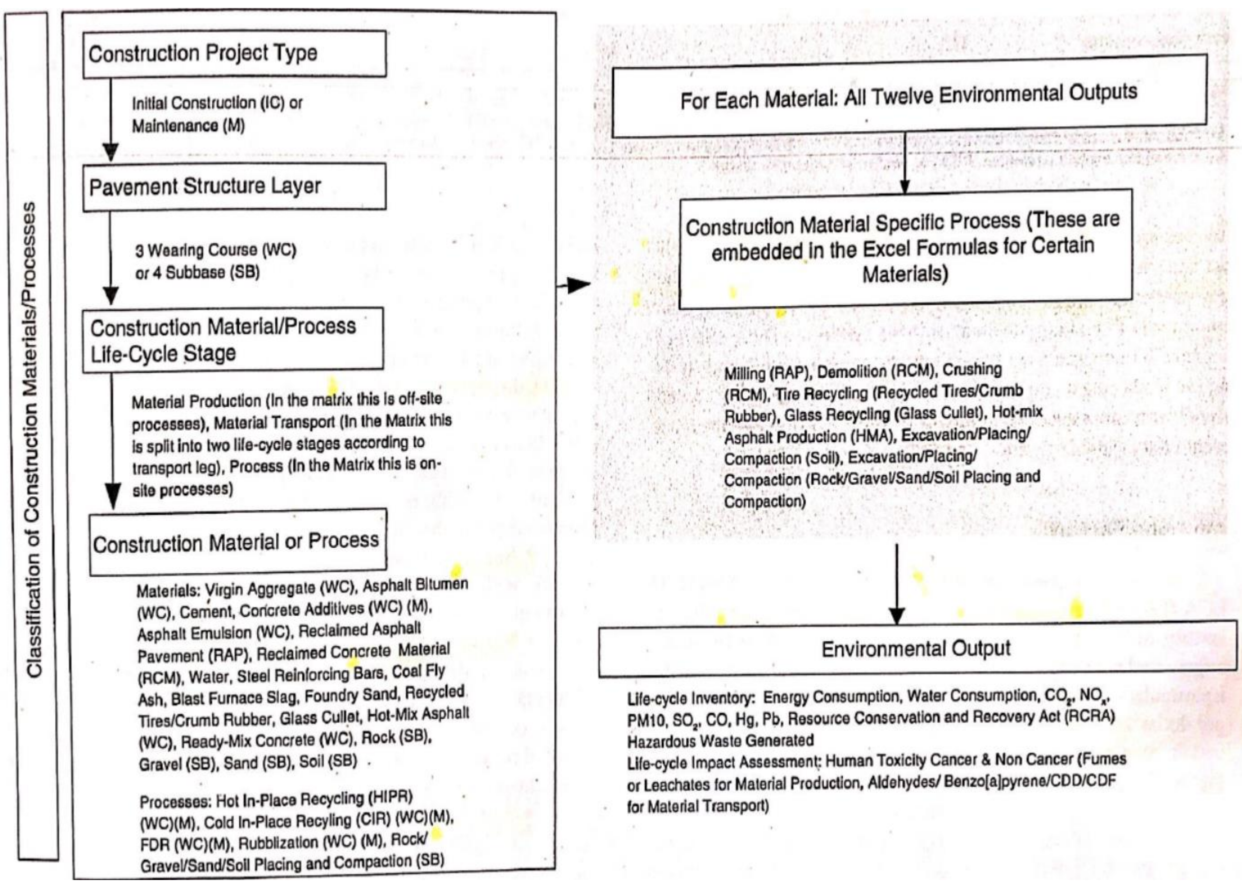

Figure 23. How PaLATE arrives to environmental calculations (Nathman et al., 2009).

1) First of all, it is of utmost importance to understand, and it was already named in chapter 3, that PaLATE gives results for Initial Construction and Maintenance life-cycle stages, and for completeness the sum of both stages. At the same time the software in order to be organized divides results in material production for Initial Construction, material transportation for Initial Construction and processes (equipment) for Initial Construction. That is to say that the software is considering in its calculation the environmental costs for material production involved, environmental costs for the transportation of material involved and the environmental costs for the equipment involved. The same thing is done for Maintenance. So, this first step is understanding results organization and Figure 24 is shown with **Energy output as an example but is the same for the 12 outputs.**

		Energy [MJ]
Initial Construc tion	Materials Production	0
	Materials Transportation	0
	Processes (Equipment)	0
Maintena nce	Materials Production	0
	Materials Transportation	0
	Processes (Equipment)	0
Total	Materials Production	0
	Materials Transportation	0
	Processes (Equipment)	0
	Total	**0**

Figure 24. Results organization.

2) Focusing on Initial Construction, Materials Production. The final value for this cell is the sum of the emission generated for every layer which compounds the pavement. See Figure 25.

Phase	Layer	Energy [MJ]
Initial Construction Material Production	Wearing Course 1	0
	Wearing Course 2	0
	Wearing Course 3	0
	Subbase 1	0
	Subbase 2	0
	Subbase 3	0
	Subbase 4	0
	Embankment and Shoulder	0
	Total	**0**

Figure 25. Initial Construction, Material Production results organization by layers.

The same is done regarding Initial Construction, Material Transportation and Initial Construction Processes.

3) Focusing on Wearing course 1 for Initial Construction, Material Production, because then is the same for every layer, the final result here embraces the sum of every emission generated from each material composing this wearing course 1. See Figure 26.

Initial Construction Materials WC1	Energy [MJ]	Water Consumption [g]	CO_2 [kg]	NOx [g]	PM-10 [g]	SO_2 [g]	CO [g]	Hg [g]	Pb [g]	RCRA Hazardous Waste Generated [g]	HTP cancer (g)	HTP non cancer (g)
Virgin Aggregates	0	0	0	0	0	0	0	0	0	0	0	0
Asphalt Bitumen	0	0	0	0	0	0	0	0	0	0	0	0
Cement	0	0	0	0	0	0	0	0	0	0	0	0
Concrete Additives	0	0	0	0	0	0	0	0	0	0		
RAP milling	0	0	0	0	0	0	0	0	0	0	0	0
FRAP milling & grinding	0	0	0	0	0	0	0	0	0	0	0	0
RAS Grinding	0	0	0	0	0	0	0	0	0	0	0	0
RCM demolition	0	0	0	0	0	0	0	0	0	0	0	0
RCM crushing	0	0	0	0	0	0	0	0	0	0		
Water	0	0	0	0	0	0	0	0	0	0		
Steel Reinforcing Bars	0	0	0	0	0	0	0	0	0	0		
Coal Fly Ash	0	0	0	0	0	0	0	0	0	0	0	0
Coal Bottom Ash	0	0	0	0	0	0	0	0	0	0	0	0
Blast Furnace Slag	0	0	0	0	0	0	0	0	0	0	0	0
Foundry Sand	0	0	0	0	0	0	0	0	0	0	0	0
Recycled Tires/ Crumb Rubber	0	0	0	0	0	0	0	0	0	0		
Glass Cullet	0	0	0	0	0	0	0	0	0	0		
Hot-mix Asphalt Plant Process	0	0	0	0	0	0	0					
Ready-mix Concrete	0	0	0	0	0	0	0	0	0	0	0	0
Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

Figure 26. Output result for each material.

In this step is where calculations are done, and it can be demonstrated the phrase said before that each material has assigned to it 12 calculations, one for each output. In this case, calculations done for every material take into account information from the "EMF transport" sheet about environmental costs of producing each material, which is related to the table of economic sectors, and this is a critical point because this is one of the most important tables of this thesis, it contributes in a huge way to results and it is where default data of the software is changed with further detailed explanation in this chapter. Calculations regarding Material Transportation have involved for each material everything related to data about diesel engines (because of the trucks that transports the material) from "EMF transport" sheet and calculations regarding Processes the data involved in its calculation it comes from "Equipment" and "Equipment Details" sheet, because it considers every machine used for paving.

4) As a final step it can be said that it is needed to understand now the bottom-up approach, that is to say, first, every calculation with its correspondent data for each layer and each task (Material Prod, Mat. Transp. and Processes) is done, then, the sum of every layer gives the total of output generated for each task, afterwards, the sum of the three tasks gives the total for a life-cycle stage (Initial Construction or Maintenance) and, finally, the sum of both Initial Construction and Maintenance gives the Total Environmental Impact of the Road Construction for a certain Output (this steps were explained with Energy). As it was already said the same is correct for the 12 outputs.

4.2 Analysis of default data provided by PaLATE

Before starting with the case studies analysis, an important step should be done. As the objective of this thesis is to analyze PaLATE through European road´s construction, it is not coherent to use the default data from USA. Focus in this situation was made and it took a lot of research and investigation. Principal data to be modified is the one from the "EMF transport" sheet when it refers to different economic sectors for the calculous of environmental outputs regarding material production for Initial Construction and for Maintenance, this will be demonstrated and explained as follows.

4.2.1 PaLATE background data

PaLATE performs a hybrid LCA approach combining an IO-LCA with a Process LCA. In order to give an overview about data in PaLATE, it can be seen that three different categories of data are used: emissions data, construction-process related data and data on HTP. The Data used for each disaggregate calculation vary according to the material, the material life-cycle stage, and the environmental output considered (Nathman et al., 2009). Six data sources conform these three different categories, these are:

<u>Emissions factors</u>

1) Emission factors, EIO-LCA
2) Other emission factors

<u>Construction Process Related</u>

3) Construction process related, equipment

<u>Human Toxicity Potential</u>

4) HTP, leaching potential
5) HTP, asphalt fumes
6) HTP, aldehydes, benzo[a]pyrene, and CDD/CDF

Table 2 gives further explanation specific to materials and material life-cycle stages related with data required. Common to all calculations is the use of volume and density data.

Material	Life-Cycle Stage 1 Material Production Off-Site Processes	Life-Cycle Stage 2 Transport to Site	Life-Cycle Stage 3 Initial Construction/Maintenance On-Site Processes	Life-Cycle Stage 4 Transport to Recycling Plant/Land▯ll
Virgin aggregate	1, 2, 4	1, 2, 6	1, 2, 3 (asphalt paving) or	1, 2, 6
Asphalt bitumen	1, 2, 5	1, 2, 6	1, 2, 3 (concrete paving) or	1, 2, 6
Cement	1, 4	1, 2, 6	1, 2, 3 (HIPR(M)) or	1, 2, 6
Concrete additives	1	1, 2, 6	1, 2, 3 (CIR(M)) or	1, 2, 6
Asphalt emulsion (M)	1	1, 2, 6	1, 2, 3 (FDR(M)) or	1, 2, 6
RAP	1, 2, 3 (milling), 4	1, 2, 6	1, 2, 3 (rubblization (M)) or	1, 2, 6
RCM	1, 2, 3 (concrete demolition), 4 and/or 1, 2, 3 (concrete crushing), 4	1, 2, 6	1, 2, 3 (rock, gravel, sand, and soil placing and compaction (S))	1, 2, 6
Water	1	1, 2, 6		1, 2, 6
Steel reinforcing bars	1	1, 2, 6		1, 2, 6
Coal ▯y ash	2, 4	1, 2, 6		1, 2, 6
Coal bottom ash	4	1, 2, 6		1, 2, 6
Blast furnace slag	4	1, 2, 6		1, 2, 6
Foundry sand	4	1, 2, 6		1, 2, 6
Recycled tires/crumb rubber	1, 2, 3 (tire recycling)	1, 2, 6		1, 2, 6
Glass cullet	1, 2, 3 (glass recycling)	1, 2, 6		1, 2, 6
Rock (S)	1, 2	1, 2, 6		1, 2, 6
Gravel (S)	1, 2, 4	1, 2, 6		1, 2, 6
Sand (S)	1, 2, 4	1, 2, 6		1, 2, 6
Soil (S)	2, 3 (excavation, placing, compaction)	1, 2, 6		1, 2, 6
Hot-mix asphalt	2, 3 (HMA production)	1, 2, 6		1, 2, 6
Ready-mix concrete	1, 2, 4	1, 2, 6		1, 2, 6

Table 2. Data Required for Environmental Calculations by Material and Stage in Life Cycle (Nathman et al., 2009).

(M)= maintenance pavement construction projects; (S)= subbase pavement structure layers

Data used in PaLATE is available online or it was extracted from U.S. government reports, it was never changed since its creation so it is outdated, exemplified by the use of the 1992 EIO-LCA model as the source of many of its key environmental assumptions (Santero et al., 2010), as well as road construction materials used for pavements that in the last decade have changed abruptly, therefore, this data should be updated.

In this thesis a focus was done in the first data source called emission factors, EIO-LCA. It is the one that is important to modify because, as it was said before, it provides fundamental data for environmental outputs during material production stage that it is known to be the most influencing life-cycle stage when constructing a road, and in addition, it is not the same to produce virgin aggregates in USA or Europe, different processes are carried out. As this information is contained in the "EMF transport" sheet, a better explanation of this sheet should be done.

4.2.1.1 EMF transport sheet detailed

This worksheet was found to be the one to be modified, and as it was said in chapter 3, contains information about emissions of diesel engines for material transportation and emissions for each economic sector for material production. So, this sheet is focusing in 2 life-cycle stages: material transportation and material production. Yet, the most important part to be modified is that of material production, due to the fact that was already explained but it is very important to remark that is not the same to produce virgin aggregates in USA or in Europe, while a diesel engine doesn't vary that much from one continent to another. So now, a brief explanation of these two parts will be done, giving more details in the material production one.

<u>Material Production</u>

Environmental impacts for material production are calculated using information from the economic sector table, where the EIO-LCA is performed. Economic Input-Output LCA is used as the default emission factor and combines economic costs for a particular sector in industry with environmental emissions for this sector. Data for EIO-LCA comes from the national EIO table (in this case from USA) that is augmented with environmental vectors, such as the emissions from a particular economic sector. These vectors are expressed in some quantity of emission produced per dollar amount (g/$) (see Table 3) that combined with the cost to produce certain quantity of an economic sector expressed in $/ton (see Table 4), generates a conversion similar to an emission factor expressed in g/ton (see Table 5). The national EIO table that contains the information of the cost to produce a certain quantity of an economic sector is called “R. S. Means Building Construction Cost Data”, R. S. Means Co., Kingston, MA, 1995. Therefore, the calculation for each economic sector recognizes the contribution of related industries. The tool which performs an EIO-LCA in PaLATE was available through Carnegie Mellon University on the basis of 1997 data. As explained by the University:

“The Economic Input-Output Life Cycle Assessment (EIO-LCA) method estimates the materials and energy resources required for, and the environmental emissions resulting from, activities in our economy. The EIO-LCA method was theorized and developed by economist Wassily Leontief in the 1970s based on his earlier input-output work from the 1930s for which he received the Nobel Prize in Economics. […] Results from using the EIO-LCA on-line tool provide guidance on the relative impacts of different types of products, materials, services, or industries with respect to resource use and emissions throughout the supply chain” [12].

		g/$	g/$	g/$	g/$	g/$	MJ/$	kWh/$	g/$	g/$	g/$	gal/$
	Sector	CO_2	CO	NO_2	SO_2	PM10	Energy	Electricity	Hg	Pb	RCRA Hazardous Waste Generated	Water Consumption
1	Asphalt paving mixt	7,203.00	1.64	1.74	1.07	1.90	77.47	0.69	3.88E-05	0.0020	140.13	3.79
2	Ready-mixed conc	1,318.80	11.97	19.59	17.19	6.12	19.06	0.67	3.88E-05	0.0021	33.13	6.03
3	Blast furnaces and	1,999.93	6.71	3.56	2.81	1.24	31.55	1.26	4.E-02	0.0157	49.49	66.26
4	Sand and Gravel	1,094.22	1.44	2.20	1.07	3.27	15.45	1.02	4.05E-08	0.0003	17.96	2.15
5	Bitumen	1,236.42	5.22	6.88	6.23	1.17	21.77	0.86	3.88E-05	0.0018	386.74	9.14
6	cement	3,153.87	13.47	37.93	37.60	7.10	44.94	1.96	3.88E-05	0.0037	19.48	22.27
7	concrete additives	1,200.34	6.15	4.89	3.61	1.76	20.05	0.84	3.88E-05	0.0027	299.11	18.71
8	asphalt emulsion	1,236.42	5.22	6.88	6.23	1.17	21.77	0.86	3.88E-05	0.0018	386.74	9.14
9	water	609.87	2.43	3.22	3.30	1.14	7.96	0.23	4.67E-07	0.0012	36.00	2.01
10	Electric services (u	12,439.74	3.66	35.60	69.69	2.42	129.02	0.15	4.67E-07	0.0019	15.23	0.81

Table 3. Environmental vectors table by sector.

	Sector	all prices from [Means 1995]			
1	Asphalt paving mixtures and blocks	28 $/Mg	25 $/ton		
2	Ready-mixed concrete	31 $/Mg	28 $/ton		
3	Blast furnaces and steel mills	300 $/Mg	272 $/ton		
4	Sand and Gravel	11 $/Mg	10 $/ton		
5	Bitumen	1,000 $/Mg	907 $/ton		
6	cement		84 $/ton		
7	concrete additives	2,114 $/Mg	1,918 $/ton	$8 /gal	264.200793
8	asphalt emulsion	864 $/Mg	784 $/ton	$3 /gal	264.200793
9	water		0.00082 $/ton		
10	Electric services (utilities)	0.10 $/kWh			

Table 4. EIO prices for each sector.

Prices used in Table 4 are those from the second column, except for Electric Services that uses the first column.

Sector	CO_2	CO	NO_2	SO_2	PM10	Energy	Electricity	Hg	Pb	RCRA Hazardous Waste Generated	Water Consumption
units	g/ton	g/ton	g/ton	g/ton	g/ton	MJ/ton	kWh/ton	g/ton	g/ton	g/ton	g/ton
Asphalt paving mixt	183,016	42	44	27	48	1,968	18	1.E-03	5.E-02	3,560	96
Ready-mixed concr	37,099	337	551	484	172	536	19	1.E-03	6.E-02	932	169
Blast furnaces and	544,446	1,828	969	766	338	8,589	342	1.E+01	4.E+00	13,473	18,037
Sand and Gravel	10,922	14	22	11	157	154	10	4.E-07	3.E-03	179	79,490
Bitumen	1,121,978	4,736	6,239	5,653	1,057	19,757	784	4.E-02	2.E+00	350,942	31,388,630
cement	264,925	1,132	3,186	3,158	597	3,775	165	3.E-03	3.E-01	1,636	1,871
concrete additives	2,302,229	11,804	9,374	6,930	3,371	38,464	1,619	7.E-02	5.E+00	573,686	35,885
asphalt emulsion	969,318	4,092	5,390	4,884	914	17,069	678	3.E-02	1.E+00	303,191	27,118,690
water	0.497	0.002	0.003	0.003	0.001	0.006	0.000	4.E-10	9.E-07	0	0
units	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	MJ/kWh	kWh/kWh	g/kWh	g/kWh	g/kWh	g/kWh
Electric services (u	1243.97	0.37	3.56	6.97	0.24	12.90	0.02	4.67E-08	1.89E-04	1.52	0.08

Table 5. Emissions factor for each sector- default from PaLATE (Sector Table).

Table 5 will be called "Sector table"[7] and shows the results of the methodology EIO-LCA implemented in PaLATE (with the value of water consumption corrected for sand and gravel, bitumen and asphalt emulsion sectors) and it is exactly the table which was modified in this thesis with the help of literature. Now the second part of the "EMF transport" sheet will be explained and further on, the changes made to this table.

[7] HTP emission are not considered in the sector table because PaLATE calculates it with another procedure that enhance leachate for aggregates production and fumes for bitumen production.

<u>Material Transportation</u>

In chapter 3 in the "Initial Construction" sheet it was named that information about transportation should be input so as the program can make its calculation for environmental results.

But:

- these environmental outputs regarding material transportation, where do they come from?

They come from the emissions that contains the diesel engines of the different trucks used.

-and, who knows data about diesel engines?

EMF transport sheet.

Hence, this sheet as a starting point shows information of carbon content in diesel engines in order to calculate the carbon dioxide emissions (CO_2) during transportation considering the transport distance already input. As the diesel properties are the same in Europe or in USA, this information is not modified. The information shown is:

- Diesel density.
- Weight percent of carbon content: how much of the diesel is made up of carbon.
- CO_2 efficiency factor: how much of the diesel is converted to CO_2 after combustion. See Figure 27.

DIESEL CARBON CONTENT						
REFERENCE: Gasoline and Diesel Industrial Engines-Emission Factor Documentation for AP-42 Section 3.3, USEPA, October 1996; http://www.epa.gov/ttn/chief/ap42/ch03/bgdocs/b03s03.pdf; Accessed 03/20/02 at 12PM						
Density	7.1	lb/gal	3223.4	g/gal	848.3	g/l
Weight Percent of Carbon Content	87%		0.0032234	Mg/gal	0.00084826	Mg/l
CO_2 Efficiency Factor	99%					

Figure 27. Diesel Carbon Content.

In order to calculate NOx, SO_2, PM_{10} and CO emissions data provided by the OECD is used and is shown in Figure 28.

BARGE EMISSIONS

REFERENCE: TIET-4-10-03, transportation emissions factors.

	Emission Factors (grams/passenger mile)			Emissions Factors (grams/tonne-km)		
	NMHC	NOx	PM_{10}	NMHC	NOx	PM_{10}
Ferry Boat Diesel	0.014	8.224	0.143	0.01799856	10.5728685	0.183842435

FREIGHT TRUCKING EMISSIONS

REFERENCE: OECD. 1997. The Environmental Effects of Freight. Table 9. Truck Air Pollution Emission Factors, in grams/tonne-km

		Emission factor, grams/tonne-km					
		CO	CO_2	HC	NOx	SO_2	PM
OECD (Europe)	Long distance trucks	0.25	140	0.32	3.00	0.18	0.17

FREIGHT RAIL EMISSIONS

REFERENCE: OECD. 1997. The Environmental Effects of Freight.

		Emission factor, grams/tonne-km					
		CO	CO2	HC	NOx	SO2	PM
OECD	Rail	0.15	48	0.07	0.4	0.18	0.07

Figure 28. Emissions from different transportation modes.

These data vary depending on the mode of transportation chosen. It can be clearly seen that there is information provided for barge[8] transport mode, rail transport mode and truck transport mode which considers all three types of trucks: cement, tanker and dump. The information is different for each mode of transportation for obvious reasons, not all the modes emit the same quantity of a certain gas, whereas for CO_2 it was the same for all transportation modes because every transport runs with a diesel engine. Emission factors then combined with transport distances, volume and density of the transported material gives as a result environmental impacts.

Regarding HTP impacts, information form the US EPA is provided, which focuses on the diesel toxic emissions from engines (see Figure 29). These toxic emissions are evaluated in terms

[8] Barge emissions weren't studied in detail and it is a point to deepen in future studies.

of Aldehydes, benzo[a]pyrene and CDD/CDF, which, combined with transport distances, volume and density of the transported material gives an environmental output, but, it is necessary yet to combine this result with a Human Toxicity Potential Emissions Weighting in order to be able to calculate a final environmental output with sense (see Figure 30). This weighting is necessary to get a real value of magnitude in which these emissions are affecting humans.

DIESEL TOXIC EMISSIONS

REFERENCE: Health Assessment Document for Diesel Engine Exhaust, US EPA, EPA/600/8-90/057F, May 2002.

	Aldehydes g/mile	Benzo[a]pyrene g/mile	CDD/CDF pg TEQ/km driven	CDD/CDF g TEQ/mile
Heavy-duty diesel	0.20	0.000013	172	2.77E-10

Figure 29. Diesel Toxic Emissions.

Human Toxicity Potential Emissions Weighting

Source: Hertwich E G, Mateles S F, Pease W S, McKone T E, "Human Toxicity Potentials for Life Cycle Assessment and Toxics Release Inventory Risk Screening", Environmental Toxicology and Chemistry, 20(4), 2001.

Chemical Name	CAS #	Cancer HTP		Non-cancer HTP	
		air	water	air	water
2,3,7,8 - TCDD	1746-01-6	1.80E+09	1.00E+09	2.30E+12	1.30E+12
Acetaldehyde	75-07-0	3.50E-03	6.30E-03	3.90E+00	1.10E+01
Aldehydes	N/A	3.13E-03	1.80E-03	4.58E+00	3.14E+00
Benzo[a]pyrene	50-32-8	1.60E+03	1.10E+01	0.00E+00	0.00E+00
Formaldehyde	50-00-0	3.00E-03	3.00E-04	4.80E+00	5.20E-01

Figure 30. Human Toxicity Potential Emissions Weighting.

The values used from Figure 30 are those referring to the rows of "2,3,7,8 – TCDD", "Aldehydes" and "Benzo[a]pyrene" for both cancer and non-cancer HTP in correspondence to CDD/CDF, aldehydes and benzo[a]pyrene calculations respectively, and the columns of emissions in air.

To calculate the remaining outputs such as energy, water consumption, mercury, lead and hazardous wastes for material transportation other information of diesel was used combined with transport distances, volume and density of the transported material, to reach an environmental output. The information required is as follows.

- Energy: uses heat content in diesel engines information = 3,58+E07 J/l

- Water consumption, mercury, lead and hazardous wastes: use information about diesel density combined with the environmental impact to produce asphalt emulsion taken from the economic sector table.

Having finished with the detail explanation of "EMF transport" sheet, the changes made in the sector table will be demonstrated.

4.2.2 Research made and Sector table edition

In order to modify the default Sector table (shown in Table 5) and put estimated values, an exhaustive research was done, and a lot of European literature was reviewed. As Table 5 is showing emission factors for different outputs generated for several economic sectors in the United States, the investigation consisted in searching emissions generated during the production of the materials named in the Sector Table in Europe. Principally, the focus was put in looking for emissions during bitumen, virgin aggregates and asphalt emulsion production, which are the main sectors involved in the case studies to be analyzed. Therefore, literature applying an LCA methodology to the material production was mainly studied.

After a long search, the most important literatures found to be valuable where:

- Eurobitume (European Bitumen Association, 2012),
- A study made by the Technical Research Centre of Finland (Häkkinen & Mäkelä, 1996),
- A study made by the Swedish Environmental Research Institute for the Swedish National Road Administration (Stripple, 2001),
- A study made by the Imperial College of London (Korre & Durucan, 2009), and
- A study made in the Piedmont Region, Italy (Blengini & Garbarino, 2010).

Eurobitume

It provides a Life Cycle Inventory of bitumen for Europe, giving as results emissions to produce bitumen. To do so, it performs a cradle-to-gate study and covers:

- ✓ Crude oil extraction
- ✓ Transport to Europe
- ✓ Manufacturing of bitumen in refinery
- ✓ Bitumen storage
- ✓ Takes into account the infrastructure (construction of production facilities)

Figure 31 shows the system boundaries considered.

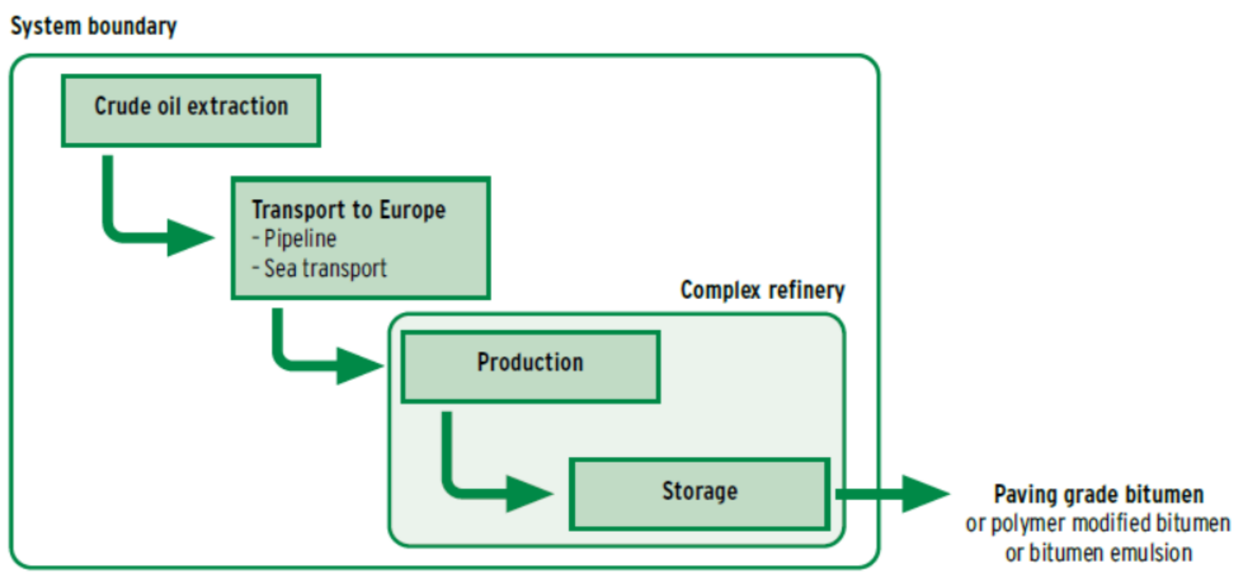

Figure 31. System boundaries for the bitumen eco-profile (cradle-to-gate approach).

The study covers paving grade bitumen as defined in the product standard EN 12591[9], including penetration grades 20 to 220 1/10 mm. The main route of production of bitumen is straight-run distillation (atmospheric distillation + vacuum distillation).

Eurobitume is not just performing an LCI for bitumen production, but also for polymer modified bitumen (PMB) with 3,5% polymer and for bitumen emulsion with 65% bitumen (European Bitumen Association, 2012).

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[9] *"This European Standard provides a framework for specifying a range of properties and relevant test methods for bitumens, which are suitable for use in the construction and maintenance of roads, airfields and other paved areas, together with requirements for evaluation of conformity" [13].*

Technical Research Centre of Finland study

This is a Finnish study which performs a Process LCA to a stone-mastic asphalt (SMA) and a doweled jointed plain concrete pavement (JPCP). It considers every phase of the life-cycle except for the EOL phase. Environmental burdens for the production of materials involved in both cases are quantified by tracing the upstream supply chain of it (Santero et al., 2010). Emissions that are interesting for the scope of the thesis are that of virgin aggregates and bitumen production. Virgin aggregates in this study were divided into gravel and crushed aggregates.

The environmental burdens calculated for the bitumen production in this study were taken from another Nordic source. The processes enhanced are:

- ✓ Production of raw oil
- ✓ Transportation of raw oil
- ✓ Refining

Processes considered for gravel production:

- ✓ Extraction
- ✓ Transportation

Processes considered for crushed aggregates:

- ✓ Quarrying and breaking
- ✓ Transportation of broken rock
- ✓ Crushing
- ✓ Transportation of crushed materials

(Häkkinen & Mäkelä, 1996)

Swedish Environmental Research Institute

This is a Swedish study that performs an LCA to a JPCP and two asphalt pavements produced using hot and cold production techniques. This work, as the Finnish one, considers every life-cycle phase except for the EOL. Environmental burdens of material production is accounted in great detail, every process is defined and quantified, resulting in a transparent methodology

(Santero et al., 2010). Emissions that are interesting for the scope of the thesis are that of virgin aggregates and bitumen production. Virgin aggregates in this study were divided into sand and gravel, and crushed aggregates.

Processes included in bitumen production:

- ✓ Crude oil extraction
- ✓ Transportation
- ✓ Refining
- ✓ Storage

Figure 32 provides a better explanation.

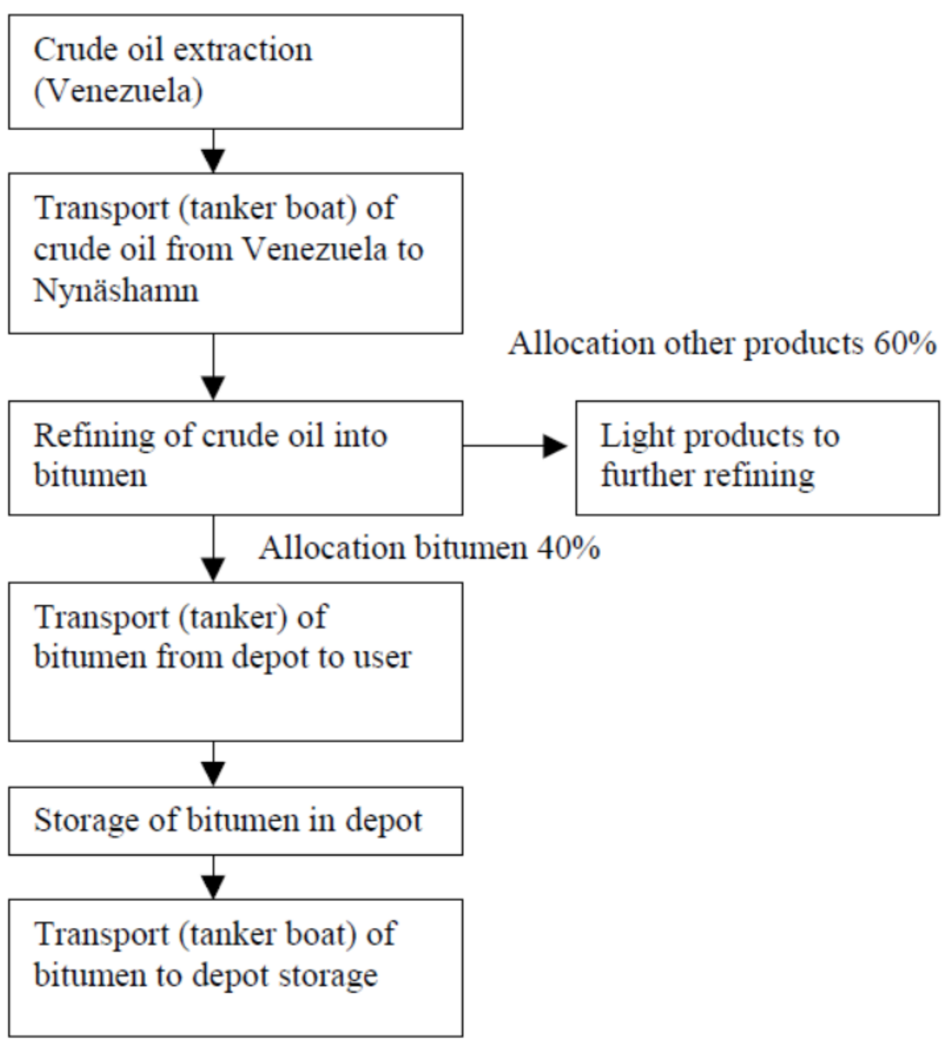


Figure 32. Overview of a model structure for production of bitumen (Stripple, 2001).

Processes included in sand and gravel production:

- ✓ Extraction
- ✓ Transportation

Processes included in crushed aggregates production:

- ✓ Blasting and breaking
- ✓ Transportation of blasted rock
- ✓ Crushing

(Stripple, 2001).

Imperial College of London

This is a study carried out in United Kingdom (UK) where the objective was to apply an LCI and an LCA to the aggregates industries. So, in this work, bitumen was not analyzed, and environmental burdens were just calculated for aggregates, and for this thesis, the interesting values are just those for sand and gravel, and crushed aggregates. The work includes:

- ✓ Extraction
- ✓ Processing of aggregates (including overburden stripping, drilling and blasting, and restoration)

(Korre & Durucan, 2009)

Study made in the Piedmont Region

It is a study which is mainly focused on resources and waste management in Turin, Italy. The paper presents a research aimed at evaluating environmental impacts of construction and demolition waste (C&DW) recycling chain through an LCA methodology in the territory of Provincia di Torino. This work considers the phase of natural aggregates quarrying. Information about environmental impact for natural aggregates was provided by a quarry located in the surroundings of Turin.

The processes included for natural aggregates are:

- ✓ Extraction (by means of a grab dredge)
- ✓ Processing in plant

(Blengini & Garbarino, 2010)

In this case, values for the production of aggregates were directly extracted from another study that was based on Blengini & Garbarino 2010, and it is another case study in the Piedmont Region named "Life Cycle Assessment applied to bituminous mixtures containing recycled materials: crumb rubber and reclaimed asphalt pavement" (Farina et al., 2017) which was developed by professors of the Politecnico di Torino from the Department of Environment, Land and Infrastructure Engineering.

Having finished with a brief description of the most important literature regarding material production for the objective of this thesis, now, several tables will be presented showing the values for emission extracted from each literature, which are possible values to input in the Sector Table, for bitumen, asphalt emulsion and aggregates production.

Table 6 shows values for bitumen production for the different outputs considered in PaLATE. In the table, the letter I means that the construction of the facilities is considered, and PM polymer modified bitumen.

BITUMEN	CO2	CO	NO2	SO2	PM10
Units	g/ton	g/ton	g/ton	g/ton	g/ton
PaLATE	1,121,978.11	4,736.37	6,239.04	5,653.10	1,057.47
Eurobitume I	244,142	1,040	1,142	899	300
Eurobitume	189,119	613	770	781	161.2
Hakinen and Makela, Technical research centre of Finland	330,000	100	2,900	800	300
Stripple, Swedish Env. Research institute	173,032.43	111	1,020	612	8.1
PM Eurobitume I	376,141	1,083	1,734	1,744	400
PM Eurobitume	323,035	671	1,375	1,630	265

BITUMEN	Energy	Electricity	Hg	Pb	RCRA Hazardous Waste	Water Consumption
Units	MJ/ton	kWh/ton	g/ton	g/ton	g/ton	l/ton
PaLATE	19,757.38	784.39	0.035	1.64	350,941.65	31,426.68
Eurobitume I	3,769.45	-	-	-	-	1,239
Eurobitume	2,939.82	-	-	-	-	143
Hakinen and Makela, Technical research centre of Finland	6,000	-	-	-	1,900	370
Stripple, Swedish Env. Research institute	3,635	252	-	-	263	-
PM Eurobitume I	6,334.24	-	-	-	-	8,135
PM Eurobitume	5,533.55	-	-	-	-	7,078

Table 6. Values for emissions from different literature for bitumen production.

Table 7 shows values for asphalt emulsion production for the different outputs considered in PaLATE. In the table, the letter I means that the construction of the facilities is considered, and BE bitumen emulsion.

BITUMEN EMULSION	CO2	CO	NO2	SO2	PM10
Units	g/ton	g/ton	g/ton	g/ton	g/ton
PaLATE	969,317.94	4,091.92	5,390.14	4,883.92	913.59
BE Eurobitume I	274,769	1,057	1,207	993	324.9
BE Eurobitume	219,746	629	835	876	185.5

BITUMEN EMULSION	Energy	Electricity	Hg	Pb	RCRA Hazardous Waste	Water Consumption
Units	MJ/ton	kWh/ton	g/ton	g/ton	g/ton	l/ton
PaLATE	17,069.13	677.66	0.030	1.41	303,191.33	7,163.93
BE Eurobitume I	4,265.47	-	-	-	-	2,073
BE Eurobitume	3,439.18	-	-	-	-	977

Table 7. Values for emissions from different literature for bitumen emulsion production.

Table 8 shows values for virgin aggregates production for the different outputs considered in PaLATE. Blengini and Garbarino values are not divided into different categories of aggregates.

VIRGIN AGGREGATES		CO2	CO	NO2	SO2	PM10
Units		g/ton	g/ton	g/ton	g/ton	g/ton
PaLATE	Sand and Gravel	10,922.35	14.38	22.01	10.72	156.51
Hakinen and Makela, Technical	Crushed Agg.	2107.50	2.50	12.00	6.50	1.90
	Gravel	1,742.50	3.1	14	1.8	2.7
Stripple, Swedish Env.	Sand and Gravel	73.49	0.0736	0.597	0.0467	0.0231
	Crushed Agg.	1,430.85	1.49	0.123	0.788	0.477
Anna Korre, UK LCA	Sand and Gravel	270 -2,390	-	-	1.34 -13.5	-
	Crushed Agg.	1,480 - 2,520	-	-	8.58 - 14.8	-
Blengini and Garbarino, Piedmont region		2,913.79	-	-	-	-

VIRGIN AGGREGATES		Energy	Electricity	Hg	Pb	RCRA Hazardous Waste	Water Consumption
Units		MJ/ton	kWh/ton	g/ton	g/ton	g/ton	l/ton
PaLATE	Sand and Gravel	154.22	10.16	4.00E-07	0.0031559	179.23	79.59
Hakinen and Makela, Technical	Crushed Agg.	52.00	11.39	2.70E-07	0.00018	-	-
	Gravel	24	-	5.60E-07	0.00037	3	-
Stripple, Swedish Env.	Sand and Gravel	6.25	0.67	-	-	-	-
	Crushed Agg.	38.18	5.88	-	-	-	-
Anna Korre, UK LCA	Sand and Gravel	-	-	-	-	-	-
	Crushed Agg.	-	-	-	-	-	-
Blengini and Garbarino, Piedmont region		-	5.3	-	-	-	2,301.29

Table 8. Values for emissions from different literature for virgin aggregates production.

4.2.3 Final values for Sector table

In this section, the Sector Tables to be used in both case studies will be defined, choosing values from the already named literature.

Before presenting the table, a clarification should be done. In the case of CO_2 emissions, these are carbon dioxide equivalent (CO_2 eq.) emissions, meaning that for CO_2 also other greenhouse gases (GHG) were taken into account and converted through a weight of global warming potential to CO_2 equivalent emissions. The principal gases considered to be converted are methane (CH_4) and nitrous oxide (N_2O). This was done in order to consider a wider range of pollutant gases.

The weight of the methane compared to CO_2 is 25, that is to say that releasing 1 kg of CH_4 into the atmosphere is about equivalent to releasing 25 kg of CO_2.

The weight of the nitrous oxide compared to CO_2 is 298, that is to say that releasing 1kg of N_2O into the atmosphere is about equivalent to releasing 298 kg of CO_2.

There are other GHG which have far greater GWP but are much less prevalent. These are Sulphur hexafluoride (SF_6), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs) [14].

Now the tables showing the final values selected will be presented and calculations for CO_2eq. emissions will be demonstrated.

i. **Estimated Sector Table with values chosen from literature for Sitalfa S.p.A. case study** which uses polymer modified bitumen is presented in Table 9. This Polymer used in Sitalfa is not the traditional one which comes included in the bitumen. It is added to the mixture at the same time with the aggregates to obtain the HMA.

Sector	CO_2	CO	NO_2	SO_2	PM10
units	g/ton	g/ton	g/ton	g/ton	g/ton
Sand and Gravel	2,914	6	26	8	128
Bitumen	376,141	1,083	1,734	1,744	400
asphalt emulsion	274,769	1,057	1,207	993	325

Sector	Energy	Electricity	Hg	Pb	RCRA Hazardous Waste Generated	Water Consumption
units	MJ/ton	kWh/ton	g/ton	g/ton	g/ton	g/ton
Sand and Gravel	76	5	8.E-07	6.E-04	179	2,300,000
Bitumen	6,334	252	4.E-02	2.E+00	1,900	8,135,000
asphalt emulsion	4,265	678	3.E-02	1.E+00	303,191	2,073,000

Table 9. Emission factor values, Sitalfa case study.

Bitumen values

For the bitumen sector, values for CO_2, CO, NO_2, SO_2, PM_{10}, Energy and Water Consumption were all taken from Eurobitume LCI from the table of PMB considering the facilities construction (European Bitumen Association, 2012). This literature was chosen because it represents (in a general overview) every case in Europe and it is a trustworthy source. Values for CO, NO_2, SO_2, PM_{10} were directly copied, while for CO_2 (CO_2eq. already explained), Energy and Water Consumption, some calculations were made.

CO_2eq.: in this case Eurobitume provides information for CO_2 and CH_4, so to convert the methane gas into CO_2

$$CO_2eq. = CO_2 + CH_4\ x\ 25 = 346{,}016\frac{g}{ton} + 1{,}205\frac{g}{ton}\ x\ 25 = 376{,}141\ g/ton$$

Energy: Eurobitume provides values for Energy as Natural Gas, Crude Oil, Coal and Uranium in kg/ton of bitumen produced, but PaLATE expresses energy values in MJ/ton, so, what it was made is to multiply each value by its calorific power and then sum every value in order to get a Total value for Energy consumption during PMB production.

- Calorific powers: Natural gas = 52.3 MJ/kg

  Crude Oil = 44.5 MJ/kg

  Coal = 18 MJ/kg

  Uranium = 500,000 MJ/kg

$$Energy = 52.3\frac{kg}{ton}x\ 52.3\frac{MJ}{kg} + 69.1\frac{kg}{ton}\ x\ 44.5\frac{kg}{ton} + 18\frac{kg}{ton}\ x\ 18\frac{MJ}{kg} + 0.0004\frac{kg}{ton}\ x\ 500{,}000\frac{MJ}{kg} = 6{,}334.24\frac{MJ}{ton}$$

Water Consumption: this value is provided by Eurobitume in liters (l), so to insert it in PaLATE was converted into grams.

$$Water\ Consumption = 8{,}135\ l = 8{,}135\ kg = 8{,}135{,}000\ g$$

Values for Hg and Pb were left as default from PaLATE because no values for them were found in literature. Therefore, it was assumed that at least the default values are a good gross approximation. Whereas in the case of Hazardous Wastes its value was extracted from the Finnish case study (Häkkinen & Mäkelä, 1996).

Value for Electricity was taken from the Swedish study (Stripple, 2001) because it was the only one which provides values for this output.

Asphalt Emulsion values

For the asphalt emulsion sector, values for CO_2, CO, NO_2, SO_2, PM_{10}, Energy and Water Consumption were all taken from Eurobitume LCI from the table of asphalt emulsion considering the facilities construction (European Bitumen Association, 2012). This literature was chosen because it represents (in a general overview) every case in Europe and it is a trustworthy source. Values for CO, NO_2, SO_2, PM_{10} were directly copied, while for CO_2 (CO_2eq. already explained), Energy and Water Consumption, some calculations were made (the same calculations as for bitumen).

CO_2eq.: in this case Eurobitume provides information for CO_2 and CH_4, so to convert the methane gas into CO_2

$$CO_2eq. = CO_2 + CH_4\ x\ 25 = 255{,}669\frac{g}{ton} + 764\frac{g}{ton}\ x\ 25 = 274{,}769\ g/ton$$

Energy: Eurobitume provides values for Energy as Natural Gas, Crude Oil, Coal and Uranium in kg/ton of bitumen produced, but PaLATE expresses energy values in MJ/ton, so, what it was made is to multiply each value by its calorific power and then sum every value in order to get a Total value for Energy consumption during asphalt emulsion production.

- Calorific powers: Natural gas = 52.3 MJ/kg

  Crude Oil = 44.5 MJ/kg

  Coal = 18 MJ/kg

  Uranium = 500,000 MJ/kg

$$Energy = 24.3 \frac{kg}{ton} x\ 52.3 \frac{MJ}{kg} + 54.4 \frac{kg}{ton}\ x\ 44.5 \frac{MJ}{kg} + 15.21 \frac{kg}{ton}\ x\ 18 \frac{MJ}{kg} + 0.0006 \frac{kg}{ton}\ x\ 500{,}000 \frac{MJ}{kg} = 4{,}265.47 \frac{MJ}{ton}$$

Water Consumption: this value is provided by Eurobitume in liters (l), so to insert it in PaLATE was converted into grams.

$$Water\ Consumption = 2{,}073\ l = 2{,}073\ kg = 2{,}073{,}000\ g$$

Values for Hg, Pb, Electricity and Hazardous Wastes were left as default from PaLATE because no values for them were found in literature. Therefore, it was assumed that at least the default values are a good gross approximation.

Aggregates values

For the Sand and Gravel sector (it is called like this but accounts for aggregates), values for CO, NO_2, SO_2, PM_{10}, Energy, Hg and Pb were all taken from the Finnish study (Häkkinen & Mäkelä, 1996). This literature was chosen because it is a trustworthy and famous source when it comes to LCA methodologies. As this study divides aggregates in gravel and crushed aggregates, in order to insert them in the Sector Table, a sum between both values was done because in the Sitalfa case, the procedure followed to obtain aggregates is: aggregates are excavated from a river by means of a grab dredge (where sand and gravel is taken), then loaded and transported by means of a dump truck and finally processed (crushed to obtain the desired size) in a crushing plant. The same reason accounts for the case of CO_2eq., Electricity and Water Consumption, which values are taken from both Piedmont Region studies (considering that one of them is already based on Blengini)(Blengini & Garbarino, 2010).

In the case of CO_2 emission, Blengini already provides this value as CO_2eq., and can be extracted from the supplementary information provided in the C&DW study, named in the Appendix of this thesis.

Electricity and Water Consumption values are directly taken from the study of Farina et al, 2017. These values are found in the section that explains inventory for raw materials. In this study it can also be seen that for bitumen production the literature used was Eurobitume, thus, confirming that is a reliable and good piece of information for Europe.

Water Consumption: this value is provided in m^3, so a conversion was done

$$Water\ Consumption = 2.3\ m^3 = 2{,}300\ l = 2{,}300\ kg = 2{,}300{,}000\ g$$

ii. **Estimated Sector Table with values chosen from literature for case study extracted from an study called "Life Cycle Assessment of Road Pavements containing crumb rubber from end-of-life tires"** (Farina et al., 2014) which uses bitumen without polymer is presented in Table 10.

Sector	CO_2	CO	NO_2	SO_2	PM10
units	g/ton	g/ton	g/ton	g/ton	g/ton
Sand and Gravel	2,914	6	26	8	128
Bitumen	244,142	1,040	1,142	899	300
asphalt emulsion	274,769	1,057	1,207	993	325

Sector	Energy	Electricity	Hg	Pb	RCRA Hazardous Waste Generated	Water Consumptio n
units	MJ/ton	kWh/ton	g/ton	g/ton	g/ton	g/ton
Sand and Gravel	76	5	8.E-07	6.E-04	179	2,300,000
Bitumen	3,769	252	4.E-02	2.E+00	1,900	1,239,000
asphalt emulsion	4,265	678	3.E-02	1.E+00	303,191	2,073,000

Table 10. Emission factor values, 2nd case study.

<u>Bitumen values</u>

Analogous to Sitalfa case. For the bitumen sector, values for CO_2, CO, NO_2, SO_2, PM_{10}, Energy and Water Consumption were all taken from Eurobitume LCI from the table of bitumen considering the facilities construction (European Bitumen Association, 2012). This literature was chosen because it represents (in a general overview) every case in Europe and it is a trustworthy source. Values for CO, NO_2, SO_2, PM_{10} were directly copied, while for CO_2 (CO_2eq. already explained), Energy and Water Consumption, some calculations were made.

CO_2eq.: in this case Eurobitume provides information for CO_2 and CH_4, so to convert the methane gas into CO_2

$$CO_2eq. = CO_2 + CH_4\ x\ 25 = 226{,}167\frac{g}{ton} + 719\frac{g}{ton}\ x\ 25 = 244{,}142\ g/ton$$

Energy: Eurobitume provides values for Energy as Natural Gas, Crude Oil, Coal and Uranium in kg/ton of bitumen produced, but PaLATE expresses energy values in MJ/ton, so, what it was made is to multiply each value by its calorific power and then sum every value in order to get a Total value for Energy consumption during bitumen production.

- Calorific powers: Natural gas = 52.3 MJ/kg

  Crude Oil = 44.5 MJ/kg

  Coal = 18 MJ/kg

  Uranium = 500,000 MJ/kg

$$Energy = 22.5\frac{kg}{ton}x\ 52.3\frac{MJ}{kg} + 50.5\frac{kg}{ton}\ x\ 44.5\frac{kg}{ton} + 10.9\frac{kg}{ton}\ x\ 18\frac{MJ}{kg} + 0.0003\frac{kg}{ton}\ x\ 500{,}000\frac{MJ}{kg} = 3769.45\frac{MJ}{ton}$$

Water Consumption: this value is provided by Eurobitume in liters (l), so to insert it in PaLATE was converted into grams.

$$Water\ Consumption = 1{,}239\ l = 1{,}239\ kg = 1{,}239{,}000\ g$$

Values for Hg and Pb were left as default from PaLATE because no values for them were found in literature. Therefore, it was assumed that at least the default values are a good gross approximation. Whereas in the case of Hazardous Wastes its value was extracted from the Finnish case study (Häkkinen & Mäkelä, 1996).

Value for Electricity was taken from the Swedish study (Stripple, 2001) because it was the only one which provides values for this output.

Asphalt Emulsion values

Are exactly the same values that were used for the Sitalfa case study, with the same argument.

Aggregates values

Are exactly the same values that were used for the Sitalfa case study, with the same argument.

Having finished showing the tables that will be used in both case studies (Table 8 and 9), it can be said that by doing these changes, the LCA methodology is being transformed into a pure Process LCA and no more Hybrid LCA, because now emissions factors are being obtained for each material with a bottom-up approach, studying emissions generated through the whole supply chain and no more economic factors are being used. It has been a tough job to read literature following each process for each material looking for emissions, but it is worthy to do it so as it can be more specific. PaLATE does a hybrid approach to simplify data and save time doing a bottom-up analysis. Another good idea would have been to look for an European book that contain prices for each economic sector and environmental burdens per sector expressed in g/€ in order to continue with this hybrid LCA, but is too difficult to get an updated information of this kind.

In the following section both case studies will be analyzed.

4.3 Case Studies

The aim of this study is to evaluate the use of PaLATE tool with European background data, for that, the already explained modifications were done. The intended use of the results it is to highlight eventual criticisms or limitations related to the use of this tool in Europe. An application of PaLATE will be demonstrated with two different case studies. In both case studies an internal comparison will be done by obtaining results using the estimated Sector Table (the one which was modified) and the default (USA) Sector Table. In addition, for the second case study environmental impacts will be compared with those from another software called SimaPro 7.3, for a better reasoning and understanding of the tool.

4.3.1 1ST Case Study: Sitalfa S.p.A. with estimated data

4.3.1.1 System Description and functional unit

For the purpose of the proposed thesis, a road length of 382 m (0.24 mi) was assumed as the functional unit of analysis. The analysis was carried out on a case provided by Sitalfa S.p.A. company and it is the "Torre del Colle" viaduct from the highway A32. It is an asphalt pavement, and in this specific case it is just the fast lane in climbing direction to be constructed. The length of the road is of 382 m, having a lane width of 3.75 m and paved left shoulder of 0.90 m. <u>Every information of the case study was provided by the company.</u>

4.3.1.2 Pavement life cycle and system boundaries

The whole life cycle of a pavement can be divided into five phases:

1- Material production phase: including from extraction of raw materials to their conversion into final product.

2- Construction phase: includes all the execution for construction of the road infrastructure.

3- Use phase: is the longest phase of the life cycle. Factors to be included are related to pavement deterioration, traffic growth and pollution due to road vehicles.

4- Maintenance and rehabilitation: fundamental activities (in terms of bearing capacity, surface regularity and friction, mainly for user´s safety) over the analysis period of the road infrastructure.
5- End-of-life phase: definition of final disposal of materials, they can be recycled or waste.

But this thesis, and as long as the tool allows it, is just focusing in the analysis of environmental impacts during material production, construction, maintenance and EOL phases. These are considered as the system boundary of the analysis.

4.3.1.3 Design sheet

In this case as it is a viaduct, just two courses are considered above the concrete slab, wearing and binder course. Geometric parameters are inserted in this sheet and remind that as it is a software from USA every measurement unit is changed to the USCU, so meters are converted into yards, feet, inches and miles.

The analysis period is set equal to 20 years. Embankment and shoulder are not considered for this case because it is just the fast lane and left paved shoulder. The sheet was filled in as follows:

Layer Specifications				
Layer	Width [ft]	Length [miles]	Depth [inches]	Volume [yd^3]
Wearing Course	15.25	0.24	1.97	116
Binder	15.25	0.24	2.76	163
Wearing Course 3				0
Subbase 1				0
Subbase 2				0
Subbase 3				0
Subbase 4				0
Total			4.72	279

Embankment and Shoulder Volume [yd^3]:	

Period of Analysis [yrs] (40 yrs or less)	**20**

SI units:

Layer Specifications				
Layer	Width [m]	Length [m]	Depth [m]	Volume [m^3]
Wearing Course 1	4.65	382	0.05	89
Wearing Course 2	4.65	382	0.07	124
Wearing Course 3				0
Subbase 1				0
Subbase 2				0
Subbase 3				0
Subbase 4				0
Total			0.12	213

Figure 33. Design sheet Sitalfa.

The scheme of the pavement is the following:

Figure 34. Pavement scheme Sitalfa.

4.3.1.4 Iinitial Construction sheet

From "Initial Construction" sheet till "Equipment" sheet, and also considering the Sector Table and every useful data for pollution it is considered as the **Life Cycle Inventory**, because these worksheets is where PaLATE quantifies every raw material used, every energy, atmospheric emissions, waterborne emissions, solid wastes and other releases for each process within the entire life cycle.

Starting from the "Initial Construction" sheet, it is where data regarding materials for each layer of the pavement should be input. Materials and composition were directly provided by Sitalfa, but some calculations must be done.

Information provided by Sitalfa:

Wearing Course

	SETACCI [mm]	0,075	0,18	0,4	2	-	-	-	-	-	-	-	%
	CRIVELLI [mm]					5	10	15	20	25	30	40	CURVA
Aggregati		*passante in %*											
Sabbione		2,6	7,5	16,5	55,0	83,0	100,0	100,0	100,0	100,0	100,0	100,0	**42**
3/8		0,0	0,0	1,0	8,2	49,3	100,0	100,0	100,0	100,0	100,0	100,0	**18**
8/18		0,0	0,0	0,0	0,0	1,0	27,0	80,0	100,0	100,0	100,0	100,0	**33**
18/30		0,0	0,0	0,0	0,0	0,0	0,0	2,0	31,0	99,0	100,0	100,0	**0**
-		0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	**0**
-		0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	**0**
-		0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	**0**
filler		90,2	98,4	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	**7**

Figure 35. Aggregate´s composition for wearing course.

It uses a modified bitumen[10] in the mix.

Bitumen percentage with respect to the mix: 5.21 %

Bitumen density: 1.025 g/cm^3

Polymer density: 0.50 g/cm^3

Polymer percentage: 0.3 %

Compacted density of the sample (MV): 2.360 ton/m^3

Percentage of voids v (%): 5.39 %

P_b: percentage of bitumen in the mix = 5.51 % (considering the polymer), 5.21 % is the 94.55 % of 5.51 %.

[10] Modified bitumen is considering the polymer + bitumen. As it was said before, Sitalfa does not use a traditional modified bitumen, but the polymer comes inserted in the mix at the same time with the aggregates. The bitumen used is 50/70.

A mean value for the bitumen density considering the polymer will be done:

$$\gamma_b = \frac{94.55\ \%}{100}\ x\ 1.025\frac{g}{cm^3} + \frac{5.45\ \%}{100}\ x\ 0.50\frac{g}{cm^3} = 0.99\frac{g}{cm^3} = 0.76\ ton/yd^3$$

PaLATE requires volumetric information, so:

$$V_b\ (\%) = \frac{P_b\ x\ MV}{\gamma_b} = \frac{5.51\ x\ 2360\ kg/m^3}{990\ kg/m^3} = 13.13\ \%$$

$$V_G\ (\%) = 100 - V_b(\%) - v(\%) = 100 - 13.13 - 5.39 = 81.48\ \%$$

Where: V_b (%): Volumetric percentage of bitumen

V_G (%): Volumetric percentage of aggregates

Now to calculate the aggregates density γ_G:

$$V_G\ (\%) = \frac{(100 - P_b)}{\gamma_G}\ x\ MV$$

$$\gamma_G = \frac{(100 - 5.51)\ x\ 2360\ kg/m^3}{81.48\ \%} = 2737\frac{kg}{m^3} = 2.09\ ton/yd^3$$

In order to calculate the volumes, first, it is necessary to calculate masses, then:

$$M_G = \frac{100 - P_b}{100}\ x\ M = \frac{100 - 5.51}{100} x\ 210040\ kg = 198467\ kg$$

$$M_b = \frac{P_b}{100}\ x\ M = \frac{5.51}{100} x\ 210040\ kg = 11573\ kg$$

Where: M = Compacted Volume x Compacted Density

$$M = 89\ m^3\ x\ 2360\ \frac{kg}{m^3} = 210040\ kg$$

M_G = Aggregate´s mass in the mix

M_b = Bitumen´s mass in the mix

Finally, the volumes to input in PaLATE can be calculated as follows:

$$Vol.\,Agrgegates = \frac{198467\ kg}{2737\ kg/m^3} = 72.51\ m^3 = 94.96\ yd^3$$

$$Vol.\,Bitumen = \frac{11573\ kg}{990\ kg/m^3} = 11.69\ m^3 = 15.31\ yd^3$$

It can be seen that the sum of these volumes it is not equal to 89 m^3 which is the volume of the wearing course, because voids are not considered in the volumes of materials to input obviously. Densities for bitumen and virgin aggregates have been modified in PaLATE with the values used for the calculation.

Binder Course

SETACCI [mm]	0,075	0,18	0,4	2	-	-	-	-	-	-	-	%
CRIVELLI [mm]					5	10	15	25	30	40	50	CURVA
Aggregati	passante in %											
Sabbione	2,6	7,5	16,5	55,0	83,0	100,0	100,0	100,0	100,0	100,0	100,0	**37**
3/8	0,0	0,0	1,0	8,2	49,3	100,0	100,0	100,0	100,0	100,0	100,0	**20**
8/18	0,0	0,0	0,0	0,0	1,0	27,0	80,0	100,0	100,0	100,0	100,0	**38**
18/30	0,0	0,0	0,0	0,0	0,0	0,0	2,0	83,0	99,0	100,0	100,0	**0**
-	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	**0**
-	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	**0**
-	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	**0**
filler	90,2	98,4	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	**5**

Figure 36. Aggregate´s composition for binder.

It uses a modified bitumen in the mix.

Bitumen percentage with respect to the mix: 4.76 %

Bitumen density: 1.025 g/cm^3

Polymer density: 0.50 g/cm^3

Polymer percentage: 0.3 %

Compacted density of the sample (MV): 2.373 ton/m^3

Percentage of voids v (%): 6.10 %

P_b: percentage of bitumen in the mix = 5.06 % (considering the polymer), 4.76 % is the 94.07 % of 5.06 %.

A mean value for the bitumen density considering the polymer will be done:

$$\gamma_b = \frac{94.07\ \%}{100}\ x\ 1.025\frac{g}{cm^3} + \frac{5.93\ \%}{100}\ x\ 0.50\frac{g}{cm^3} = 0.99\ g/cm^3 = 0.76\ ton/yd^3$$

PaLATE requires volumetric information, so:

$$V_b\ (\%) = \frac{P_b\ x\ MV}{\gamma_b} = \frac{5.06\ x\ 2373\ kg/m^3}{990\ kg/m^3} = 12.13\ \%$$

$$V_G\ (\%) = 100 - V_b(\%) - v(\%) = 100 - 12.13 - 6.10 = 81.77\ \%$$

Where: V_b (%): Volumetric percentage of bitumen

V_G (%): Volumetric percentage of aggregates

Now to calculate the aggregates density γ_G:

$$V_G\ (\%) = \frac{(100 - P_b)}{\gamma_G}\ x\ MV$$

$$\gamma_G = \frac{(100 - 5.06)\ x\ 2373\ kg/m^3}{81.77\ \%} = 2755\ kg/m^3 = 2.11\ ton/yd^3$$

In order to calculate the volumes, first, it is necessary to calculate masses then:

$$M_G = \frac{100 - P_b}{100}\ x\ M = \frac{100 - 5.06}{100} x\ 294252\ kg = 279363\ kg$$

$$M_b = \frac{P_b}{100}\ x\ M = \frac{5.06}{100} x\ 294252\ kg = 14889\ kg$$

Where: M = Compacted Volume x Compacted Density

$$M = 124\ m^3\ x\ 2373\ \frac{kg}{m^3} = 294252\ kg$$

M_G = Aggregate´s mass in the mix

M_b = Bitumen´s mass in the mix

Finally, the volumes to input in PaLATE can be calculated as follows:

$$Vol.Agrgegates = \frac{279363\,kg}{2755\,kg/m^3} = 101.40\,m^3 = 132.80\ \ yd^3$$

$$Vol.Bitumen = \frac{14889\,kg}{990\,kg/m^3} = 15.04\,m^3 = 19.70\ \ yd^3$$

It can be seen that the sum of these volumes it is not equal to 124 m^3 which is the volume of the binder course, because voids are not considered in the volumes of materials to input obviously. Densities for bitumen and virgin aggregates have been modified in PaLATE with the values used for the calculation.

It is possible now to insert values in PaLATE.

Regarding transport distances some calculations were done in order to be the more specific as possible.

1) Distance from material source to asphalt plant.

<u>Virgin aggregates</u>

Aggregates are extracted from the river Dora Riparia that is 3 km far from Sitalfa where the asphalt plant is located, and the filler is provided by a quarry called NICEM S.r.l. from Bergamo, which is 280 km far from Sitalfa, therefore, a weighted mean over the mass has been done considering the percentages of each type of aggregate in the mix for both wearing and binder course.

- Wearing Course:

For wearing course from a total 100 % of aggregates, 7% is filler, so the transport distance for virgin aggregates is

$$3\,km\,x\,0.93 + 280\,x\,0.07 = 22.39\,km = 13.92\,mi$$

And the predominant transportation mode is a dump truck.

- Binder Course:

For wearing course from a total 100 % of aggregates, 5 % is filler, so the transport distance for virgin aggregates is

$$3\ km\ x\ 0.95 + 280\ x\ 0.05 = 16.85\ km = 10.47\ mi$$

And the predominant transportation mode is a dump truck.

Bitumen

Bitumen is provided by Iplom S.p.A. (Genova) refinery which is 230 km far from the asphalt plant in Sitalfa, and the polymer is provided by Iterchimica S.r.l. (Bergamo) which is 250 km far from Sitalfa. Also, a weighted mean over the mass have been done depending the content percentage of polymer and bitumen.

- Wearing Course:

The bituminous mixture contains 5.21 % bitumen according to Marshall´s test and 0.3 % polymer, so, making some changes over a 100 % it would be 95 % bitumen and 5 % polymer approximately.

$$230\ km\ x\ 0.95 + 250\ km\ x\ 0.05 = 231\ km = 143.57\ mi$$

And the predominant transportation mode is a tanker truck.

- Binder Course:

The bituminous mixture contains 4.76 % bitumen according to Marshall´s test and 0.3 % polymer, so, making some changes over a 100 % it would be 94 % bitumen and 6 % polymer approximately.

$$230\ km\ x\ 0.94 + 250\ km\ x\ 0.06 = 231.2\ km = 143.69\ mi$$

And the predominant transportation mode is a tanker truck.

2) Distance from asphalt plant to the working site.

This is the transport distance of the whole asphalt-mix to the working site, and according to the data obtained by the company, a mean value should be calculated.

Going distance from asphalt plant (Sitalfa) to working site = 57 km

Return distance from working site to asphalt plant = 52 km

This difference is because when a loaded truck leaves Sitalfa and is heading to the working site, in order to arrive, this should change direction and do a loop which is some few kilometers away from the site, thus, resulting in a longer trip than when returning because the truck doesn't need to do a loop in order to change direction (it can go across the other lane directly). So:

$$\frac{57\ km + 52\ km}{2} = 54.5\ km = 33.87\ mi$$

And the predominant transportation mode is a dump truck.

With all this information, PaLATE Initial Construction sheet looks:

		Material	Density [tons/(yd^3)]	New Asphalt Pavement	New Concrete Pavement	New Subbase & Embankment Construction	Transportation	
				Volume [yd^3]	Volume [yd^3]	Volume [yd^3]	One-way transport distance [mi]	Transportation mode
Wearing Course 1	Materials	Virgin Aggregate	2.09	94.96	0		13.92	dump truck
		Bitumen	0.76	15.31			143.57	tanker truck
		Cement	1.27		0		0	barge
		Concrete Additives	0.84		0		0	tanker truck
		RAP	1.85	0	0		0	dump truck
		FRAP	1.85	0	0		0	dump truck
		RAS	1.12	0	0		0	dump truck
		RCA	1.88	0	0		0	dump truck
		Coal Fly Ash	2.20	0	0		0	cement truck
		Coal Bottom Ash	2.00	0	0		0	dump truck
		Blast Furnace Slag	1.72	0	0		0	dump truck
		Foundry Sand	1.50	0	0		0	dump truck
		Recycled Tires/ Crumb Rubber	1.92	0	0		0	dump truck
		Glass Cullet	1.93	0	0		0	dump truck
		Water	0.84		0			
		Steel Reinforcing Bars	0.24		0		0	dump truck
		Total: Asphalt mix to site	1.23	**110.27**			33.87	dump truck
		Total: Ready-mix concrete mix to site	2.03		**0**		0	mixing truck
	Waste material to landfill	RAP from site to landfill	1.85	0			0	dump truck
		RAS from site to landfill	1.12	0	0		0	dump truck
		RCM from site to landfill	1.88		0		0	dump truck

		Material	Density [tons/(yd^3)]	New Asphalt Pavement	New Concrete Pavement	New Subbase & Embankment Construction	Transportation	
				Volume [yd^3]	Volume [yd^3]	Volume [yd^3]	One-way transport distance [mi]	Transportation mode
Binder	Materials	Virgin Aggregate	2.11	132.80	0		10.47	dump truck
		Bitumen	0.76	19.70			143.69	tanker truck
		Cement	1.27		0		0	cement truck
		Concrete Additives	0.84		0		0	tanker truck
		RAP	1.85	0	0		0	dump truck
		FRAP	1.85	0	0		0	dump truck
		RAS	1.12	0	0		0	dump truck
		RCA	1.88	0	0		0	dump truck
		Coal Fly Ash	2.20	0	0		0	rail
		Coal Bottom Ash	2.00	0	0		0	dump truck
		Blast Furnace Slag	1.72	0	0		0	dump truck
		Foundry Sand	1.50	0	0		0	dump truck
		Recycled Tires/ Crumb Rubber	1.92	0	0		0	dump truck
		Glass Cullet	1.93	0	0		0	dump truck
		Water	0.84		0			
		Steel Reinforcing Bars	0.24		0		0	dump truck
		Total: Asphalt mix to site	1.23	**152.50**			33.87	dump truck
		Total: Ready-mix concrete mix to site	2.03		**0**		0	mixing truck
	Waste material to landfill	RAP from site to landfill	1.85	0			0	dump truck
		RAS from site to landfill	1.12	0	0		0	dump truck
		RCM from site to landfill	1.88		0		0	dump truck

Figure 37. Initial Construction sheet Sitalfa.

4.3.1.5 Maintenance sheet

Having considered an analysis period of 20 years, the company provided the maintenance plan to be followed.

<u>Plan</u>

- Every 3 years a full-depth reclamation (FDR) process for wearing course should be applied.
- Every year a patching process should be applied in the wearing course, except those years that coincides with the FDR process.
- The year 20 the pavement should be demolished completely (wearing and binder course).

Year 1 ⟶ Patching wearing course

Year 2 ⟶ Patching wearing course

Year 3 ⟶ FDR wearing course

Year 4 ⟶ Patching wearing course

Year 5 ⟶ Patching wearing course

Year 6 ⟶ FDR wearing course

Year 7 → Patching wearing course

Year 8 → Patching wearing course

Year 9 → FDR wearing course

Year 10 → Patching wearing course

Year 11 → Patching wearing course

Year 12 → FDR wearing course

Year 13 → Patching wearing course

Year 14 → Patching wearing course

Year 15 → FDR wearing course

Year 16 → Patching wearing course

Year 17 → Patching wearing course

Year 18 → FDR wearing course

Year 19 → Patching wearing course

Year 20 → Demolition of the pavement, wearing and binder course

In order to fill in this sheet some calculation regarding materials should be done.

To accomplish with the proposed plan, the volume of materials to be used should be calculated for every time that they are needed. Maintenance is just applied for the wearing course, hence:

In 20 years of analysis period 6 FDR processes and 13 Patching processes will be applied.

<u>FDR</u>

Virgin aggregates = 6 x 72.51 m^3 = 435 m^3 = 569.78 yd^3

Bitumen = 6 x 11.69 m^3 = 70.14 m^3 = 91.86 yd^3

569.78 + 91.86 = 661.64 yd^3

Patching

As it was specified by Sitalfa, around the 1.8% of the wearing course is patched every year, that is equal to 1.6 m^3 of the total 89 m^3. With an equivalence, volumetric values for virgin aggregates and bitumen needed for patching can be obtained:

Virgin aggregates $x : 1.6 = 72.51 : 89$ $x = 1.30\ m^3 = 1.70\ yd^3$

Modified bitumen $x : 1.6 = 11.69 : 89$ $x = 0.21\ m^3 = 0.27\ yd^3$

Applying maintenance,

Virgin aggregates = 13 x 1.30 m^3 = 16.9 m^3 = 22.12 yd^3

Bitumen = 13 x 0.21 m^3 = 2.73 m^3 = 3.59 yd^3

22.12 + 3.59 = 25.71 yd^3

Total Material for Maintenance

Virgin aggregates = 435 m^3 + 16.9 m^3 = 452 m^3 = 591.92 yd^3

Bitumen = 70.14 m^3 + 2.73 m^3 = 72.87 m^3 = 95.44 yd^3

591.92 + 95.44 = 687.36 yd^3

As the quantity of material going to landfill is considered by PaLATE and in the year 20 the whole pavement is going to landfill (so wearing and binder courses are considered in this year) the corresponding values going to landfill are:

1- Wearing course
   Due to FDR = 661.64 yd^3
   Due to Patching = 25.71 yd^3
   Demolition of the pavement = 110.27 yd^3
   661.64 + 25.71 + 110.27 = 797.62 yd^3

2- Binder

Demolition of the pavement = 152.50 yd^3

Regarding transport distances and transportation modes, considerations are the same as for Initial Construction, but in this case, the same as with materials should be done. Transport distances are repeated every time that material is going to be laid (13 times for Patching, 6 times for FDR = 19 times) or to landfill (20 times in total with Patching and FDR). In addition, the distance from the working site to the final disposal, which is a special site that the company has in Bruzolo for this type of waste, is 16 km, therefore:

1- Wearing course

Virgin aggregates distance = 22.39 km x 19 = 425.41 km = 264.39 mi

Bitumen distance = 231 km x 19 = 4389 km = 2727.78 mi

Asphalt mix to site distance = 54.5 km x 19 = 1035.5 km = 643.57 mi

Pavement going to landfill = 16 km x 20 = 320 km = 198.88 mi

2- Binder

Pavement going to landfill = 16 km x 1 = 16 km = 9.94 mi

Transportation mode for material going to landfill is a dump truck.

In this way the maintenance sheet looks as Figure 38.

		Material	Density [tons/(yd^3)]	Lifetime Asphalt Repaving	Lifetime Concrete Repaving	Lifetime Subbase Reconstruction	Lifetime Embankment Reconstruction	Transportation	
				Volume [yd^3]	Volume [yd^3]	Volume [yd^3]	Volume [yd^3]	One-way transport distance [mi]	Transportation mode
Wearing Course 1	Materials	Virgin Aggregate	2.09	591.92	0			264.39	dump truck
		Bitumen	0.76	95.44				2727.78	tanker truck
		Cement	1.27		0			0	cement truck
		Concrete Additives	0.84		0			0	tanker truck
		Asphalt Emulsion	0.84	0				0	tanker truck
		RAP	1.85	0	0			0	dump truck
		FRAP	1.85	0	0			0	dump truck
		RAS	1.12	0	0			0	dump truck
		RCA	1.88	0	0			0	dump truck
		Coal Fly Ash	2.20	0	0			0	tanker truck
		Coal Bottom Ash	2.00	0	0			0	dump truck
		Blast Furnace Slag	1.72	0	0			0	dump truck
		Foundry Sand	1.50	0	0			0	dump truck
		Recycled Tires/ Crumb Rubber	1.92	0	0			0	dump truck
		Glass Cullet	1.93	0	0			0	dump truck
		Water	0.84		0				
		Steel Reinforcing Bars	0.24		0			0	dump truck
		Total: Hot-mix Asphalt to site	1.23	**687.35**				643.57	dump truck
		Total: Ready-mix Concrete mix to site	2.03		**0**			0	mixing truck
	Processes	HIPR	1.83	0					
		CIR	1.83	0					
		Patching	1.23	25.71	0				
		Microsurfacing	1.23	0	0				
		Crack Sealing	0.84	0	0				
		Whitetopping	2.03		0				
		Rubblization	1.95		0				
		Full-depth Reclamation	1.83	661.64	0				
	Waste material to landfill	RAP from site to landfill	1.85	797.63				198.88	dump truck
		RAS from site to landfill	1.12	0				0	dump truck
		RCM from site to landfill	1.88		0			0	dump truck

		Material	Density [tons/(yd^3)]	Lifetime Asphalt Repaving	Lifetime Concrete Repaving	Lifetime Subbase Reconstruction	Lifetime Embankment Reconstruction	Transportation	
				Volume [yd^3]	Volume [yd^3]	Volume [yd^3]	Volume [yd^3]	One-way transport distance [mi]	Transportation mode
Binder	Materials	Virgin Aggregate	2.11	0	0			0	dump truck
		Bitumen	0.76	0				0	tanker truck
		Cement	1.27		0			0	cement truck
		Concrete Additives	0.84		0			0	tanker truck
		Asphalt Emulsion	0.84	0				0	tanker truck
		RAP	1.85	0	0			0	dump truck
		FRAP	1.85	0	0			0	dump truck
		RAS	1.12	0	0			0	dump truck
		RCA	1.88	0	0			0	dump truck
		Coal Fly Ash	2.20	0	0			0	rail
		Coal Bottom Ash	2.00	0	0			0	dump truck
		Blast Furnace Slag	1.72	0	0			0	dump truck
		Foundry Sand	1.50	0	0			0	dump truck
		Recycled Tires/ Crumb Rubber	1.92	0	0			0	dump truck
		Glass Cullet	1.93	0	0			0	dump truck
		Water	0.84		0				
		Steel Reinforcing Bars	0.24		0			0	dump truck
		Total: Hot-mix Asphalt to site	1.23	**0**				0	dump truck
		Total: Ready-mix Concrete mix to site	2.03		**0**			0	mixing truck
	Processes	HIPR	1.83	0					
		CIR	1.83	0					
		Rubblization	1.95		0				
		Full-depth Reclamation	1.83	0	0				
	Waste material to landfill	RAP from site to landfill	1.85	152.50				9.94	dump truck
		RAS from site to landfill	1.12	0				0	dump truck
		RCM from site to landfill	1.88		0			0	dump truck

Figure 38. Maintenance sheet Sitalfa.

4.3.1.6 Equipment sheet

The equipment involved for the construction of the road will be described in this section.

The activities involved in this case study regarding equipment are: asphalt paving, full-depth reclamation and HMA production. As PaLATE offers machinery used in USA, these were modified with the equipment available by Sitalfa, by choosing the option “other” as it was already explained in chapter 4. Hence, the Equipment sheet takes this form:

ACTIVITY	Equipment	Brand/Model	Engine Capacity	Productivity	Fuel Consumption	Fuel Type
Concrete Paving	Slipform paver	Wirtgen SP 250	106 hp	564 tons/h	19.7 l/h	diesel
	Texture curing machine	Gomaco T/C 400	70 hp	187 tons/h	20.2 l/h	diesel
Asphalt Paving	Paver	other	173 hp	30 tons/h	46.0 l/h	diesel
	Pneumatic roller	none	0 hp	1 tons/h	0.0 l/h	diesel
	Tandem roller	other	82 hp	341 tons/h	18.0 l/h	diesel
Cold in Place Recycling	CIR recycler	Wirtgen 2200 CR	800 hp	1,713 tons/h	150.00 l/h	diesel
	Pneumatic roller	Dynapac CP134	100 hp	884 tons/h	25.1 l/h	diesel
	Tandem roller	Ingersol rand DD110	125 hp	285 tons/h	32.7 l/h	diesel
Full Depth Reclamation	Asphalt road reclaimer	other	550 hp	2,000 tons/h	110.0 l/h	diesel
	Vibratory soil compactor	other	82 hp	341 tons/h	18.0 l/h	diesel
Hot In Place Recycling	Heating machine	Wirtgen HM4500	49 hp	256 tons/h	9.1 l/h	diesel
	Asphalt remixer	Wirtgen 4500	295 hp	208 tons/h	55.0 l/h	diesel
	Pneumatic roller	Dynapac CP132	100 hp	668 tons/h	26.1 l/h	diesel
	Tandem roller	Ingersol rand DD110	125 hp	285 tons/h	32.7 l/h	diesel
Rubblization	Multi head breaker	Badger MHB Breaker	350 hp	520 tons/h	76.5 l/h	diesel
	Vibratory soil compactor	Dynapac CA 262D	150 hp	1,832 tons/h	37.6 l/h	diesel
Milling	Milling machine	Wirtgen W2200	875 hp	1,100 tons/h	156.2 l/h	diesel
Grinding	Grinding machine	CBI Magnum Force Shingle F	1050 hp	115 tons/h	161.1 l/h	diesel
Concrete Demolition	Multi head breaker	Badger MHB Breaker	350 hp	520 tons/h	76.5 l/h	diesel
	Wheel loader	John Deere 644E	160 hp	490 tons/h	40.1 l/h	diesel
Crushing Plant	Excavator	John Deere 690E	131 hp	225 tons/h	34.2 l/h	diesel
	Wheel loader	John Deere 624E	135 hp	225 tons/h	35.3 l/h	diesel
	Dozer	Caterpillar D8N	285 hp	225 tons/h	71.4 l/h	diesel
	Generator	Caterpillar 3406C TA	519 hp	225 tons/h	98.4 l/h	diesel
Excavation, placing and compaction	Excavator	John Deere 690E	131 hp	315 tons/h	34.2 l/h	diesel
	Vibratory soil compactor	Dynapac CA 262D	174 hp	1,832 tons/h	27.6 l/h	diesel
Tire Recycling	Shredder + Granulator + Classifier + Aspirator System	Wendt Corporation	630 hp	3.00 tons/h	104.73 kWh/ton	105 hp
Glass Recycling	Hopper + Conveyor + Shredder System	Andela GP-05 Pulverizer	10 hp	1.00 tons/h	7.46 kWh/ton	17 hp
HMA Production	asphalt mixer	other		278.00 tons/h		oil

Figure 39. Equipment sheet Sitalfa.

Where the characteristics of every modified machine are recovered from the "Equipment Details" sheet. It was necessary to have information about the brand and model of the machine (provided by Sitalfa) to look for information. The modifications adopted are shown in the next figures.

ACTIVITIES

Asphalt Paving

- Paver: the paver used by Sitalfa is a Dynapac SD2500W and further information was studied from the data sheet. See Figure 40 the "other" row.

type	brand/model	engine model	hp	Productivity (non-standard units)	Conversion Factors	Productivity	fuel consumption
Asphalt Paver	Blaw-knox PF-5510	Cummins 6BTA	184 hp			?	46.1 l/h
	Cedarapids CR451		172 hp			?	43.1 l/h
	Dynapac F25C	Cummins 6BTA 5,9	126 hp			1,700 tons/h	31.6 l/h
	Dynapac F30C	Cummins 6BTA 5,10	196 hp			2,400 tons/h	49.1 l/h
	none		0			1	0
	other	Cummins QSB 6.7-C173	173			30	46

Figure 40. Asphalt Paver characteristics.

-Engine Model: from data sheet [15]

-Horsepower (hp): from data sheet [15]

-Productivity: information provided by the company. 5 ton/10 min = 30 ton/h. The productivity is low because the productivity is referred to this specific case where the worksite is quite small.

-Fuel consumption (FC): information provided by the company and a calculation was made. It consumes 343 l/8h and 200 l/4h, doing a mean value

$$FC = \frac{\frac{343l}{8h} + \frac{200l}{4h}}{2} = 46.44\ l/h$$

-Fuel type: diesel

- Pneumatic roller: no pneumatic roller was used that's why in Figure 39 it can be seen "none" in the chosen model.
- Tandem roller: the tandem roller used by Sitalfa is a Dynapac CC232 HF and further information was studied from the data sheet. See Figure 41.

type	brand/model	engine model	hp	Productivity (non-standard units)	Conversion Factors	Productivity	fuel consumption
Tandem Roller	Ingersol rand DD130	Cummins 6BTA 5.9	174 hp			?	27.6 l/h
	Ingersol rand DD110	Cummins 4BTA 3.9	125 hp			285 tons/h	32.7 l/h
	Ingersol rand DD90	Cummins 4BTA 3.9	110 hp			?	27.6 l/h
	Ingersol rand DD90HF	Cummins B3.9C	110 hp			395 tons/h	27.6 l/h
	Hypac C778B		125 hp			?	31.3 l/h
	none	0	0			1	0
	other	Deutz BF4L 1011F	82			341	18

Figure 41. Tandem roller characteristics.

-Engine model: from data sheet (in Appendix)

-hp: from data sheet (in Appendix)

-Productivity: information provided by the company and a brief calculation was done. If the machine compacts an area of 100 m^2 in 5 minutes (Sitalfa value), and the depth of the pavement considered is 0.12 m, then, a volume of 100 x 0.12 = 12 m^3 is compacted in 5 minutes. The compacted density according to Marshall is 2.367 ton/m^3, then, 12 x 2.367 = 28.40 tons are compacted in 5 minutes and it is equal to 341 ton/h.

-Fuel consumption: information provided by the company and a calculation was made. It consumes 120 l/8h and 80 l/4h, doing a mean value

$$FC = \frac{\frac{120l}{8h} + \frac{80l}{4h}}{2} = 17.5\ l/h$$

-Fuel type: diesel

Full-depth reclamation

- Asphalt road reclaimer: the model used by Sitalfa is a Wirtgen 200 and further information was studied from the data sheet. See Figure 42.

type	brand/model	engine model	hp	Productivity (non-standard units)	Conversion Factors	Productivity	fuel consumption
Asphalt Road Reclaimer	Wirtgen WR 2500 S	Mercedes Benz OM 444 LA	670 hp	15000 m^3/shift	0.32	4,800 tons/h	120.0 l/h
	Caterpilar RR 250 B	Cat 3406C	335 hp			?	?
	Caterpilar RM 350 B	Cat 3406 Dita	500 hp			?	109.3 l/h
	CMI RS 425	Cat 3406 Dita	425 hp			?	106.5 l/h
	CMI RS 500 B	Cat 3408 Dita	525 hp			?	?
	none		0			1	0
	other	Cummins QSX15	550			2000	110

Figure 42. Asphalt Road Reclaimer characteristics.

-Engine model: from data sheet [16]

-hp: from data sheet [16]

-Productivity: an assumed value was input due to the lack of information.

-Fuel consumption: an assumed value was input taking into account the consumption of the Cat 3406 Dita, which has a number of hp similar (500 hp), due to the lack of information.

- Vibratory soil compactor: the company does not have a vibratory soil compactor and the tandem roller is used as one of this, doing the same job. Hence the characteristics are the same of the Tandem Roller (See Figure 41).

HMA production

- Asphalt mixer: is powered by oil principally.

			energy	PM10	CO	CO_2	NOx	SO_2
HMA Production	Uncontrolled Batch-mix	214 tons/h	227 MJ/ton	2.043 kg/ton	0.18 kg/ton	16.798 kg/ton	0.054 kg/ton	0.040 kg/ton
	Fabric Filter-Controlled Batch-mix	214 tons/h	227 MJ/ton	0.004 kg/ton	0.18 kg/ton	16.798 kg/ton	0.054 kg/ton	0.040 kg/ton
	Uncontrolled Drum-mix	272 tons/h	202 MJ/ton	2.951 kg/ton	0.06 kg/ton	14.982 kg/ton	0.025 kg/ton	0.026 kg/ton
	Fabric Filter-controlled Drum-mix	272 tons/h	202 MJ/ton	0.010 kg/ton	0.06 kg/ton	14.982 kg/ton	0.025 kg/ton	0.026 kg/ton
	none	0	0	0	0	0	0	0
	other	272	278	0.010	0.030	46.77	0.060	0.022

Figure 43. Asphalt mixer characteristics.

-The asphalt mixer is a Fabric Filter-controlled Drum-mix so the productivity was assumed equal to the one that has as default the software = 272 tons/h.

-Energy: for this parameter a calculation was made. Considering that according to the information provided by Sitalfa, the asphalt mixer consumes 7 kg/ton of fuel oil BTZ (Basso Tenore di Zolfo) and that a kg of fuel oil is equal to an energy consumption of 39.77 MJ, then, the total energy consumption per ton produced is equal to 278.38 MJ (39.77 MJ x 7).

-For the emissions produced during the HMA production information was provided by Sitalfa except for PM_{10}, so, in this case, the value for the Fabric Filter-Controlled Drum-mix was considered. For CO, CO_2, NOx and SO_2 some calculations to change the measurement unit were done:

Information by Sitalfa: CO = 35 mg/Nm^3

NOx = 206 mg/Nm^3

SO_2 = 60 mg/Nm^3

CO_2 = 4.4 %v/v

Where Nm^3 is normal cubic meter, which is the volume of a gas measured under the standard conditions of 0 degrees Celsius and 1 atmosphere of pressure [17]. And %v/v expresses the volume percentage of a solute in a solution [18]. In order to transform the units to kg/ton a webpage was used as help [19]. Then,

For CO, through this webpage it can be seen that 1 Nm^3 is equal to 1.17 kg. So:

$$35\frac{mg}{Nm^3} = \frac{35\,mg}{1.17\,kg} = 29.91\frac{mg}{kg} = 0.030\,kg/ton$$

For NOx, through this webpage it can be seen that 1 Nm^3 is equal to 3.358 kg. So:

$$206\frac{mg}{Nm^3} = \frac{206\,mg}{3.358\,kg} = 61.35\frac{mg}{kg} = 0.060\,kg/ton$$

For SO_2, through this webpage it can be seen that 1 Nm^3 is equal to 2.725 kg. So:

$$60\frac{mg}{Nm^3} = \frac{60\,mg}{2.725\,kg} = 22.02\frac{mg}{kg} = 0.022\,kg/ton$$

For CO_2, the thing is different because first %v/v should be transformed in ppm (parts per million) and then to mg/Nm^3 in order to do the conversion.

$$4.4\,\%\frac{v}{v} = 44000\ ppm$$

The conversion from ppm to mg/Nm^3 is done according the following formula [20]:

$$\frac{mg}{Nm^3} = ppm\ x\ \frac{MW}{22.4} = 44000\ x\frac{44.01}{22.4} = 86448.21\ mg/Nm^3$$

Where MW stands for molecular weight and for CO_2 is equal to 44.01 g/mol.

Now it is possible to finally obtain the value in kg/ton, knowing from the previous webpage [19] that 1Nm^3 of CO_2 is equal to 1.848 kg. So:

$$86448.21\frac{mg}{Nm^3} = \frac{86448.21\ mg}{1.848\ kg} = 46779.34\frac{mg}{kg} = 46.77\ kg/ton$$

4.3.1.7 Environmental Results sheet

This is the **Life Cycle Impact Assessment** phase of an LCA and it is where final environmental impacts are provided and different categories are assigned for some outputs (for example GWP category). For this road provided by Sitalfa using the estimated input values for the Sector Table, results are presented in the following Figure.

GRAND TOTALS

		Energy [MJ]	Water Consumption [kg]	CO_2 [kg] = GWP	NO_x [g]	PM_{10} [g]	SO_2 [g]
Initial Construc tion	Materials Production	294,752	1,311,301	26,519	77,903	75,382	57,340
	Materials Transportation	22,507	1,109	1,683	89,644	15,163	5,379
	Processes (Equipment)	18,370	905	1,379	1,947	567	129
Maintena nce	Materials Production	788,465	3,435,389	70,428	208,660	196,426	154,991
	Materials Transportation	1,501,506	73,975	112,251	5,980,356	1,166,999	358,821
	Processes (Equipment)	52,729	2,598	3,958	13,878	990	918
Total	Materials Production	1,083,218	4,746,690	96,947	286,564	271,808	212,331
	Materials Transportation	1,524,013	75,083	113,934	6,070,000	1,182,163	364,200
	Processes (Equipment)	71,099	3,503	5,336	15,825	1,557	1,046
	Total	**2,678,330**	**4,825,276**	**216,217**	**6,372,389**	**1,455,528**	**577,578**

GRAND TOTALS

		CO [g]	Hg [g]	Pb [g]	RCRA Hazardous Waste Generated [kg]	Human Toxicity Potential (Cancer)	Human Toxicity Potential (Non-cancer)
Initial Construction	Materials Production	41,382	1	44	136	166,818	88,475,306
	Materials Transportation	7,470	0	1	162	482	591,902
	Processes (Equipment)	420	0	1	132	0	0
Maintenance	Materials Production	111,337	3	119	360	453,779	228,664,586
	Materials Transportation	498,363	1	50	10,819	32,186	39,487,163
	Processes (Equipment)	2,990	0	0	0	0	0
Total	Materials Production	152,719	3	163	496	620,597	317,139,892
	Materials Transportation	505,833	1	51	10,982	32,668	40,079,065
	Processes (Equipment)	3,410	0	1	132	0	0
	Total	**661,963**	**5**	**215**	**11,610**	**653,266**	**357,218,957**

Figure 44. Environmental results Sitalfa, European Sector Table.

4.3.2 1ST Case Study: Sitalfa S.p.A. with default data

In this case every sheet is equal to the case recently done, therefore, the explanation will not be done again, with the only difference of the Sector Table used, that in this case will be the default one (containing USA data) already shown in the previous section. So, immediately environmental results will be presented, which are not identical.

4.3.2.1 Environmental Results sheet

GRAND TOTALS

		Energy [MJ]	Water Consumption [kg]	CO_2 [kg] = GWP	NO_x [g]	PM_{10} [g]	SO_2 [g]
Initial Construction	Materials Production	689,335	872,955	50,196	195,863	106,286	162,647
	Materials Transportation	22,507	14,506	1,683	89,644	15,163	5,379
	Processes (Equipment)	18,370	11,840	1,379	1,947	567	129
Maintenance	Materials Production	1,858,849	2,374,987	134,432	530,478	278,775	441,889
	Materials Transportation	1,501,506	967,725	112,251	5,980,356	1,166,999	358,821
	Processes (Equipment)	52,729	33,984	3,958	13,878	990	918
Total	Materials Production	2,548,184	3,247,942	184,628	726,341	385,061	604,536
	Materials Transportation	1,524,013	982,231	113,934	6,070,000	1,182,163	364,200
	Processes (Equipment)	71,099	45,823	5,336	15,825	1,557	1,046
	Total	**4,143,297**	**4,275,996**	**303,898**	**6,812,166**	**1,568,781**	**969,783**

GRAND TOTALS

		CO [g]	Hg [g]	Pb [g]	RCRA Hazardous Waste Generated [kg]	Human Toxicity Potential (Cancer)	Human Toxicity Potential (Non-cancer)
Initial Construction	Materials Production	142,594	1	45	9,423	166,818	88,475,306
	Materials Transportation	7,470	0	1	162	482	591,902
	Processes (Equipment)	420	0	1	132	0	0
Maintenance	Materials Production	386,687	3	123	25,676	453,779	228,664,586
	Materials Transportation	498,363	1	50	10,819	32,186	39,487,163
	Processes (Equipment)	2,990	0	0	0	0	0
Total	Materials Production	529,282	3	168	35,099	620,597	317,139,892
	Materials Transportation	505,833	1	51	10,982	32,668	40,079,065
	Processes (Equipment)	3,410	0	1	132	0	0
	Total	**1,038,525**	**5**	**220**	**46,213**	**653,266**	**357,218,957**

Figure 45. Environmental results Sitalfa, USA Sector Table.

4.3.3 2ND Case Study: extracted from literature with estimated data

4.3.3.1 System Description and functional unit

This second case study was taken from the reviewed literature and its name is "Life Cycle Assessment of Road Pavements containing Crumb rubber from end-of-life tires" (Farina et al., 2014). It is a study made to compare environmental impacts as GWP and GER (Gross Energy Requirement), of a standard road construction whit a pavement construction using crumb rubber in the mixes, there are two cases, the crumb rubber can be added to the base bitumen as a modifying agent ("wet technology") or in hot mix plants as an additional aggregate fraction ("dry technology") (Farina et al., 2014). The software used originally was SimaPro 7.3. But, for the goal and scope of this study, it will be used just the standard case and simulated through PaLATE, in order to then be able to make a comparison of results between softwares.

The case study considered is that of an Italian extra-urban road, which is composed by two lanes per direction and has a total carriageway of 21.9 m. The functional unit employed in the analysis is 1 m of built pavement.

4.3.3.2 Pavement life cycle and system boundaries

The whole life cycle of a pavement can be divided into five phases:

1- Material production phase: including from extraction of raw materials to their conversion into final product.

2- Construction phase: includes all the execution for construction of the road infrastructure.
3- Use phase: is the longest phase of the life cycle. Factors to be included are related to pavement deterioration, traffic growth and pollution due to road vehicles.
4- Maintenance and rehabilitation: fundamental activities (in terms or bearing capacity, surface regularity and friction, mainly for user´s safety) over the analysis period of the road infrastructure.
5- End-of-life phase: definition of final disposal of materials, they can be recycled or waste.

But this thesis, and as long as the tool allows it, is just focusing in the analysis of environmental impacts during material production, construction, maintenance and EOL phases. These are considered as the system boundary of the analysis.

4.3.3.3 Design sheet

In this case, based on predicted total heavy traffic (4 million vehicles) and on the required minimum bearing capacity of the subgrade (resilient modulus = 90 MPa), the pavement cross section was selected from the Italian Catalogue for Pavement design (Farina et al., 2014), and it is the following:

Layer Specifications				
Layer	Width [ft]	Length [miles]	Depth [inches]	Volume [yd^3]
Wearing Course	71.80	0.0006	1.97	1.43
Binder	71.80	0.0006	2.36	1.72
Base	71.80	0.0006	3.94	2.86
Foundation	71.80	0.0006	7.87	5.73
Subbase 2				0
Subbase 3				0
Subbase 4				0
Total			**16.14**	11.74

Embankment and Shoulder Volume [yd^3]:	

Period of Analysis [yrs] (40 yrs or less)	**18**

SI units:

Layer Specifications				
Layer	Width [m]	Length [m]	Depth [m]	Volume [m^3]
Wearing Course 1	21.9	1	0.05	1.10
Wearing Course 2	21.9	1	0.06	1.31
Wearing Course 3	21.9	1	0.1	2.19
Subbase 1	21.9	1	0.2	4.38
Subbase 2				0
Subbase 3				0
Subbase 4				0
Total			0.41	8.98

Figure 46. Design sheet 2nd case.

The analysis period is set equal to 18 years. Embankment and shoulder are not considered for this case because it provides the same environmental impact if constructed for standard, wet or dry technology, therefore, it doesn't have sense to include it in the analysis.

The scheme of the pavement is the following:

Figure 47. Pavement scheme 2nd case.

4.3.3.4 Initial Construction sheet

From "Initial Construction" sheet till "Equipment" sheet, and also considering the sector table and every useful data for pollution it is considered as the **Life Cycle Inventory**, because these worksheets is where PaLATE quantifies every raw material used, every energy, atmospheric emissions, waterborne emissions, solid wastes and other releases for each process within the entire life cycle.

Starting from the "Initial Construction" sheet, it is where data regarding materials for each layer of the pavement should be input. Materials and composition were directly indicated in the study, in Figure 48 it can be seen volumetric percentages and quantity per cubic meter of bitumen and virgin aggregates, whereas in Figure 49 quantity of material [kg] to be used for each layer in a meter of built pavement is presented, but some calculations were done in order to input them in PaLATE.

	Volumetric percentage [%]				Quantity [kg/m^3]		
	%B	%A	%CR	%v	Q_B	Q_A	Q_{CR}
Wearing "W"	5.5	86.6	1.4	6.5	56.8	1991	14.2
Wearing "D"	5.2	89.4	0.9	4.5	52.5	2057	10.4
Wearing "S"	4.8	90.7	-	4.5	49.0	2086	-
Binder	4.5	90.5	-	5.0	46.1	2081	-
Base	4.1	90.4	-	5.5	41.5	2080	-
Foundation	-	94.8	-	5.2	-	2201	-

Figure 48. Volumetric percentages and quantity of material per cubic meter.

LAYER	MATERIAL	Standard Q [kg]
Wearing	Bitumen	54
	Aggregates	2284
Binder	Bitumen	61
	Aggregates	2734
Base	Bitumen	91
	Aggregates	4555
Foundation	Aggregates	9641

Figure 49. Layers composition 2nd case study.

"S" stands for Standard pavement, which are the values that focus will be made on.

Each quantity in kg was divided for its correspondent density in order to obtain a volume to input in PaLATE, but densities were calculated as following:

$$\gamma_G = \frac{(100 - P_b)}{V_G\ (\%)} x\ MV$$

$$\gamma_b = \frac{P_b}{V_b\ (\%)} x\ MV$$

Where: γ_G : Density of aggregates

γ_b: Density of bitumen

P_b: percentage of bitumen in the mix

MV: compacted density of the mix

V_b (%): Volumetric percentage of bitumen

V_G (%): Volumetric percentage of aggregates

Wearing Course

$$P_b = \frac{49}{49 + 2086} = 0.023 = 2.3\%$$

$$MV = 49 + 2086 = 2135\ kg/m^3$$

$$\gamma_G = \frac{(100 - P_b)}{V_G\ (\%)} x\ MV = \frac{(100 - 2.3)}{90.7} x2135 = 2300 \frac{kg}{m^3} = 1.76\ ton/yd^3$$

$$\gamma_b = \frac{P_b}{V_b\ (\%)} x\ MV = \frac{2.3}{4.8} x\ 2135 = 1023 \frac{kg}{m^3} = 0.78\ ton/yd^3$$

$$Vol. Agrgegates = \frac{2284\ kg}{2300\ kg/m^3} = 0.99\ m^3 = 1.30\ \ yd^3$$

$$Vol. Bitumen = \frac{54\ kg}{1023\ kg/m^3} = \ 0.053 m^3 = 0.07\ \ yd^3$$

Binder Course

$$P_b = \frac{46.1}{46.1 + 2081} = 0.022 = 2.2\%$$

$$MV = 46.1 + 2081 = 2127.1\ kg/m^3$$

$$\gamma_G = \frac{(100 - P_b)}{V_G\ (\%)} x\ MV = \frac{(100 - 2.2)}{90.5} x2127.1 = 2299 \frac{kg}{m^3} = 1.76\ ton/yd^3$$

$$\gamma_b = \frac{P_b}{V_b\ (\%)} x\ MV = \frac{2.2}{4.5} x\ 2127.1 = 1040\ kg/m^3 = 0.80\ ton/yd^3$$

$$Vol. Agrgegates = \frac{2734\ kg}{2299\ kg/m^3} = 1.19\ m^3 = 1.56\ yd^3$$

$$Vol. Bitumen = \frac{61\ kg}{1040\ kg/m^3} = 0.059\ m^3 = 0.08\ yd^3$$

Base Course

$$P_b = \frac{41.5}{41.5 + 2080} = 0.020 = 2\%$$

$$MV = 41.5 + 2080 = 2121.5\ kg/m^3$$

$$\gamma_G = \frac{(100 - P_b)}{V_G\ (\%)} x\ MV = \frac{(100 - 2)}{90.4} x2121.5 = 2300 \frac{kg}{m^3} = 1.76\ ton/yd^3$$

$$\gamma_b = \frac{P_b}{V_b\ (\%)} x\ MV = \frac{2}{4.1} x\ 2121.5 = 1035\ kg/m^3 = 0.79\ ton/yd^3$$

$$Vol. Agrgegates = \frac{4555\ kg}{2300\ kg/m^3} = 1.98\ m^3 = 2.59\ yd^3$$

$$Vol. Bitumen = \frac{91\ kg}{1035\ kg/m^3} = 0.088\ m^3 = 0.12\ yd^3$$

Foundation

$$MV = 2201\ kg/m^3$$

$$\gamma_G = \frac{(100 - P_b)}{V_G\ (\%)} x\ MV = \frac{(100 - 0)}{94.8} x2201 = 2322 \frac{kg}{m^3} = 1.78\ ton/yd^3$$

$$Vol. Agrgegates = \frac{9641\ kg}{2322\ kg/m^3} = 4.15\ m^3 = 5.44\ yd^3$$

It can be seen that the sum of volumes of materials of each layer it is not equal to the total volume of the layer because voids are not considered in the volumes of materials to input obviously. Densities for bitumen and virgin aggregates have been modified in PaLATE with the values used for the calculation.

Regarding transport distances, these were also provided in the study.

1) Distances from material source to asphalt plant can be seen in Figure 50.

LAYER	MATERIAL	Standard	
		Dist. [km]	Dist. [mi]
Wearing	Bitumen	100	62.15
	Aggregates	30	18.65
Binder	Bitumen	100	62.15
	Aggregates	30	18.65
Base	Bitumen	100	62.15
	Aggregates	30	18.65
Foundation	Aggregates	30	18.65

Figure 50. Distances from material source to asphalt plant.

The predominant transportation mode for aggregates is dump truck and for bitumen tanker truck.

2) Distance from asphalt plant to working site in the study is assumed to be 50 km = 31.08 mi. The predominant transportation mode is a dump truck.

Initial construction sheet in PaLATE can be seen in Figure 51.

		Material	Density [tons/(yd^3)]	New Asphalt Pavement Volume [yd^3]	New Concrete Pavement Volume [yd^3]	New Subbase & Embankment Construction Volume [yd^3]	Transportation One-way transport distance [mi]	Transportation mode
Wearing Course 1	Materials	Virgin Aggregate	1.76	1.30	0		18.65	dump truck
		Bitumen	0.78	0.07			62.15	tanker truck
		Cement	1.27		0		0	barge
		Concrete Additives	0.84		0		0	tanker truck
		RAP	1.85	0	0		0	dump truck
		FRAP	1.85	0	0		0	dump truck
		RAS	1.12	0	0		0	dump truck
		RCA	1.88	0	0		0	dump truck
		Coal Fly Ash	2.20	0	0		0	cement truck
		Coal Bottom Ash	2.00	0	0		0	dump truck
		Blast Furnace Slag	1.72	0	0		0	dump truck
		Foundry Sand	1.50	0	0		0	dump truck
		Recycled Tires/ Crumb Rubber	1.92	0	0		0	dump truck
		Glass Cullet	1.93	0	0		0	dump truck
		Water	0.84		0			
		Steel Reinforcing Bars	0.24		0		0	dump truck
		Total: Asphalt mix to site	1.23	**1.37**			31.08	dump truck
		Total: Ready-mix concrete mix to site	2.03		**0**		0	mixing truck
	Waste material to landfill	RAP from site to landfill	1.85	0			0	dump truck
		RAS from site to landfill	1.12	0	0		0	dump truck
		RCM from site to landfill	1.88		0		0	dump truck

		Material	Density [tons/(yd^3)]	New Asphalt Pavement Volume [yd^3]	New Concrete Pavement Volume [yd^3]	New Subbase & Embankment Construction Volume [yd^3]	Transportation One-way transport distance [mi]	Transportation mode
Binder	Materials	Virgin Aggregate	1.76	1.56	0		18.65	dump truck
		Bitumen	0.8	0.08			62.15	tanker truck
		Cement	1.27		0		0	cement truck
		Concrete Additives	0.84		0		0	tanker truck
		RAP	1.85	0	0		0	dump truck
		FRAP	1.85	0	0		0	dump truck
		RAS	1.12	0	0		0	dump truck
		RCA	1.88	0	0		0	dump truck
		Coal Fly Ash	2.20	0	0		0	rail
		Coal Bottom Ash	2.00	0	0		0	dump truck
		Blast Furnace Slag	1.72	0	0		0	dump truck
		Foundry Sand	1.50	0	0		0	dump truck
		Recycled Tires/ Crumb Rubber	1.92	0	0		0	dump truck
		Glass Cullet	1.93	0	0		0	dump truck
		Water	0.84		0			
		Steel Reinforcing Bars	0.24		0		0	dump truck
		Total: Asphalt mix to site	1.23	**1.64**			31.08	dump truck
		Total: Ready-mix concrete mix to site	2.03		**0**		0	mixing truck
	Waste material to landfill	RAP from site to landfill	1.85	0			0	dump truck
		RAS from site to landfill	1.12	0	0		0	dump truck
		RCM from site to landfill	1.88		0		0	dump truck

		Material	Density [tons/(yd^3)]	New Asphalt Pavement	New Concrete Pavement	New Subbase & Embankment Construction	Transportation	
				Volume [yd^3]	Volume [yd^3]	Volume [yd^3]	One-way transport distance [mi]	Transportation mode
Base	Materials	Virgin Aggregate	1.76	2.59	0		18.65	dump truck
		Bitumen	0.79	0.12			62.15	tanker truck
		Cement	1.27		0		0	cement truck
		Concrete Additives	0.84		0		0	tanker truck
		RAP	1.85	0	0		0	dump truck
		FRAP	1.85	0	0		0	dump truck
		RAS	1.12	0	0		0	dump truck
		RCA	1.88	0	0		0	dump truck
		Coal Fly Ash	2.20	0	0		0	cement truck
		Coal Bottom Ash	2.00	0	0		0	dump truck
		Blast Furnace Slag	1.72	0	0		0	dump truck
		Foundry Sand	1.50	0	0		0	dump truck
		Recycled Tires/ Crumb Rubber	1.92	0	0		0	dump truck
		Glass Cullet	1.93	0	0		0	dump truck
		Water	0.84		0			dump truck
		Steel Reinforcing Bars	0.24		0		0	
		Total: Asphalt mix to site	1.23	**2.71**			31.08	dump truck
		Total: Ready-mix concrete mix to site	2.03		**0**		0	mixing truck
	Waste mat'l sent to landfill	RAP from site to landfill	1.85	0			0	dump truck
		RAS from site to landfill	1.12	0			0	dump truck
		RCM from site to landfill	1.88		0		0	dump truck

		Material	Density [tons/(yd^3)]	New Asphalt Pavement	New Concrete Pavement	New Subbase & Embankment Construction	Transportation	
				Volume [yd^3]	Volume [yd^3]	Volume [yd^3]	One-way transport distance [mi]	Transportation mode
Foundation	Materials	RAP to recycling plant	1.85			0	0	dump truck
		RAP from recycling plant to site	1.85			0	0	dump truck
		RAS to recycling plant	1.12			0	0	dump truck
		RAS from recycling plant to site	1.12			0	0	dump truck
		RCM to recycling plant	1.88			0	0	dump truck
		RCM from recycling plant to site	1.88			0	0	dump truck
		Cement	1.27			0	0	dump truck
		Coal Fly Ash	2.20			0	0	cement truck
		Coal Bottom Ash	2.00			0	0	dump truck
		Blast Furnace Slag	1.72			0	0	dump truck
		Foundry Sand	1.50			0	0	dump truck
		Recycled Tires/ Crumb Rubber	1.92			0	0	dump truck
		Glass Cullet	1.93			0	0	dump truck
		Rock	1.78			5.44	18.65	dump truck
		Gravel	1.35			0	0	dump truck
		Sand	1.25			0	0	dump truck
		Soil	1.63			0	0	dump truck
		Total: Subbase 1 materials to site	**1.78**			**5.44**		
	Waste mat'l sent to landfill	RAP from site to landfill	1.85			0	0	dump truck
		RAS from site to landfill	1.12			0	0	dump truck
		RCM from site to landfill	1.88			0	0	dump truck

Figure 51. Initial Construction sheet 2nd case study.

4.3.3.5 Maintenance sheet

The study provides the Maintenace plan to be followed. Analysis period was set to 18 years.

<u>Plan</u>

- Every 5 years a full-depth reclamation (FDR) process for wearing course should be applied.
- The year 18 the pavement should be demolished completely (wearing, binder and base course).

Year 5 → FDR wearing course

Year 10 → FDR wearing course

Year 15 → FDR wearing course

Year 18 → Demolition of the pavement, wearing, binder and base course

In order to fill in this sheet some calculation regarding materials should be done.

To accomplish with the proposed plan, the volume of materials to be used should be calculated for every time that they are needed. Maintenance is just applied for the wearing course, hence:

In 18 years of analysis period 3 FDR processes will be applied.

<u>FDR</u>

Virgin aggregates = 3 x 0.99 m^3 = 2.97 m^3 = 3.89 yd^3

Bitumen = 3 x 0.053 m^3 = 0.16 m^3 = 0.21 yd^3

3.89 + 0.16 = 4.05 yd^3

<u>Total Material for Maintenance</u>

Virgin aggregates = 2.97 m^3 = 3.89 yd^3

Bitumen = 0.16 m^3 = 0.21 yd^3

3.89 + 0.21 = 4.05 yd^3

As the quantity of material going to landfill is considered by PaLATE and in the year 18 the whole pavement is going to landfill (so wearing, binder and base courses are considered in this year) the corresponding values <u>going to landfill</u> are:

1- Wearing course

Due to FDR = 4.05 yd^3

Demolition of the pavement = 1.37 yd^3

4.05+1.37 = 5.42 yd^3

2- Binder

Demolition of the pavement = 1.64 yd^3

3- Base

Demolition of the pavement = 2.71 yd^3

Regarding transport distances and transportation modes, considerations are the same as for Initial Construction, but in this case, the same as with materials should be done. Transport distances are repeated every time that material is going to be laid (3 times for FDR) or to landfill (4 times in total). In addition, the distance from the working site to the final disposal is 50 km (as indicated in the study), therefore:

1) Wearing course

Virgin aggregates distance = 30 km x 3 = 90 km = 55.94 mi

Bitumen distance = 100 km x 3 = 300 km = 186.45 mi

Asphalt mix to site distance = 50 km x 3 = 150 km = 93.23 mi

Pavement going to landfill = 50 km x 4 = 200 km = 124.30 mi

2) Binder

Pavement going to landfill = 50 km x 1 = 50 km = 31.08 mi

3) Base

Pavement going to landfill = 50 km x 1 = 50 km = 31.08 mi

Predominant transportation mode for material going to landfill is dump truck.

In this way the maintenance sheet looks as Figure 52.

		Material	Density [tons/(yd^3)]	Lifetime Asphalt Repaving	Lifetime Concrete Repaving	Lifetime Subbase Reconstruction	Lifetime Embankment Reconstruction	Transportation	
				Volume [yd^3]	Volume [yd^3]	Volume [yd^3]	Volume [yd^3]	One-way transport distance [mi]	Transportation mode
Wearing Course 1	Materials	Virgin Aggregate	1.76	3.89	0			55.94	dump truck
		Bitumen	0.78	0.21				186.45	tanker truck
		Cement	1.27		0			0	cement truck
		Concrete Additives	0.84		0			0	tanker truck
		Asphalt Emulsion	0.84	0				0	tanker truck
		RAP	1.85	0	0			0	dump truck
		FRAP	1.85	0	0			0	dump truck
		RAS	1.12	0	0			0	dump truck
		RCA	1.88	0	0			0	dump truck
		Coal Fly Ash	2.20	0	0			0	tanker truck
		Coal Bottom Ash	2.00	0	0			0	dump truck
		Blast Furnace Slag	1.72	0	0			0	dump truck
		Foundry Sand	1.50	0	0			0	dump truck
		Recycled Tires/ Crumb Rubber	1.92	0	0			0	dump truck
		Glass Cullet	1.93	0	0			0	dump truck
		Water	0.84		0				
		Steel Reinforcing Bars	0.24		0			0	dump truck
		Total: Hot-mix Asphalt to site	1.23	**4.10**				93.23	dump truck
		Total: Ready-mix Concrete mix to site	2.03		**0**			0	mixing truck
	Processes	HIPR	1.83	0					
		CIR	1.83	0					
		Patching	1.23	0	0				
		Microsurfacing	1.23	0	0				
		Crack Sealing	0.84	0	0				
		Whitetopping	2.03		0				
		Rubblization	1.95		0				
		Full-depth Reclamation	1.83	4.05	0				
	Waste material to landfill	RAP from site to landfill	1.85	5.46				124.30	dump truck
		RAS from site to landfill	1.12	0				0	dump truck
		RCM from site to landfill	1.88		0			0	dump truck

		Material	Density [tons/(yd^3)]	Lifetime Asphalt Repaving	Lifetime Concrete Repaving	Lifetime Subbase Reconstruction	Lifetime Embankment Reconstruction	Transportation	
				Volume [yd^3]	Volume [yd^3]	Volume [yd^3]	Volume [yd^3]	One-way transport distance [mi]	Transportation mode
Binder	Materials	Virgin Aggregate	1.76	0	0			0	dump truck
		Bitumen	0.8	0				0	tanker truck
		Cement	1.27		0			0	cement truck
		Concrete Additives	0.84		0			0	tanker truck
		Asphalt Emulsion	0.84	0				0	tanker truck
		RAP	1.85	0	0			0	dump truck
		FRAP	1.85	0	0			0	dump truck
		RAS	1.12	0	0			0	dump truck
		RCA	1.88	0	0			0	dump truck
		Coal Fly Ash	2.20	0	0			0	rail
		Coal Bottom Ash	2.00	0	0			0	dump truck
		Blast Furnace Slag	1.72	0	0			0	dump truck
		Foundry Sand	1.50	0	0			0	dump truck
		Recycled Tires/ Crumb Rubber	1.92	0	0			0	dump truck
		Glass Cullet	1.93	0	0			0	dump truck
		Water	0.84		0				
		Steel Reinforcing Bars	0.24		0			0	dump truck
		Total: Hot-mix Asphalt to site	1.23	**0**				0	dump truck
		Total: Ready-mix Concrete mix to site	2.03		**0**			0	mixing truck
	Processes	HIPR	1.83	0					
		CIR	1.83	0					
		Rubblization	1.95		0				
		Full-depth Reclamation	1.83	0	0				
	Waste material to landfill	RAP from site to landfill	1.85	1.64				31.08	dump truck
		RAS from site to landfill	1.12	0				0	dump truck
		RCM from site to landfill	1.88		0			0	dump truck

		Material	Density [tons/(yd^3)]	Lifetime Asphalt Repaving	Lifetime Concrete Repaving	Lifetime Subbase Reconstruction	Lifetime Embankment Reconstruction	Transportation	
				Volume [yd^3]	Volume [yd^3]	Volume [yd^3]	Volume [yd^3]	One-way transport distance [mi]	Transportation mode
Base	Materials	Virgin Aggregate	1.76	0	0			0	dump truck
		Bitumen	0.79	0				0	tanker truck
		Cement	1.27		0			0	cement truck
		Concrete Additives	0.84		0			0	tanker truck
		Asphalt Emulsion	0.84	0				0	dump truck
		RAP	1.85	0	0			0	dump truck
		FRAP	1.85	0	0			0	dump truck
		RAS	1.12	0	0			0	dump truck
		RCA	1.88	0	0			0	dump truck
		Coal Fly Ash	2.20	0	0			0	cement truck
		Coal Bottom Ash	2.00	0	0			0	dump truck
		Blast Furnace Slag	1.72	0	0			0	dump truck
		Foundry Sand	1.50	0	0			0	rail
		Recycled Tires/ Crumb Rubber	1.92	0	0			0	dump truck
		Glass Cullet	1.93	0	0			0	dump truck
		Water	0.84		0				
		Steel Reinforcing Bars	0.24		0			0	dump truck
		Total: Hot-mix Asphalt to site	1.23	**0**				0	dump truck
		Total: Ready-mix Concrete mix to site	2.03		**0**			0	mixing truck
	Processes	HIPR	1.83	0					
		CIR	1.83	0					
		Rubblization	1.95		0				
		Full-depth Reclamation	1.83	0	0				
	Waste material to landfill	RAP from site to landfill	1.85	2.71				31.08	dump truck
		RAS from site to landfill	1.12	0				0	dump truck
		RCM from site to landfill	1.88		0			0	dump truck

Figure 52. Maintenance sheet 2nd case study.

4.3.3.6 Equipment sheet

The equipment involved for the construction of the road will be described in this section.

The activities involved in this case study regarding equipment are: asphalt paving, full-depth reclamation and HMA production. As PaLATE offers machinery used in USA, and the paper does not tell in detail about the machinery used, some assumptions were made.

Information of equipment provided by the study were just that a paver and rollers were used with a fuel consumption of 30 l/h and 17 l/h respectively.

ACTIVITIES

Asphalt Paving

- Paver: the chosen one in this case is the Dynapac F25C due to the similarity in fuel consumption. The paver in the study consumes 30 l/h while the chosen one 31.6 l/h.

- Pneumatic roller: as no further information about the roller was provided, it was assumed that no pneumatic roller was used.

- Tandem roller: in this case it is just known the fuel consumption of the roller, and as there is no machine offered by PaLATE with a similar consumption, the machine used was that offered with the minor consumption, so characteristics were copied except for fuel consumption that was assumed to be that provided by the company (17 l/h). So, in this specific case in the correspondent cell of the "Equipment" sheet it was chosen the option "other" and have been modified in the "Equipment details" sheet. The used machine is the Ingersol DD90HF, and characteristics with modified fuel consumption can be seen in Figure 53.

type	brand/model	engine model	hp	Productivity (non-standard units)	Conversion Factors	Productivity	fuel consumption
Tandem Roller	Ingersol rand DD130	Cummins 6BTA 5.9	174 hp			?	27.6 l/h
	Ingersol rand DD110	Cummins 4BTA 3.9	125 hp			285 tons/h	32.7 l/h
	Ingersol rand DD90	Cummins 4BTA 3.9	110 hp			?	27.6 l/h
	Ingersol rand DD90HF	Cummins B3.9C	110 hp			395 tons/h	27.6 l/h
	Hypac C778B		125 hp			?	31.3 l/h
	none	0	0			1	0
	other	Cummins B3.9C	110			395	17

Figure 53. Tandem roller characteristics for 2^{nd} case study.

Full-depth reclamation

- Asphalt road reclaimer: the chosen one was the Wirtgen WR 2500 S, because is the only reclaimer that has the information complete in PaLATE.

- Vibratory soil compactor: the chosen one was the Dynapac CA262 D, because is the only compactor that has the information complete in PaLATE.

HMA production

- Asphalt mixer: as it is a study developed in Italy, the asphalt mixer was supposed to be the same type as the one of Sitalfa case, a Fabric Filter-controlled Drum mix.

But in this case, emissions of the asphalt mixer and energy consumption was left as default due to the lack of information.

Hence, with all this assumptions made, the Equipment sheet takes the following form:

ACTIVITY	Equipment	Brand/Model	Engine Capacity	Productivity	Fuel Consumption	Fuel Type
Concrete Paving	Slipform paver	Wirtgen SP 250	106 hp	564 tons/h	19.7 l/h	diesel
	Texture curing machine	Gomaco T/C 400	70 hp	187 tons/h	20.2 l/h	diesel
Asphalt Paving	Paver	Dynapac F25C	126 hp	1,700 tons/h	31.6 l/h	diesel
	Pneumatic roller	none	0 hp	1 tons/h	0.0 l/h	diesel
	Tandem roller	other	110 hp	395 tons/h	17.0 l/h	diesel
Cold in Place Recycling	CIR recycler	Wirtgen 2200 CR	800 hp	1,713 tons/h	150.00 l/h	diesel
	Pneumatic roller	Dynapac CP134	100 hp	884 tons/h	25.1 l/h	diesel
	Tandem roller	Ingersol rand DD110	125 hp	285 tons/h	32.7 l/h	diesel
Full Depth Reclamation	Asphalt road reclaimer	Wirtgen WR 2500 S	670 hp	4,800 tons/h	120.0 l/h	diesel
	Vibratory soil compactor	Dynapac CA 262D	150 hp	1,832 tons/h	37.6 l/h	diesel
Hot In Place Recycling	Heating machine	Wirtgen HM4500	49 hp	256 tons/h	9.1 l/h	diesel
	Asphalt remixer	Wirtgen 4500	295 hp	208 tons/h	55.0 l/h	diesel
	Pneumatic roller	Dynapac CP132	100 hp	668 tons/h	26.1 l/h	diesel
	Tandem roller	Ingersol rand DD110	125 hp	285 tons/h	32.7 l/h	diesel
Rubblization	Multi head breaker	Badger MHB Breaker	350 hp	520 tons/h	76.5 l/h	diesel
	Vibratory soil compactor	Dynapac CA 262D	150 hp	1,832 tons/h	37.6 l/h	diesel
Milling	Milling machine	Wirtgen W2200	875 hp	1,100 tons/h	156.2 l/h	diesel
Grinding	Grinding machine	CBI Magnum Force Shingle F	1050 hp	115 tons/h	161.1 l/h	diesel
Concrete Demolition	Multi head breaker	Badger MHB Breaker	350 hp	520 tons/h	76.5 l/h	diesel
	Wheel loader	John Deere 644E	160 hp	490 tons/h	40.1 l/h	diesel
Crushing Plant	Excavator	John Deere 690E	131 hp	225 tons/h	34.2 l/h	diesel
	Wheel loader	John Deere 624E	135 hp	225 tons/h	35.3 l/h	diesel
	Dozer	Caterpillar D8N	285 hp	225 tons/h	71.4 l/h	diesel
	Generator	Caterpillar 3406C TA	519 hp	225 tons/h	98.4 l/h	diesel
Excavation, placing and compaction	Excavator	John Deere 690E	131 hp	315 tons/h	34.2 l/h	diesel
	Vibratory soil compactor	Dynapac CA 262D	174 hp	1,832 tons/h	27.6 l/h	diesel
Tire Recycling	Shredder + Granulator + Classifier + Aspirator System	Wendt Corporation	630 hp	3.00 tons/h	104.73 kWh/ton	105 hp
Glass Recycling	Hopper + Conveyor + Shredder System	Andela GP-05 Pulverizer	10 hp	1.00 tons/h	7.46 kWh/ton	17 hp
HMA Production	asphalt mixer	Fabric Filter-controlled Drum		202.28 tons/h		oil

Figure 54. Equipment sheet 2nd case.

4.3.3.7 Environmental Results sheet

This is the **Life Cycle Impact Assessment** phase of an LCA and it is where final environmental impacts are provided and different categories are assigned for some outputs (for example GWP category). For this road extracted from Farina et al., 2014, using the estimated input values in the Sector Table, results are presented in the following Figure.

GRAND TOTALS

		Energy [MJ]	Water Consumption [kg]	CO_2 [kg] = GWP	NO_x [g]	PM_{10} [g]	SO_2 [g]
Initial Construction	Materials Production	3,665	44,562	212	913	2,611	531
	Materials Transportation	649	32	49	2,586	496	155
	Processes (Equipment)	58	3	4	116	14	8
Maintenance	Materials Production	2,152	15,947	135	489	981	336
	Materials Transportation	2,628	129	196	10,466	2,047	628
	Processes (Equipment)	23	1	2	56	4	4
Total	Materials Production	5,817	60,509	347	1,402	3,592	866
	Materials Transportation	3,277	161	245	13,051	2,543	783
	Processes (Equipment)	82	4	6	172	18	11
	Total	**9,176**	**60,675**	**598**	**14,625**	**6,154**	**1,661**

GRAND TOTALS

		CO [g]	Hg [g]	Pb [g]	RCRA Hazardous Waste Generated [kg]	Human Toxicity Potential (Cancer)	Human Toxicity Potential (Non-cancer)
Initial Construction	Materials Production	738	0	0	4	1,336	1,771,484
	Materials Transportation	215	0	0	5	14	17,072
	Processes (Equipment)	25	0	0	0	0	0
Maintenance	Materials Production	505	0	0	2	1,051	1,264,778
	Materials Transportation	872	0	0	19	56	69,103
	Processes (Equipment)	12	0	0	0	0	0
Total	Materials Production	1,242	0	1	5	2,387	3,036,262
	Materials Transportation	1,088	0	0	24	70	86,176
	Processes (Equipment)	37	0	0	0	0	0
	Total	**2,367**	**0**	**1**	**29**	**2,457**	**3,122,438**

Figure 55. Environmental results 2nd case, European sector table.

4.3.4 2[ND] Case Study: extracted from literature with default data

In this case every sheet is equal to the case recently done, therefore, the explanation will not be done again, with the only difference of the Sector Table used, that in this case is the default one (USA dat). So, immediately environmental results will be presented, which are not identical.

4.3.4.1 Environmental Results sheet

GRAND TOTALS

		Energy [MJ]	Water Consumption [kg]	CO_2 [kg] = GWP	NO_x [g]	PM_{10} [g]	SO_2 [g]
Initial Construction	Materials Production	8,481	8,029	548	1,891	3,307	1,562
	Materials Transportation	649	418	49	2,586	496	155
	Processes (Equipment)	58	38	4	116	14	8
Maintenance	Materials Production	5,284	5,642	333	1,290	1,296	1,124
	Materials Transportation	2,628	1,694	196	10,466	2,047	628
	Processes (Equipment)	23	15	2	56	4	4
Total	Materials Production	13,766	13,671	880	3,181	4,603	2,686
	Materials Transportation	3,277	2,112	245	13,051	2,543	783
	Processes (Equipment)	82	53	6	172	18	11
	Total	**17,124**	**15,836**	**1,132**	**16,404**	**7,165**	**3,480**

GRAND TOTALS

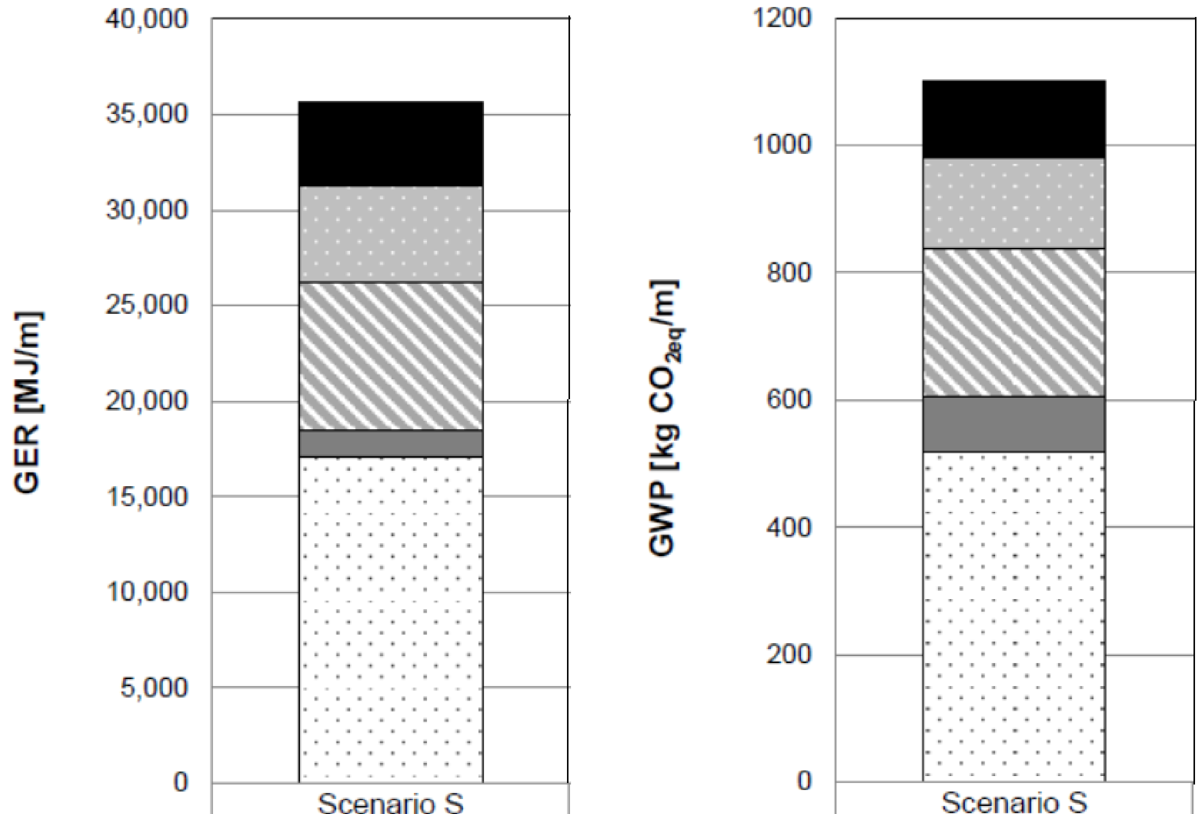
		CO [g]	Hg [g]	Pb [g]	RCRA Hazardous Waste Generated [kg]	Human Toxicity Potential (Cancer)	Human Toxicity Potential (Non-cancer)
Initial Construction	Materials Production	1,672	0	0	76	1,336	1,771,484
	Materials Transportation	215	0	0	5	14	17,072
	Processes (Equipment)	25	0	0	0	0	0
Maintenance	Materials Production	1,165	0	0	58	1,051	1,264,778
	Materials Transportation	872	0	0	19	56	69,103
	Processes (Equipment)	12	0	0	0	0	0
Total	Materials Production	2,837	0	1	134	2,387	3,036,262
	Materials Transportation	1,088	0	0	24	70	86,176
	Processes (Equipment)	37	0	0	0	0	0
	Total	**3,962**	**0**	**1**	**158**	**2,457**	**3,122,438**

Figure 56. Environmental results 2nd case, USA Sector Table.

Moreover, in this second case study, results were obtained originally with the software called SimaPro 7.3 and can be seen in Figure 57. The comparison between PaLATE and SimaPro

7.3 results will be done in the following section, together with the analysis and discussion of every result obtained for both case studies.

Results of SimaPro 7.3 are just for GWP and GER but is enough to make a good comparison with PaLATE.



	Scenario S
Wearing	4,350
Binder	5,040
Base	7,750
Foundation	1,390
Maintenance	17,100

	Scenario S
Wearing	119
Binder	142
Base	233
Foundation	87
Maintenance	519

Figure 57. SimaPro 7.3 environmental results.

4.4 Results and discussions

4.4.1 Sitalfa case study, estimated values vs default values in Sector Table

Analyzing the results shown in Figure 44 and 45 (that will be inserted again here for convenience to the reader as Figures 58 and 59 respectively), some comparisons, conclusions and discussions can be made being part of the **Interpretation** phase of an LCA methodology. Moreover, a histogram with total values for each parameter is shown in Figure 60, to achieve even a better comprehension.

GRAND TOTALS

		Energy [MJ]	Water Consumption [kg]	CO_2 [kg] = GWP	NO_x [g]	PM_{10} [g]	SO_2 [g]
Initial Construction	Materials Production	294,752	1,311,301	26,519	77,903	75,382	57,340
	Materials Transportation	22,507	1,109	1,683	89,644	15,163	5,379
	Processes (Equipment)	18,370	905	1,379	1,947	567	129
Maintenance	Materials Production	788,465	3,435,389	70,428	208,660	196,426	154,991
	Materials Transportation	1,501,506	73,975	112,251	5,980,356	1,166,999	358,821
	Processes (Equipment)	52,729	2,598	3,958	13,878	990	918
Total	Materials Production	1,083,218	4,746,690	96,947	286,564	271,808	212,331
	Materials Transportation	1,524,013	75,083	113,934	6,070,000	1,182,163	364,200
	Processes (Equipment)	71,099	3,503	5,336	15,825	1,557	1,046
	Total	**2,678,330**	**4,825,276**	**216,217**	**6,372,389**	**1,455,528**	**577,578**

GRAND TOTALS

		CO [g]	Hg [g]	Pb [g]	RCRA Hazardous Waste Generated [kg]	Human Toxicity Potential (Cancer)	Human Toxicity Potential (Non-cancer)
Initial Construction	Materials Production	41,382	1	44	136	166,818	88,475,306
	Materials Transportation	7,470	0	1	162	482	591,902
	Processes (Equipment)	420	0	1	132	0	0
Maintenance	Materials Production	111,337	3	119	360	453,779	228,664,586
	Materials Transportation	498,363	1	50	10,819	32,186	39,487,163
	Processes (Equipment)	2,990	0	0	0	0	0
Total	Materials Production	152,719	3	163	496	620,597	317,139,892
	Materials Transportation	505,833	1	51	10,982	32,668	40,079,065
	Processes (Equipment)	3,410	0	1	132	0	0
	Total	**661,963**	**5**	**215**	**11,610**	**653,266**	**357,218,957**

Figure 58. Environmental impacts for Sitalfa case study with estimated values in Sector Table.

GRAND TOTALS

		Energy [MJ]	Water Consumption [kg]	CO_2 [kg] = GWP	NO_x [g]	PM_{10} [g]	SO_2 [g]
Initial Construction	Materials Production	689,335	872,955	50,196	195,863	106,286	162,647
	Materials Transportation	22,507	14,506	1,683	89,644	15,163	5,379
	Processes (Equipment)	18,370	11,840	1,379	1,947	567	129
Maintenance	Materials Production	1,858,849	2,374,987	134,432	530,478	278,775	441,889
	Materials Transportation	1,501,506	967,725	112,251	5,980,356	1,166,999	358,821
	Processes (Equipment)	52,729	33,984	3,958	13,878	990	918
Total	Materials Production	2,548,184	3,247,942	184,628	726,341	385,061	604,536
	Materials Transportation	1,524,013	982,231	113,934	6,070,000	1,182,163	364,200
	Processes (Equipment)	71,099	45,823	5,336	15,825	1,557	1,046
	Total	**4,143,297**	**4,275,996**	**303,898**	**6,812,166**	**1,568,781**	**969,783**

GRAND TOTALS

		CO [g]	Hg [g]	Pb [g]	RCRA Hazardous Waste Generated [kg]	Human Toxicity Potential (Cancer)	Human Toxicity Potential (Non-cancer)
Initial Construction	Materials Production	142,594	1	45	9,423	166,818	88,475,306
	Materials Transportation	7,470	0	1	162	482	591,902
	Processes (Equipment)	420	0	1	132	0	0
Maintenance	Materials Production	386,687	3	123	25,676	453,779	228,664,586
	Materials Transportation	498,363	1	50	10,819	32,186	39,487,163
	Processes (Equipment)	2,990	0	0	0	0	0
Total	Materials Production	529,282	3	168	35,099	620,597	317,139,892
	Materials Transportation	505,833	1	51	10,982	32,668	40,079,065
	Processes (Equipment)	3,410	0	1	132	0	0
	Total	**1,038,525**	**5**	**220**	**46,213**	**653,266**	**357,218,957**

Figure 59. Environmental impacts for Sitalfa case study with default values in Sector Table.

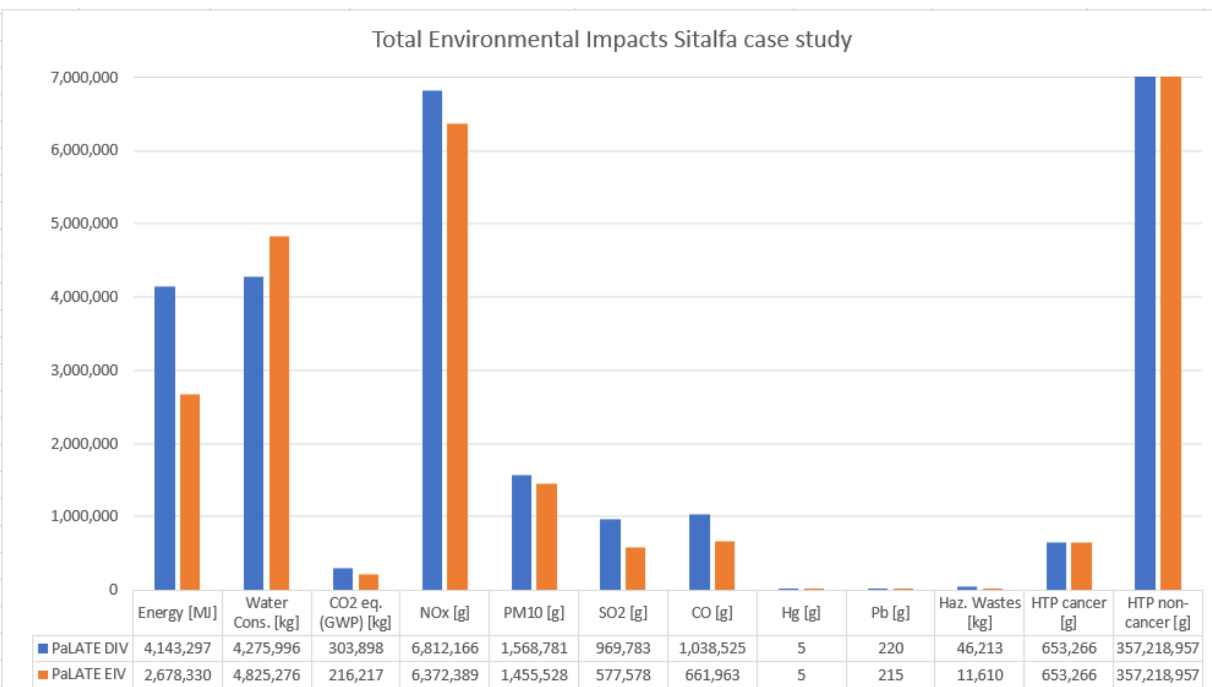


Figure 60. Total Environmental impacts comparing default and estimated input values in Sector Table – Sitalfa case study.

Where DIV stands for Default Input Values and EIV for Estimated Input Values.

About the histogram, is useful to clarify that HTP non-cancer emissions do not fit in the graph with that specific scale, that's why are both columns full, nevertheless, the numbers are written below the tag. The same, but the other way around, happens to Hg, Pb and Hazardous wastes emissions, where the numbers are too small for that specific scale used in the histogram.

First of all, the first that it can be seen at first sight is:

Total values for each environmental impact are always bigger the ones referring to the Sector Table with default values. If the total values are disaggregated into Material Production, Material Transportation and Processes, the difference between both cases is clearly in Material Production as it was expected. This is because the Sector Table is the one which provides information for this important process, and, as it was modified it is logic to see changes in this phase. Hence, entering a little bit more in detail comparing both Sector Tables (See Table 5 and 9), it can be seen that the default values are all bigger except for water consumption and NO_2 for sand and gravel sector. This difference in values for different economic sectors is due to the literature reviewed and in future studies this difference can be analyzed as deep as possible. As a general knowledge topic about emissions around the world it can be said that USA is the second biggest contributor to carbon dioxide (CO_2) emissions in the world, just behind China, and regarding Europe, processes nowadays are tending to be controlled by setting a lot of new standards and countries are changing their mentality and concerns to a less polluted world, an example of this can be the targets fixed by the European Union for 2030, where the key targets are:

- 40% cuts in greenhouse gas emissions
- 32% share for renewable energy
- 32.5% improvement in energy efficiency

  [21]

Notwithstanding, for both Sector Tables values remain coherent between them, always being bigger for the bitumen production than for virgin aggregates production, in a comparable scale.

Between both Sector Tables the bigger differences are those of CO_2, Energy and Water Consumption. Here it is interesting to analyze Water consumption in the case study using default input values, because if the mistake wouldn't have been corrected, the environmental impact for a 382 m road construction would have been 1130 kg, which is an illogic value knowing that 1130 kg of water is equal to 1130 l and 1.13 m^3. Instead, with the Sector Table corrected this environmental impact is equal to 4,275,996 kg which is equal to 4276 m^3, being this a more logic result. Hence, the found mistake is proven to be a right.

Now focusing more in each environmental output from the case study using estimated input values (Figure 58), which is more interesting taking into account that this is a real road construction in Italy, close to Turin. The following analysis can be made:

Energy

There is much more consume for Material Production and Material transportation phases than for Processes. The 40.44 % of the total energy consumption it accounts for material production, the 56.90 % for material transportation and just the 2.66 % for processes. Even more, the biggest contribution can be seen that is clearly in the Maintenance phase of the road, and this can be explained with the 20 years analysis period chosen, where every volume and distance input in this sheet was taken into account for 20 years and according to the maintenance plane indicated by the company. It is logic that consumption remain bigger for 20 years than just for initial construction. Disaggregating in Maintenance, it can be seen that the biggest part is due to material transportation, and this is because the road has to follow every year a maintenance process, which each of them needs few materials compared to the distances travelled by the trucks to deliver it. In other words, it is very little quantity of material for so much distance. Nevertheless, the value for material production is not negligible (33.66 % in maintenance) and imagine if the road were larger the material needed would be much more, resulting in a bigger contribution from material production and the travelled distances would remain the same. Instead if the Initial Construction phase is analyzed it can be seen that material production contributes to an 87.82 % of energy consumption being much bigger than material transportation, hence, justifying that material production is an important phase to take into account because of every process that has within. Moreover, the greatest contribution to energy consumption is due to bitumen production as can be seen in Figure 61 for Wearing course as an example, being this 5 times bigger than the contribution of virgin aggregates. This is coherent with the values from the Sector Table.

		Energy [MJ]
Initial Construction Materials WC1	Virgin Aggregates	15,084
	Asphalt Bitumen	73,700
	Cement	0
	Concrete Additives	0
	RAP milling	0
	FRAP milling & grinding	0
	RAS Grinding	0
	RCM demolition	0
	RCM crushing	0
	Water	0
	Steel Reinforcing Bars	0
	Coal Fly Ash	0
	Coal Bottom Ash	0
	Blast Furnace Slag	0
	Foundry Sand	0
	Recycled Tires/ Crumb Rubber	0
	Glass Cullet	0
	Hot-mix Asphalt Plant Process	37,707
	Ready-mix Concrete	0
	Total	**126,491**

Figure 61. Bitumen production contribution to Energy consumption.

The next graph is a great representation of the already explained topic.

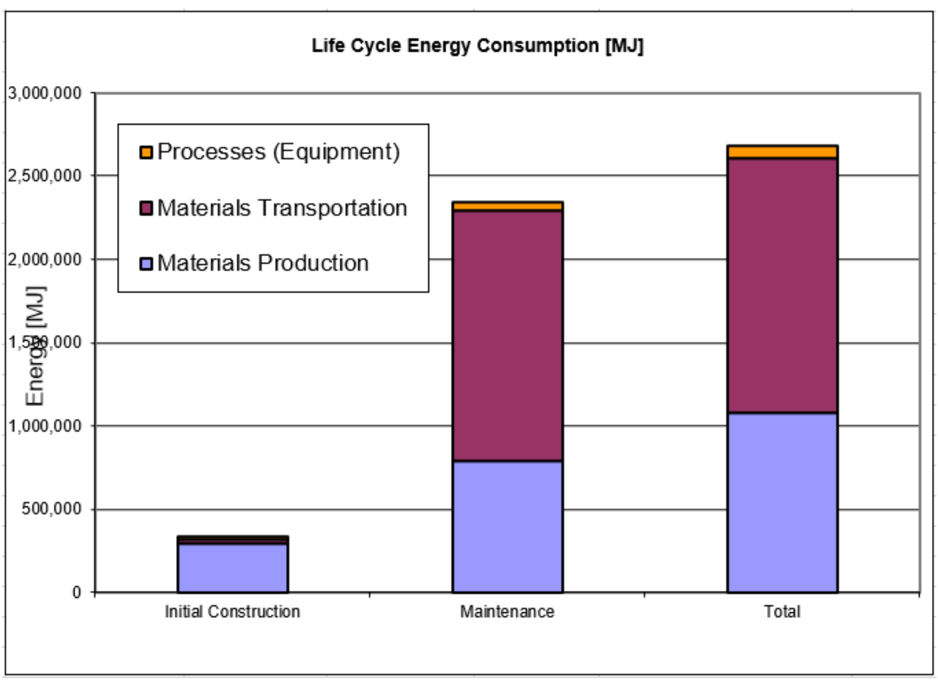


Figure 62. Energy Consumption graph.

Water Consumption

This parameter was already named and the mistake that presents the default Sector Table too. The important thing to see here is that the vast majority of water consumption is due to the material production stage and more specifically due to virgin aggregates. This is because the volume of virgin aggregates that the mix contains (72.51 m^3), against 11.69 m^3 of bitumen (See Figure 63).

		Energy [MJ]	Water Consumption [g]
Initial Construction Materials WC1	Virgin Aggregates	15,084	456,492,283
	Asphalt Bitumen	73,700	94,655,766
	Cement	0	0
	Concrete Additives	0	0
	RAP milling	0	0
	FRAP milling & grinding	0	0
	RAS Grinding	0	0
	RCM demolition	0	0
	RCM crushing	0	0
	Water	0	0
	Steel Reinforcing Bars	0	0
	Coal Fly Ash	0	0
	Coal Bottom Ash	0	0
	Blast Furnace Slag	0	0
	Foundry Sand	0	0
	Recycled Tires/ Crumb Rubber	0	0
	Glass Cullet	0	0
	Hot-mix Asphalt Plant Process	37,707	0
	Ready-mix Concrete	0	0
	Total	**126,491**	**551,148,049**

Figure 63. Virgin aggregates contribution to water consumption.

The graph representing environmental impacts for this parameter is presented in the Appendix.

It can be seen that in this particular case, final environmental impacts for default and estimated input values are quite similar.

CO_2

As it was explained in chapter 3, this is generated by the combustion of fossil fuels in industrial processes. In the reality this is one of the most important parameters that can be found due to its contribution to greenhouse effect, and an industrial plant frequently is characterized by the CO_2 generated, having more importance as the plant is bigger.

In this case the biggest contribution of CO_2 was found in material production (44.84 %) and material transportation (52.69 %) stages, being the contribute of the processes stage negligible (2.47 %). Even more, the biggest contribution was found in the maintenance phase, with the same justification than for energy consumption about the 20 years analysis period, and distances travelled, where the biggest impact can be seen in material transportation.

On the other hand, regarding Initial construction phase, where results can be seen clearly, because these 20 years are not considered, the material production stage accounts for the biggest contributions (89.65 %), remaining material transportation and processes negligible. This big difference is due to the generation of CO_2 principally from fossil fuels combustion, where bitumen production accounts for the greatest contribution (See Figure 64).

		Energy [MJ]	Water Consumption [g]	CO_2 [kg]
Initial Construction Materials WC1	Virgin Aggregates	15,084	456,492,283	578
	Asphalt Bitumen	73,700	94,655,766	4,377
	Cement	0	0	0
	Concrete Additives	0	0	0
	RAP milling	0	0	0
	FRAP milling & grinding	0	0	0
	RAS Grinding	0	0	0
	RCM demolition	0	0	0
	RCM crushing	0	0	0
	Water	0	0	0
	Steel Reinforcing Bars	0	0	0
	Coal Fly Ash	0	0	0
	Coal Bottom Ash	0	0	0
	Blast Furnace Slag	0	0	0
	Foundry Sand	0	0	0
	Recycled Tires/ Crumb Rubber	0	0	0
	Glass Cullet	0	0	0
	Hot-mix Asphalt Plant Process	37,707	0	6,344
	Ready-mix Concrete	0	0	0
	Total	**126,491**	**551,148,049**	**11,299**

Figure 64. Bitumen production contribution to CO_2 generation.

Looking at the values from the Sector Table and comparing estimated and default values, the bitumen production (for a ton) in USA generates 3 times the value of CO_2 generated in Europe. Figure 65 is a better illustration of what was already explained.

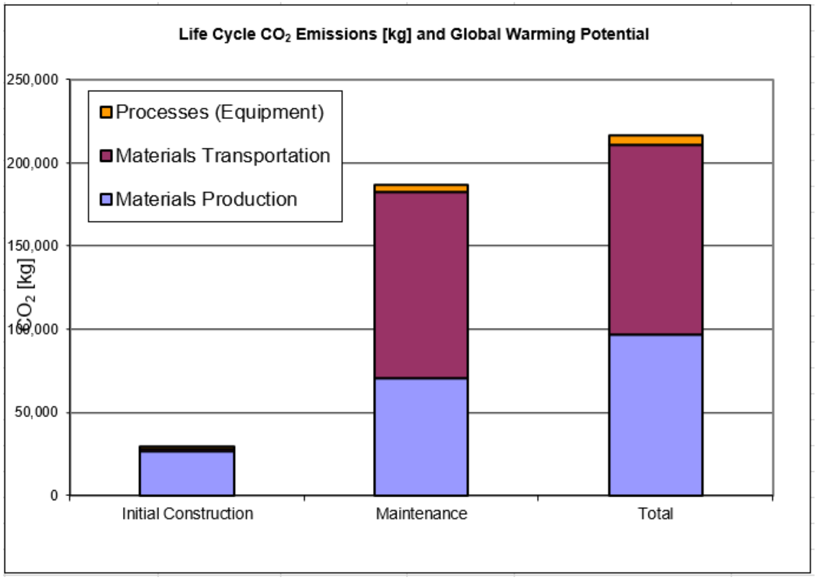


Figure 65. CO_2 emissions graph.

NOx

Nitric oxides are produced by industrial plants and transport systems, principally by the oil combustion. Having great importance vehicles and being coherent with PaLATE results, where it can be seen that a great part is due to material transportation (95.25 % from the total). In addition, the biggest contribution is due to the maintenance phase because of the distances travelled by the trucks, NOx emissions generated by diesel motors are important. On the other hand, in the initial construction phase, material transportation stage remains bigger but not too far from material production. In the case considered with the default sector table the same happens regarding maintenance phase but not with initial construction phase, where material production is clearly bigger than material transportation. This is due to the changes made in the Sector Table, nevertheless, values are not too different.

Material transportation has clearly incidence in this parameter as shown in Figure 66.

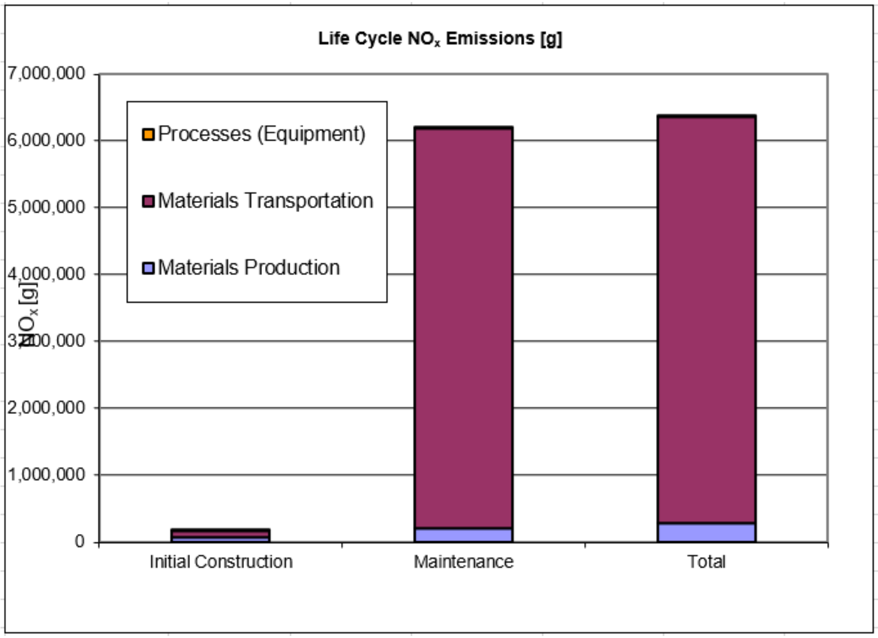


Figure 66. NOx emissions graph.

<u>PM_{10}</u>

This value, regarding the Sector Table, is similar between the estimated and default values. Both environmental results indicate that the greatest contribution is due to maintenance and by material transportation more specifically, because vehicles have great incidence in particulate generation. Another important generation source of particulates are all the processes carried out to produce material and, focusing on Initial Construction phase it can be clearly seen that material production has much more influence than material transportation stage. In addition, the greatest contribution is due to virgin aggregates production as it was expected, because of particulates generated during aggregate storage, material transfer and conveying, pile forming stacker, bulk loading and screening. The processes stage doesn't have influence in particulates. A graph in Figure 67 can be seen.

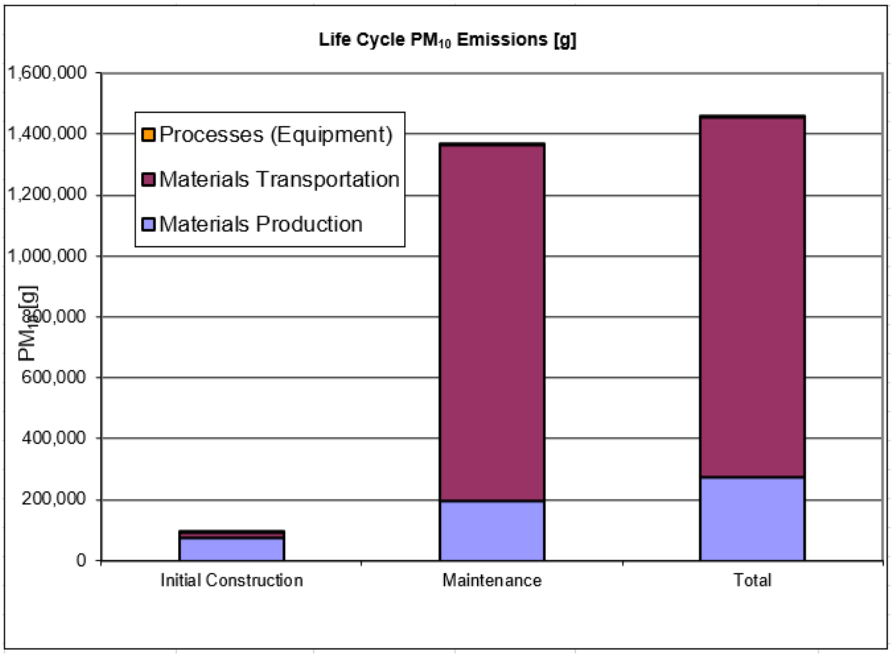


Figure 67. PM_{10} emissions graph.

SO_2

It is principally generated by fossil fuels combustion. That's why the biggest contribution is regarding material production stage in initial construction phase (91.24 %), and bitumen production more than anything.

In the case of the material transportation stage in maintenance phase, this takes a great value too, and it is not negligible, in fact, is the biggest regarding maintenance, because diesel motors also generate a lot of SO_2 and in this phase large distances must be travelled. Yet, material production has an important contribution, and this would be much greater if the material to apply to the road would be more. A graph in Figure 68 is presented.

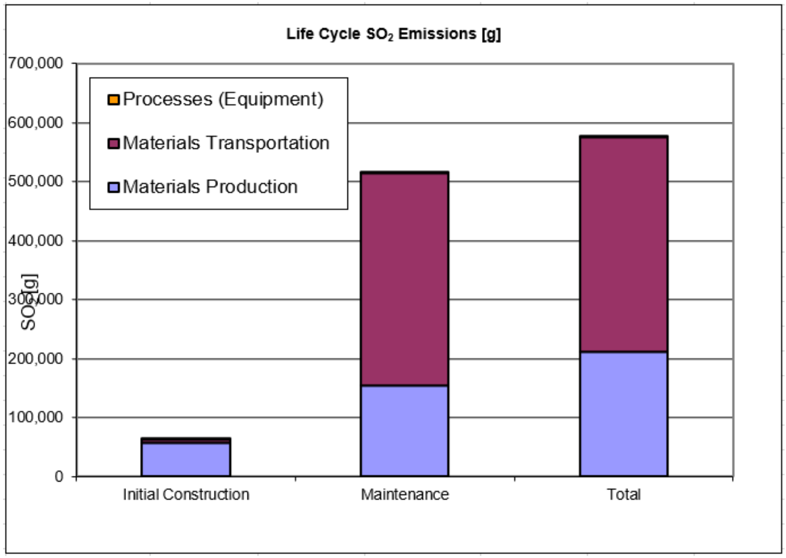


Figure 68. SO_2 emissions graph.

<u>CO</u>

It is principally generated by fossil fuels combustion and the same explanation as for SO_2 is valuable in the case of carbon monoxide. The biggest contribution is regarding material production stage in initial construction phase (84 %), and bitumen production more than anything. In the maintenance phase the biggest contribution is due to material transportation accounting for an 81.34 % of this phase, and material production is not a negligible value, since it is 1/4 part of the pollution of material transportation (not a small value considering everything already said about the distances travelled vs volume transported). Values in the default Sector Table are close to the ones found for the estimated Sector Table. Figure 69 presents the CO case.

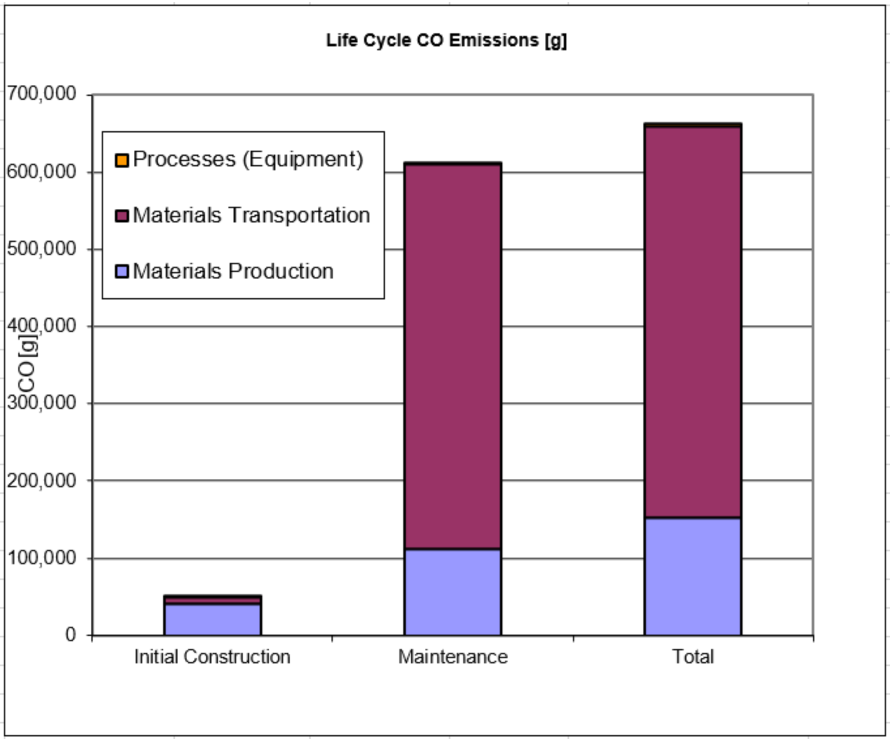


Figure 69. CO emissions.

Hg

The values are really small for both cases, close to 0 (zero), verifying that the total is 5 g. This is because the values in the Sector Table are small. Mercury is really strong and harmful to human health and it is important that this value stay low. The greatest contribution in the case that uses the estimated values for the Sector Table is due to material production stage (80 %) and principally because of bitumen production. The graph representing environmental impacts for this parameter is presented in the Appendix.

Pb

The lead contribution is also small, with a total of 215 g, and it is also harmful, so it is important that this value remain low. As mercury, the greatest contribution in this case (76 %) is due to material production stage and principally because of bitumen production. The graph representing environmental impacts for this parameter is presented in the Appendix.

HTP emissions are equal for both cases because the “EMF transport” sheet which accounts for these parameters wasn’t modified, due to the fact that these emissions comes from the diesel engines.

HTP cancer

The greatest contributor to this impact is the material production stage, and this is because to calculate this output, the leachate generated by the aggregates production and fumes generated by the bitumen production are taken into account. The leachate is the lead and arsenic coming from aggregates that carries away the water, and the fumes, which contributes the most to this carcinogenic impact, contains compounds as VOC and H_2S that stays in air. Results for material transportation and processes stages are negligible. The graph representing environmental impacts for this parameter is presented in the Appendix.

HTP non cancer

Also, in this case the vast majority of contribution is due to material production stage by leachate and fumes. But, in great part, from the leachate generated by aggregates considering the non-carcinogenic compounds of aggregates carried away by the water. Instead, the contribution of fumes is less and is also considering the non-carcinogenic compounds of this that remain in air. The graph representing environmental impacts for this parameter is presented in the Appendix.

Hazardous Wastes

In this case it can be seen a big difference between the results obtained for the case using estimated values and the case using default values in the Sector Table. This is due to the numbers from the Sector Table regarding bitumen production that for USA is 350,942 g while the one found in literature is 1,900 g.

The greatest contribution is due to material transportation in maintenance phase, while for material production in initial construction and maintenance phase is too small, which is not an expected value, and it is more logic to expect bigger values in these stages as from USA. The biggest expected value may be due to bitumen production. The graph representing environmental impacts for this parameter is presented in the Appendix.

In conclusion it can be clearly see that:

- Emissions are always bigger for the case using the default Sector Table.
- Emissions are always bigger for maintenance phase because of the 20 years considered, and within, the volumes and distances considered, which are all calculated for 20 years.
- Processes stage has the minor contribution of all, and this means that laying the pavement and the construction of the road itself is not too harmful to the environment as the other stages considered.
- In Initial Construction phase, emissions are always bigger for material production (except for NOx) stage, meaning that this stage is the most important. Just in this specific case study happens that the material to be transported is very little in respect to the travelled distances so material transportation stage has great influence in maintenance phase, not letting to the material production stage to be predominant in this phase.

4.4.2 2ND case study, estimated values vs default values in Sector Table

In this case comparing Figures 55 and 56, (that will be inserted again in this section as Figures 70 and 71 respectively, for convenience of the reader) which contains the environmental results using estimated values in the Sector Table and default values in the Sector Table respectively, is everything the same as it have been analyzed for the first case study (differences, greatest contributors and conclusions), the results when using default data remain always bigger and regarding total results these are not too much different because the functional unit is just 1 m of built pavement. In addition, a histogram is presented in Figure 72, for a better comprehension of the reader. The biggest differences are those for Water Consumption and hazardous wastes.

GRAND TOTALS

		Energy [MJ]	Water Consumption [kg]	CO_2 [kg] = GWP	NO_x [g]	PM_{10} [g]	SO_2 [g]
Initial Construction	Materials Production	3,665	44,562	212	913	2,611	531
	Materials Transportation	649	32	49	2,586	496	155
	Processes (Equipment)	58	3	4	116	14	8
Maintenance	Materials Production	2,152	15,947	135	489	981	336
	Materials Transportation	2,628	129	196	10,466	2,047	628
	Processes (Equipment)	23	1	2	56	4	4
Total	Materials Production	5,817	60,509	347	1,402	3,592	866
	Materials Transportation	3,277	161	245	13,051	2,543	783
	Processes (Equipment)	82	4	6	172	18	11
	Total	**9,176**	**60,675**	**598**	**14,625**	**6,154**	**1,661**

GRAND TOTALS

		CO [g]	Hg [g]	Pb [g]	RCRA Hazardous Waste Generated [kg]	Human Toxicity Potential (Cancer)	Human Toxicity Potential (Non-cancer)
Initial Construction	Materials Production	738	0	0	4	1,336	1,771,484
	Materials Transportation	215	0	0	5	14	17,072
	Processes (Equipment)	25	0	0	0	0	0
Maintenance	Materials Production	505	0	0	2	1,051	1,264,778
	Materials Transportation	872	0	0	19	56	69,103
	Processes (Equipment)	12	0	0	0	0	0
Total	Materials Production	1,242	0	1	5	2,387	3,036,262
	Materials Transportation	1,088	0	0	24	70	86,176
	Processes (Equipment)	37	0	0	0	0	0
	Total	**2,367**	**0**	**1**	**29**	**2,457**	**3,122,438**

Figure 70. Environmental impacts for 2nd case study with estimated values in Sector Table.

GRAND TOTALS

		Energy [MJ]	Water Consumption [kg]	CO_2 [kg] = GWP	NO_x [g]	PM_{10} [g]	SO_2 [g]
Initial Construction	Materials Production	8,481	8,029	548	1,891	3,307	1,562
	Materials Transportation	649	418	49	2,586	496	155
	Processes (Equipment)	58	38	4	116	14	8
Maintenance	Materials Production	5,284	5,642	333	1,290	1,296	1,124
	Materials Transportation	2,628	1,694	196	10,466	2,047	628
	Processes (Equipment)	23	15	2	56	4	4
Total	Materials Production	13,766	13,671	880	3,181	4,603	2,686
	Materials Transportation	3,277	2,112	245	13,051	2,543	783
	Processes (Equipment)	82	53	6	172	18	11
	Total	**17,124**	**15,836**	**1,132**	**16,404**	**7,165**	**3,480**

GRAND TOTALS

		CO [g]	Hg [g]	Pb [g]	RCRA Hazardous Waste Generated [kg]	Human Toxicity Potential (Cancer)	Human Toxicity Potential (Non-cancer)
Initial Construction	Materials Production	1,672	0	0	76	1,336	1,771,484
	Materials Transportation	215	0	0	5	14	17,072
	Processes (Equipment)	25	0	0	0	0	0
Maintenance	Materials Production	1,165	0	0	58	1,051	1,264,778
	Materials Transportation	872	0	0	19	56	69,103
	Processes (Equipment)	12	0	0	0	0	0
Total	Materials Production	2,837	0	1	134	2,387	3,036,262
	Materials Transportation	1,088	0	0	24	70	86,176
	Processes (Equipment)	37	0	0	0	0	0
	Total	**3,962**	**0**	**1**	**158**	**2,457**	**3,122,438**

Figure 71. Environmental impacts for 2nd case study with default values in Sector Table.

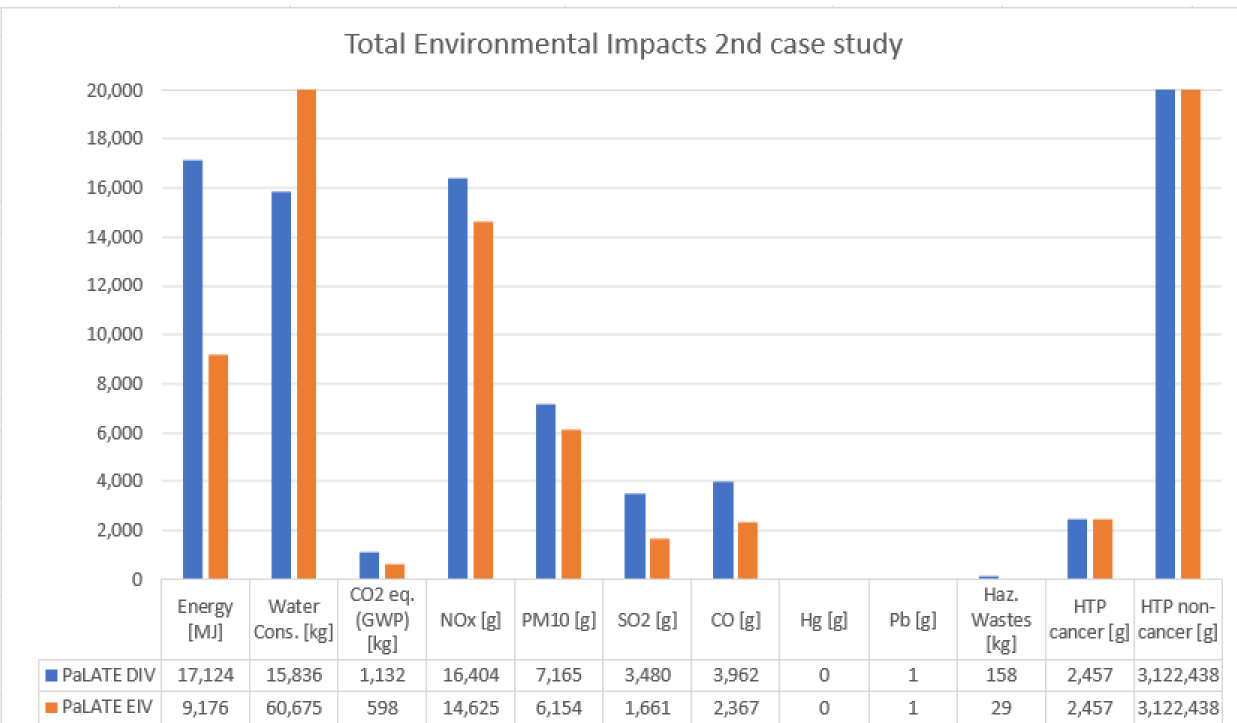


Figure 72. Total Environmental impacts comparing default and estimated input values in Sector Table – 2nd case study.

Where DIV stands for Default Input Values and EIV for Estimated Input Values.

About the histogram, is useful to clarify that HTP non-cancer emissions do not fit in the graph with that specific scale, that's why are both columns full, nevertheless, the numbers are written below the tag. The same, but the other way around, happens to Hg, Pb and Hazardous wastes emissions, where the numbers are too small for that specific scale used in the histogram.

On the other hand, the interesting of adding this case to this thesis is the fact that environmental results can be compared with another software called SimaPro which was originally used for this paper, and it is already proven that is a trustworthy software. The environmental impacts that were calculated with SimaPro 7.3 are GWP and GER and can be seen in Figure 57.

From the comparison between this two software, that is to say, comparing results for GER and GWP from Figures 55, 56 and 57, some conclusions can be made, and results are shown in Table 10.

				PaLATE	**SimaPro 7.3**
GER [MJ/m]	Initial Construction	Wearing	EIV	829	4350
			DIV	1873	
		Binder	EIV	981	5040
			DIV	2184	
		Base	EIV	1585	7750
			DIV	3398	
		Foundation	EIV	976	1390
			DIV	1733	
	Maintenance	All layers	EIV	4803	17100
			DIV	7935	
CO2 eq. [kg/m]	Initial Construction	Wearing	EIV	53	119
			DIV	119	
		Binder	EIV	63	142
			DIV	139	
		Base	EIV	102	233
			DIV	219	
		Foundation	EIV	46	87
			DIV	124	
	Maintenance	All layers	EIV	333	519
			DIV	531	

Table 11. comparison between PaLATE and SimaPro in GER and GWP.

It can be analyzed that:

- For Initial Construction phase, values for SimaPro are always bigger for GER, with exception of Foundation layer, where it is bigger for PaLATE using the default data.
- For Initial Construction phase, values for GWP emissions from SimaPro are really similar to that obtained with PaLATE when using the default Sector Table, with exception of the foundation layer, where it is bigger for PaLATE.
- For Maintenance phase, regarding GER, values for SimaPro are bigger than those of PaLATE.
- For Maintenance phase, regarding GWP, the result for SimaPro is similar to that obtained with PaLATE when using the default Sector Table.
- Environmental results from PaLATE with default data regarding Energy Consumption tend to be always 1/2 part of the result provided by SimaPro, with exception of the foundation layer in Initial Construction, where the result from PaLATE is bigger.
- Environmental results from PaLATE with estimated data regarding Energy Consumption tend to be always 1/4 part of the result provided by SimaPro, with exception of the foundation layer in Initial Construction, where the result from PaLATE is almost equal.
- Environmental results from PaLATE with default data regarding CO_2 eq. emissions tend to be always equal to the results provided by SimaPro, in fact for wearing, binder and base course results can be considered as equal, with exception of the foundation layer in Initial Construction, where the result from PaLATE is 1.5 times the result from SimaPro.
- Environmental results from PaLATE with European data regarding CO_2 eq. emissions tend to be always a 50 % smaller than results provided by SimaPro.

Hence, with all these results, in the following chapter a conclusion for the thesis will be present.

5 Conclusion

The aim of this study was to critically analyze the possibility of employing PaLATE in Europe, and to do so two case studies were analyzed, and main conclusions are presented in the following.

- The first case study from Sitalfa was developed in order to see and understand how PaLATE works completely. It was done to investigate all 12 outputs and investigate every worksheet that compounds PaLATE, once understood the whole software, it is possible to provide advantages, disadvantages and limitations from PaLATE.

Advantages

- It is user friendly. Meaning that it is easy to use, the user just needs to input data in the specific sheets and every calculous is made automatically.
- It has a clear way to express results, hence they are of easy interpretation.
- It has a good structure, due to the fact that is an excel file, and every calculous done can be followed.
- The vast majority of data used in PaLATE present its reference, providing to the user information about the data source, satisfying the characteristic of transparency named in chapter 3.
- It permits to the user to make changes in equipment, if it is not desired to use the machines offered by PaLATE. It also allows the user to select the desired material and process of maintenance from a vast array of options. Therefore, PaLATE can be globally used, complying with the characteristic of flexibility named in chapter 3.
- It is well organized and the user is easily guided. It permits to make the pavement analysis divided in phases such as: design, initial construction, maintenance and equipment, proving the characteristic of analytical structure named in chapter 3.
- As every calculous is made automatically, the user is able to change materials when desired, thus, if the user wishes to prove instantly how results would change using another material it is possible.

Disadvantages

- The user should work with US measurement units, which are uncomfortable to those accustomed to the SI units.
- Regarding the characteristic of transparency that PaLATE has, a criticize can be made by saying that there is information which is outdated and there are some webpages as reference that once you enter, indicates an error as if the information does not exist anymore.
- Continuing with the concept of outdated data, it can be said that the whole program is based on data which is outdated and needs to be actualized at least every year (for example emission factors which are calculated with prices from 1995). For doing so, it requires support from government and organizations, because a big bench of information is needed.
- The data that PaLATE contains is exceptionally for pavements in USA, so if the program needs to be used with all the respective data in another country of the world, as it was the case of this thesis, an exhaustive study should be made in order to change all the information that, in fact, is a lot. Hence, in this case it is a critical point to the flexibility characteristic.
- In the equipment sheet there are some machines offered with incomplete information, so, in case that the user wishes to use one of them, a little investigation should be done.

Limitations

- PaLATE doesn’t take into account the use phase of a road, which contributes to a large pack of emissions. But, fortunately, exists some other tools that considers the use phase, so a combination of tools can be done.
- Materials and processes offered for Initial Construction and Maintenance are just the ones offered by PaLATE, and any more can be added.
- Some specific processes cannot be taken into account. An example is the use of polymers added directly during the asphalt mixing phase and not previously mixed with bitumen according to standard preparation protocols.

- The second case study was useful to compare PaLATE results using the default input values and estimated input values in the Sector Table with those obtained from a trustworthy software called SimaPro 7.3, already used by professors from the Politecnico di Torino, and in this way provide a comparison. From this analysis it was seen that:
    - All results from PaLATE using the default Sector Table are much closer to that of SimaPro than results obtained using the estimated input values in the Sector Table. This aspect should be better analyzed in future studies.
    - The values used in the estimated Sector Table, in specific for bitumen sector, are much smaller than the default ones (USA).
    - PaLATE environmental impacts are always smaller and, in some cases, almost equal to that of SimaPro.

Beyond the precision of PaLATE results, it is strongly recommended to always use a tool of this kind applying an LCA methodology when it comes to pavements, in order to be in the "Environmental side" and contribute to the world from the engineering, more specific, from pavement constructions, since these are one of the most important civil constructions making available links between people. Being in the environmental side means contributing to the reduction of Global Warming Potential, ozone depletion and encourage sustainable practices. They are important tools for a project and principally for decision-makers.

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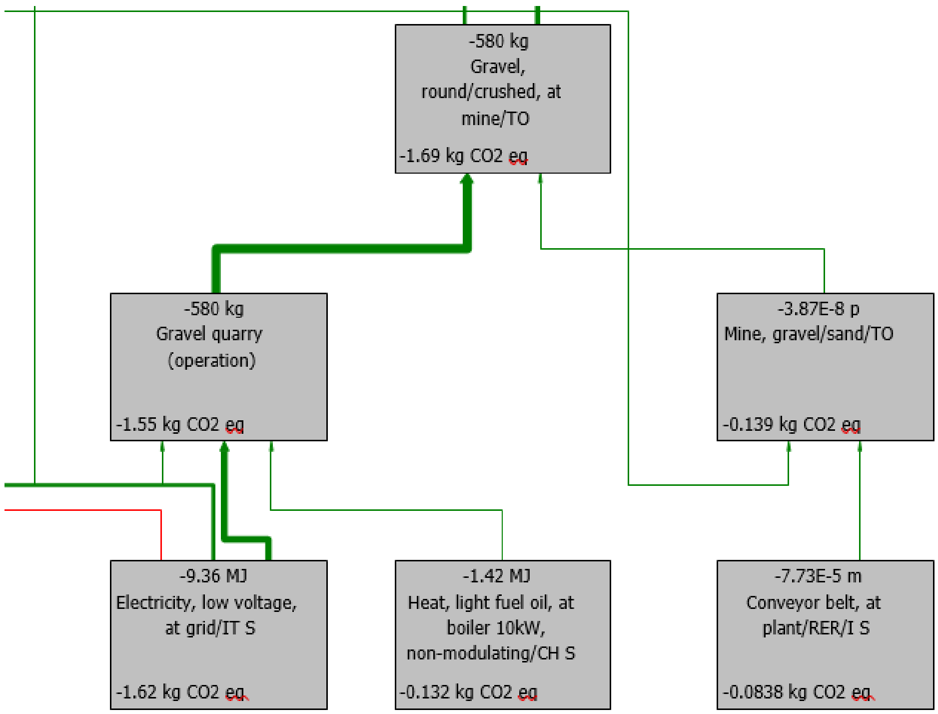
Appendix

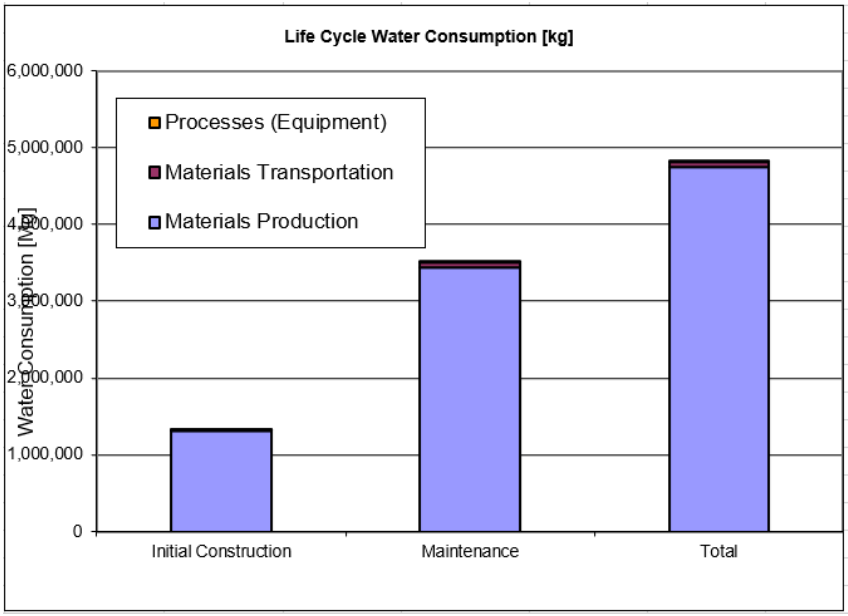
This Figure was extracted from the supplementary information of Blengini and Garbarino 2010. CO_2 equivalent emissions were extracted from here.



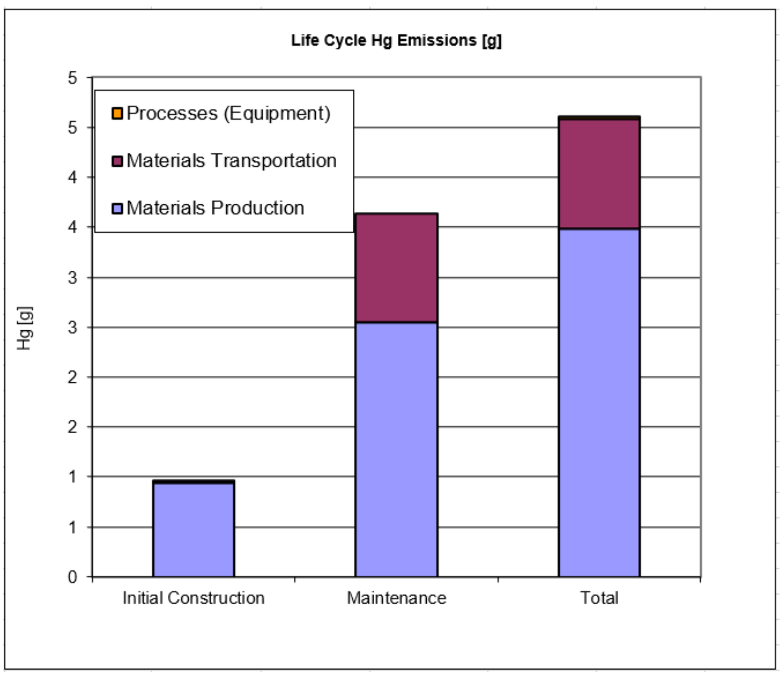
Data sheet for the Dynapac CC232HF Tandem Roller.

Engine	
Manufacturer	Deutz
Model	TD 2011 L04i
Type	Air cooled turbo diesel
Rated power	82 hp
Rated power	60 kW
Rated power @	2,800 rpm
Rated power (rating standard)	SAE J1995
Fuel tank capacity	120 l

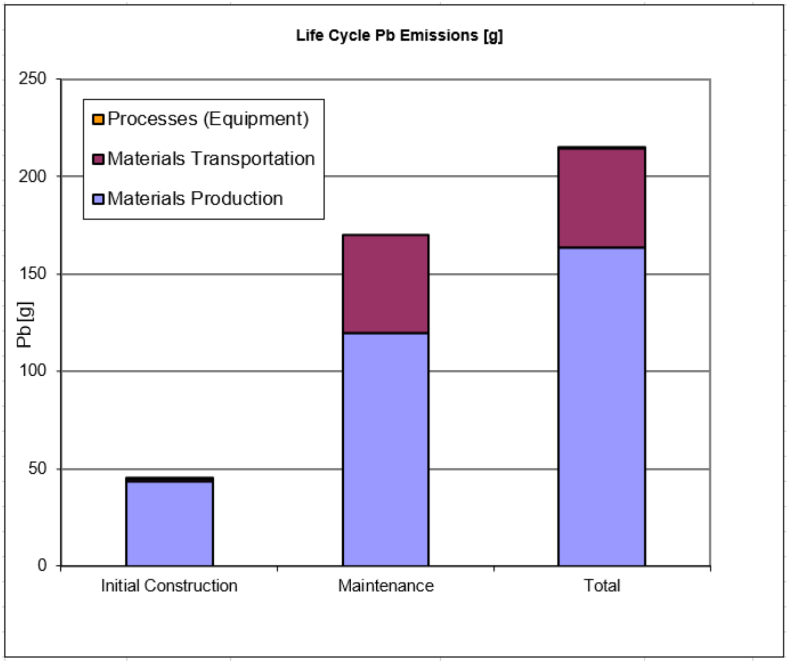
Graph with environmental results for Water Consumption



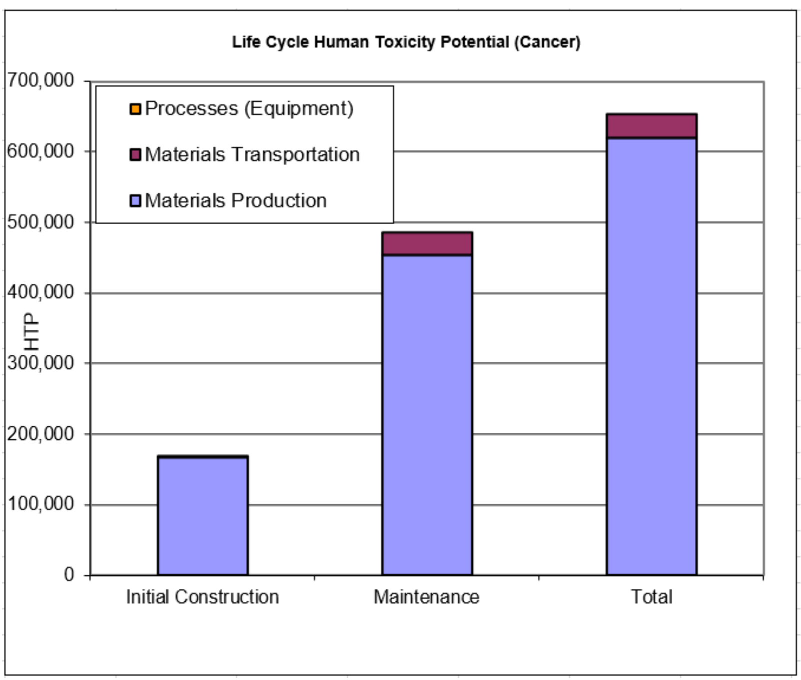
Graph with environmental results for Mercury



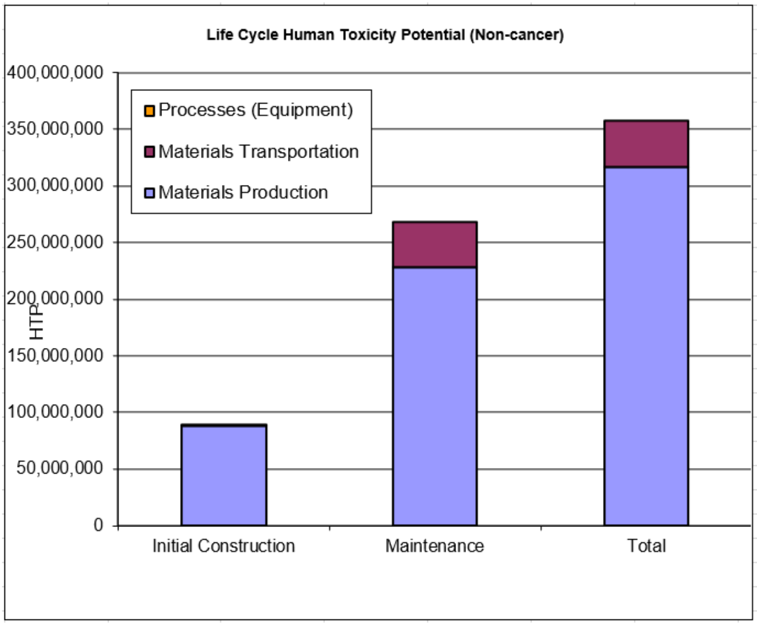
Graph with environmental results for Lead



Graph with environmental results for HTP cancer



Graph with environmental results for HTP non-cancer



Graph with environmental results for Hazardous Wastes