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Carbon Footprint Estimation in Road Construction: La Abundancia–Florencia Case Study

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Abstract: The environmental impact of road construction and rehabilitation can be associated with the increase of greenhouse gas (GHG) emissions, which are highly related to climate change. Consequently, departments of transportation have recently focused on the development and implementation of tools to evaluate the performance of projects and minimize GHG emissions. An example is the use of life cycle assessment (LCA) to analyze and quantify the environmental impact of a product, system, or process, from cradle to grave. In this regard, the present case study quantifies the carbon footprint associated with the construction of the La Abundancia–Florencia highway, located in the province of San Carlos in Costa Rica. The analysis is also intended to generate consciousness both in the public and private sectors on the environmental impacts of road construction. After an LCA study, it was determined that the construction of the hot mix asphalt (HMA) layer generates a carbon footprint of 65.8 kg of CO_2e per km of road. In addition, it was evident that HMA production generates the greatest environmental impact, among all the considered LCA production and construction stages, with a GHG contribution of 38% to 39% from bitumen only. Consequently, special attention to HMA production is required in order to minimize GHG emissions.

Keywords: carbon footprint; GHG; life cycle analysis; emissions; road; asphalt mixtures

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1. Introduction

Costa Rica has historically concerned itself with the environmental impact that is generated in the development of different activities, from the extraction of raw materials to the final disposal of finished products, and their contribution to greenhouse gas (GHG) emissions. To exemplify such considerations, the country is part of several international agreements, such as the United Nations Framework Convention on Climate Change (UNFCCC), signed on 13 June 1992 and in effect since July 1994 under Law No. 7414 [1]. It was also part of the 171 countries to sign the Paris Agreement, an international instrument that marks a milestone in the negotiations of the UNFCCC. More recently, the Carbon Neutral Program was signed, which aims to achieve carbon neutrality by the year 2100.

Also, it is important to note that in Costa Rica, one of the major sources of emissions is the energy sector (46% of total emissions) and the vast majority is attributed to the transport sector [2]. Due to this, the country has approved 117 energy laws since the 1950s. However, most of this legislation focuses on hydrocarbons and hydroelectricity [3], leaving aside the road infrastructure sector, which is affected by fuel consumption and the corresponding GHG emissions.

In the past few decades, population growth in Costa Rica has generated a significant increase in the demand for goods and services. This also generates more demand on mobility and hence an increase in traffic, which may accelerate pavement deterioration [4]. This has led to the need to have an efficient transport system, where in addition to promoting new non-motorized mobility alternatives and improving the quality of public transportation, it is very important for the system to have a road infrastructure in optimal condition. The sector where the road under study is located is an important area of agricultural production; therefore, in addition to the transport of people, there is a lot of transport of goods by land. Therefore, it is appropriate to have a good road infrastructure with the objective of satisfying the constant increases in demand. Furthermore, the selection of materials and processes that have low environmental footprints has gained popularity in recent years. Specifically, the evaluation of the environmental impact from road construction, rehabilitation, and operation has become a national interest, due to the greenhouse gases (GHGs) generated during such activities. Furthermore, the reduction of the environmental impact related to the road sector has become an international concern. In this sense, a systematic approach that has emerged to assess the environmental impact of pavements is the life cycle assessment (LCA) method. The LCA is a technique that can be used to analyze and quantify the environmental impact of a product, system, or process [5]. In addition, it provides a comprehensive approach to assess the environmental burden by examining the inputs and outputs throughout the life cycle of the product, system, or process, from obtaining raw material to the end of its useful life. In order to do so, a case study begins with an estimation of the partial carbon footprint of the product, and then continues to an LCA study. In a similar manner, several International Organization for Standardization (ISO) standards are used to establish the principles, requirements, and guidelines to quantify and communicate the carbon footprint (ISO 14067 [6]), and to regulate the LCA analysis (ISO 14040, ISO 14044, ISO 14020, ISO 14024, and ISO 14025 [7–11]). The stages of LCA are shown in Figure 1.

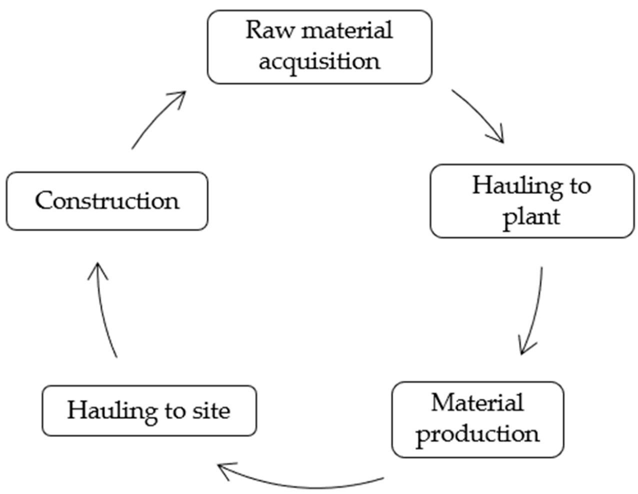

Figure 1. Stages for the life cycle assessment (LCA) used in the is study.

It is important to emphasize that the use of the LCA has additional benefits, since it allows characterization of the environmental performance of the construction road projects. This generates information that can be used by the construction companies to predict the performance of their projects and to evaluate the compliance with environmental requirements. Similarly, it allows the selection of optimal materials and construction processes, reducing the GHG emissions and permitting a more sustainable approach. As an example, the Illinois Tollway in the United States has used an LCA tool, developed by the University of Illinois at Urbana Champaign and other consulting partners, to characterize projects, to perform comparisons, and to measure progress in sustainable performance [12]. Through a case study, Yang and Al-Qadi [13] developed a tool to implement a probabilistic LCA to evaluate the environmental impact of airport pavement construction. The case study was the construction of runway 10R-28L at Chicago O'Hare International Airport. Another example was implemented in Michigan, where LCA was applied to estimate the carbon footprint of highway construction projects: the research provided a tool (Project Emission Estimator) that integrates data from construction management software to assess historical GHG emissions from highway construction projects [14]. An Indian project also developed a computer program toolkit (Carbon Footprint Calculator) to quantify the carbon footprints of various pavement systems [15].

When comparing the results of other LCA studies, some differences can be detected, which are presented in Table 1, where some similar studies made on pavement around the world are tabulated. These variations are mainly due to certain factors, such as the stages included in the analysis (material extraction, construction, transportation, operation, and end of life), the analyzed materials (conventional asphalt, polymer modified asphalt, recycled asphalt), and the project length (km). In addition, the distances of transport of the material from the production plant to the site, and the use of renewable energy can generate significant differences between projects. For example, Costa Rica uses renewably energy to supply electricity, so it is justified that, although a large percentage (23%) of energy is required to operate the plant components, the GHGs of the plant components are very small (1%).

Table 1. Some LCA studies on road pavements published in recent years.

Project Description		Analyzed Stages	Analyzed Materials	Total Emissions CO_2e (tons)	Reference
Location	**Length (km)**				
United States	4.7	Material production, Transportation, and Construction	C1. Bitumen, crushed aggregates	4064	[16]
			C2. Recycled material fly ash, and foundry sand	3255	
Sweden	1	Construction, Maintenance, and End of life	C1. Bitumen, aggregate	55.41	[17]
			C2. Asphalt, SBS polymer	47.23	
United States	2.4	Construction, Use, Maintenance, Rehabilitation, and End of life	C1. Concrete	3872	[18]
			C2. Asphalt	6730	
			C3. Overlay with asphalt	5598	
Australia	0.1	Raw material extraction, Construction, and Maintenance	C1. Asphalt, concrete, and limestone	180.6	[19]
			C2. Reused crushed rock and recycled concrete rubble	170.7	
Portugal	1	Extraction, Production, Transportation, and Construction	C1. Aggregates, bitumen, cement	121.86	[20]
			C2. Aggregates, bitumen, polymer modified	116.66	
			C3. Aggregates, bitumen	104.54	
			C4. Aggregates, recycled asphalt	100.59	
Malaysia	99.6 to 103.0	Rehabilitation	Cement, stone aggregate, quarry dust, and bitumen	3247	[21]
China	20	Mixture mixing, Transportation, Laying, Compacting, and Curing phase	Aggregate, bitumen, Portland cement	0.052	[22]
Italy	8.5	Construction and Maintenance	Aggregates, bitumen, cement	0.212	[23]

C* stands for Case and is numbered according to quantity of cases analyzed in the study. SBS is styrene–butadiene–styrene.

In this sense, Butt et al. analyzed two case studies, comparing conventional asphalt and polymer modified asphalt [17]. They found that the asphalt mixture containing conventional unmodified binder released 55.41 tons of CO_2e, and the modified mixture, 47.23 tons of CO_2e [17]. A slight difference is observed with respect to the results of the present study, which may be due to the fact that the maintenance and end of life stages were considered and the distances of material transport from the plant to the site were greater (50 km). Furthermore, it is worth noting that the modified asphalt with polymer generated lower emissions than conventional asphalt, which coincides with the results of this project. Similarly, it occurred with the results obtained by Araújo et al. with emissions of 116 tons of CO_2e for the modified asphalt with polymer and 121 tons of CO_2e emissions in the case of unmodified asphalt [20].

Furthermore, Biswas showed in his study the results of the quantification of the carbon footprint in the construction of a road using virgin materials and recycled materials (cases 1 and 2) [19]. In this case, 180 tons of CO_2e and 170 tons of CO_2e emissions were observed, respectively. However, the author explained that the maintenance operations over a lifetime of 100 years represented 79% of the total life cycle of GHG emissions, because they included the transport of materials, excavation activities, leveling, and paving [19]. This may explain the difference in results with respect to those of the present study, because the maintenance stage was not included in the analysis. Other studies that have recently been published are shown in Table 1.

After recognizing the importance of accounting for the environmental impact associated with road infrastructure, the National Laboratory of Materials and Structural Models of the University of Costa Rica (LanammeUCR) formalized a research line on sustainability in 2011. This included the establishment of the initiative called "Green Pavements" [23], which refers to a series of projects that focused on the use of waste materials in pavement structures and the reduction of energy required to produce hot mix asphalt (HMA) mixtures. More recently, a specific project on sustainability began in 2017, which seeks to promote its application in road infrastructure through a multi-criteria approach (environmental, economic, and social) to ensure efficient use of resources and optimize the conservation of the environment. For example, development of HMA mix designs including plastic components from recycled bottles, as well as other waste polymers, appears as a suitable option to dispose tons of waste materials [24–29].

In general, over the last decades Costa Rica has promoted the reduction of environmental impacts, something that has been branded at the international level as "Essential Costa Rica", which seeks to engage the national business sector to ensure the values of excellence, sustainability, innovation, social progress, and Costa Rican origin. Hence, the initiative of the present study aims at promoting the application of tools, such as LCA, that guarantee compliance with responsible practices and provide quality standards.

In this study, the construction of highway La Abundancia–Florencia, located in San Carlos (latitude 10.3351, longitude −84.4545, National Route 35, Costa Rica), was selected as the case study. The project has a length of 7 km, is four lanes (2 in each direction), and has a pavement structure comprised of: 300 mm of sub-base, 240 mm of cement treated base (CTB), 70 mm of HMA with neat asphalt, and 60 mm of polymer-modified HMA. Figure 2 shows a cross-sectional view of the roadway (the box indicates the lanes that are within scope of work).

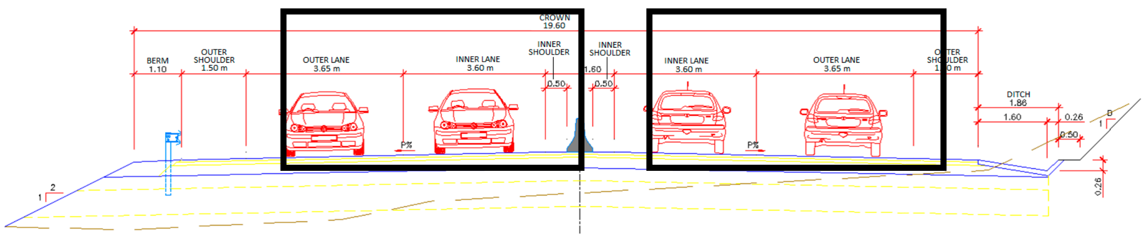

Figure 2. Cross-sectional view of roadway.

The specific project information was obtained by means of questionnaires applied to the pavement engineers of the construction companies responsible for the project. The information that could not be collected or measured was obtained using the Ecoinvent 3.0 database, which is a globally recognized LCI (life cycle inventory) database for a broad range of environmental studies.

The selection of the particular project as a case study was based on the importance of the corridor, and for being the first project in Costa Rica in which a modifying polymer was applied to the asphaltic binder. Furthermore, the project serves as a pilot plan for which the main objective is to quantify GHG emissions and to communicate to stakeholders (academia, construction companies, and the general public) the environmental impact of road projects.

2. Materials and Methods

The procedure used in this study was based on the methodologies proposed in ISO 14067 standards "Greenhouse gases—Carbon footprint of products—Requirements and guidelines for quantification and communication" and ISO 14040 "Environment management—Life cycle assessment—Principles and framework". Both standards propose four main steps for the analysis: goal and scope definition, lifecycle inventory analysis (LCI), life cycle impact assessment, and lifecycle interpretation (Figure 3). In the case of the analysis of carbon footprint of products (CFP), only climate change was considered. This change is just a variety of environmental impacts that can arise from the life cycle of a product, and in the case of LCA, several environmental impacts (depletion of resources, air, water, land, and ecosystems) are assessed throughout the analysis process.

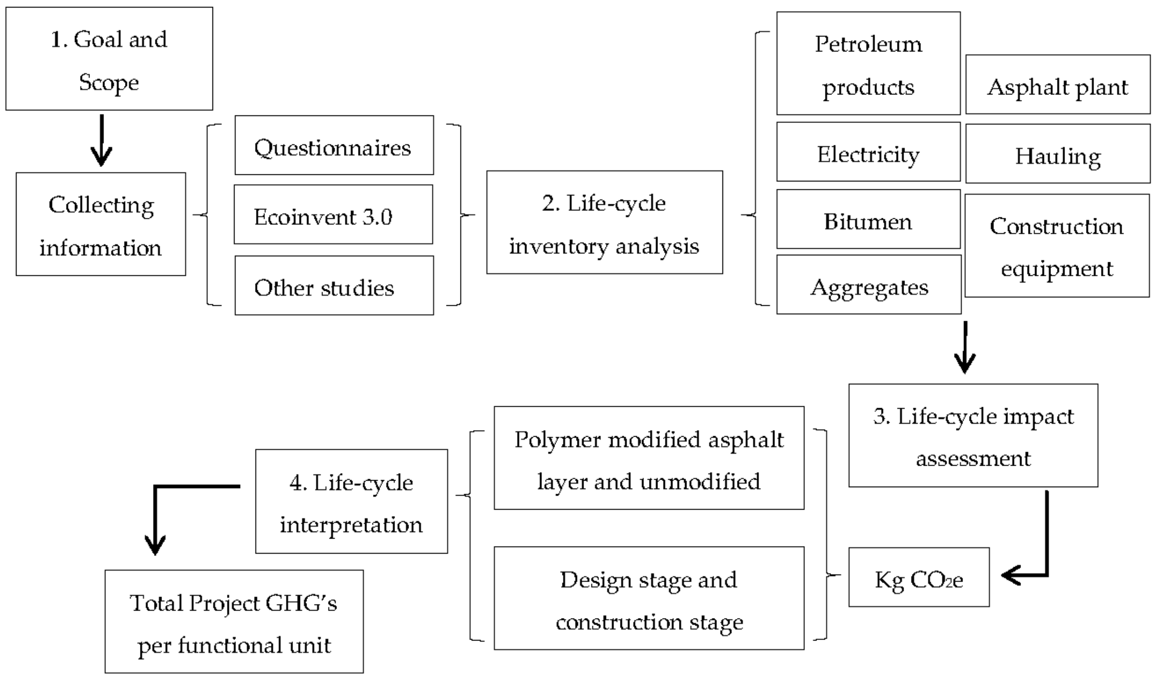

Figure 3. Steps for the development of the analysis.

Goal and Scope Definition: the evaluated product corresponds to the HMA and polymer-modified HMA mixtures for a new road, designed for a service life of 20 years without accounting for maintenance interventions, taking into account that the tack coat was not evaluated on this occasion, because the amount used (around 18 g/m^2) was not significant, so the impact would be below cut-off limits. In addition, the analyzed processes focused mainly on the extraction of raw material and construction of the HMA layers. Being the first study of this type in the region, it focused specifically on these stages since the information needed for the analysis could be collected or taken from databases, taking into account the particular conditions of the project, during the process of execution of the work. Therefore, for the subsequent stages (maintenance, waste disposals, end-of-life), there was no relevant information that would allow the obtaining of a real evaluation. Consequently, this analysis can be classified as a partial CFP since it did not consider the stages of operation, maintenance, use, and waste disposal of the project. As per ISO 14067, a partial CFP is defined as the "sum of greenhouse gas emissions and removals of one or more processes selected from a system, expressed as CO_2 equivalent (denoted here as CO_2e), and based on the relevant stages within the life cycle" [3]. According to ISO 14067, it is necessary to define a functional unit to provide a reference for which inputs and outputs are related. In the case of this study, the functional unit was one lane-km; thus the methodology was followed measuring the total impact of the GHGs in kg-CO_2 per lane-km, responding to the fact that it would allow an easier comparison with other studies, since it is a functional unit of common use.

Life Cycle Inventory: the data for the analysis was collected by two sources. First, data was collected by means of questionnaires distributed to the engineers/technicians of the company in charge of the construction. The collected information was related to the practices, techniques, equipment, and type of energy used during the analysis period. Second, the information for the systems prior to the construction process (i.e., extraction of aggregates, fuel processing) was obtained through databases specialized in the subject. The main database used for these processes was Ecoinvent 3.0. This tool was developed by the Swiss Center for Life Cycle Inventories. Although it is true that a large part of the Ecoinvent database is applicable to Europe, specific primary data were collected for each project and secondary data models were developed (for example, for petroleum fuels, electricity) to better characterize data to Costa Rica. Finally, to integrate the information from the questionnaires with that obtained from the database, the SimaPro 8.3.3 software that is specific to LCA was used for the modeling. SimaPro is a commercial LCA software that integrates with the Ecoinvent databases, is user-friendly, and contains all the software features needed to model unit processes. For conducting the study, each product required a separate evaluation process. The methodology for collecting information and processing the products considered for the analysis is summarized as follows:

(a) Petroleum products: when calculating the GHGs to produce the different petroleum products, a model developed by Yang et al. was used [30]. The evaluated impact included the extraction, transport, refinery, and transport processes to Puerto Moín, assuming that the product was transported by tanks from the Gulf Coast in the United States to Puerto Moín in Costa Rica, a distance of 2640 km.

(b) Electric energy: the generation of electric power depends on the sources used to produce electricity. These sources can be coal, oil, wind, and solar energy. However, in Costa Rica, electric power is renewable, using hydroelectric, geothermal, and wind power sources. Therefore, the GHGs emitted in Costa Rica related to energy production are among the lowest in the world [31].

(c) Asphalt: since two mix designs were used in the project, two types of asphalt were considered at the time of the analysis. The first was modeled as an AC-30 (PG 64-22). For the second, it was modeled as a polymer-modified asphalt (PMA). In this case the asphalt was mixed with a terpolymer and polyphosphoric acid. As the exact composition of these additives is patented, a generic styrene–butadiene–styrene (SBS) commonly used in PMA was assumed and modeled based on the Eurobitume life cycle inventory report [32]. It is also assumed that the SBS was 30% styrene and 70% butadiene and was mixed with the asphalt using an electric high shear stirrer. The PMA was classified as PG 76-22.

(d) Aggregates: the aggregates used were extracted from two riverbeds, one located 7 km and the other 15 km from the asphalt plant. The material was then transported and crushed (primary and secondary crushers), and finally washed. For both HMA mix designs, the same aggregates stockpiles were used: coarse (19 mm nominal maximum aggregate size (NMAS)), intermediate (16 mm NMAS), and fine aggregates. The production processes for the aggregates were modeled based on the models for crushing and production in Ecoinvent 3.0. Each of the sizes of aggregates used was analyzed separately, because the crushing and production was different for each case; due to this, the energy consumption of each product evaluated also varied. Therefore, an allocation procedure was used to distribute the total energy used in the system to each of the products, using the market value of the product supplied by the local producers. The allocation factor is presented in Table 2 and represents the relative environmental impact of the product to the average aggregate product produced in the facility.

(e) Asphalt plant: the production process in the asphalt plant was modeled using the information obtained from the questionnaires and supplementary data from the database Ecoinvent 3.0. The asphalt plant operates with diesel oil for the drying and heating processes. Similar to aggregates, the Ecoinvent 3.0 global model for asphalt production was used to estimate electricity and fuel usage for non-dryer-related plant components (28% of total energy usage in plant operations), which were then modeled with Costa Rican energy processes. The United States National Asphalt Pavement Association (NAPA) model was used to estimate the energy required for drying (78% of total energy), using a contractor survey to obtain the parameters for the NAPA model and the type of dryer fuel used, which required the mixing temperature and moisture content as inputs to the model [33]. An average temperature of 159 °C and a moisture content of 5% were used as inputs in the analysis.

(f) Hauling: the raw materials were transported in trucks to the plant and from the plant to the construction site. The environmental impacts per ton-km for a class size greater than 32 tons were determined. It should be noted that Costa Rica only complies with the EURO 1 standard requirements at this time, but in this study, it was assumed that the truck complied with the EURO 3 standards, since the EURO emissions standards target NOx, CO, and other gases that do not significantly affect GHGs. Thus, an increased emissions standard should not directly affect the GHGs. Furthermore, one-way trips were considered for hauling.

(g) Construction equipment: the specific equipment that operated in the construction of the analyzed section was determined from the questionnaires. For each type of equipment, the respective efficiency (L/h), speed (km/h), and weight (ton) was identified. The equipment consisted of one asphalt paver, two vibratory steel wheel rollers, one pneumatic tire roller, and one pavement sweeper.

Table 2. Allocation Factors for Aggregate Production by Type.

Aggregate Type	Allocation Factor
Large aggregate (76 mm)	1.49
Base/sub-base aggregate	1.93
Coarse aggregate	2.38
Intermediate aggregate	2.38
Fine aggregate	2.67

In addition to the aforementioned products, this study considered the stages of design and construction, which are detailed below.

i. Design stage: the production of materials and mixes required for the HMA layers in the pavement structure were considered. Due to this, the environmental impacts generated by the production process and transport to the asphalt plant were considered. The design of the HMA mixtures is shown in Table 3.

ii. Construction stage: in this stage the mobilization of equipment to the work site was considered, as well as their operation. In order to estimate the amount of fuel required by each equipment, the total operation time was estimated using the productivity rates defined in the NCHRP Report 744: Fuel usage factors in highway and bridge construction [34]. In addition to the fuel consumption data (L/h) obtained for each equipment, the hours of use and the corresponding environmental impacts for the equipment were obtained.

Table 3. Mix Design of Asphalt Concrete Layers.

Mix Design Hot Mix Asphalt (HMA) Layer	Category	Item	Design	Amount (Ton/Project)
Polymer-modified	Volumetric	Air voids	4.00%	-
		Voids in mineral aggregate (VMA)	14.75%	-
		Bulk specific gravity (Gmb)	2.403	-
		Maximum theoretical specific gravity (Gmm)	2.499	-
	Materials	Polymer-modified bitumen	5.10%	358
		Coarse aggregate	20.00%	1331
		Intermediate aggregate	15.00%	998
		Fine aggregate	65.00%	4327
Unmodified	Volumetric	Air voids	4.00%	-
		Voids in mineral aggregate (VMA)	14.72%	-
		Bulk specific gravity (Gmb)	2.397	-
		Maximum theoretical specific gravity (Gmm)	2.497	-
	Materials	AC-30	5.55%	453
		Coarse aggregate	27.00%	2082
		Intermediate aggregate	20.00%	1542
		Fine aggregate	53.00%	4086

3. Results and Discussion

In this CFP study, analyzing the La Abundancia–Florencia highway project, it was possible to evaluate the GHG emissions from the production and construction processes. The primary data (on processes, techniques, equipment, and fuel sources used) were obtained by means of questionnaires that requested information from the project contractors and the administration. The secondary data (information which could not be measured in the project) were acquired from the Ecoinvent LCI 3.0 database, and the application of LCA SimaPro 8.3.3.

The use of petroleum products (diesel, gasoline, and lubricants) was modeled first because they are used in several processes for the production of the paving material, construction, transportation, and vehicular operation. It is highlighted that Costa Rica does not extract crude oil or refined asphalt but imports them from other regions; since 2016 they have been imported from ten different countries, such as Venezuela, Panama, Belgium, Trinidad and Tobago, the United States, among others. The United States has five distinct Petroleum Administration for Defense Districts (PADD). In this study we assumed that all products exported to Costa Rica came from PADD3 (Gulf Coast), because over the last five years, out of the five PADDs, PADD3 has consistently exported the greatest volume of crude oil and petroleum products internationally [35].

Other factors included in the modeling were electricity and energy sources for production. In the case of Costa Rica, renewable energy is used to supply electricity, which positions the country as one of the countries with the lowest GHG emission from electric generation in the world.

The main components of the HMA mix, such as asphalt and aggregates, were also modeled. The GHG results for the polymer-modified asphalt were 11,369 kg of CO_2e per lane-km with 16,572 kg of CO_2e produced by the HMA plant, while the GHG results for the unmodified asphalt were 13,668 kg of CO_2e per lane-km with 19,285 kg of CO_2e generated by the HMA plant. The difference was associated with the structural design of the layers: the modified layer was thinner than the unmodified layer, and the optimum binder content for the modified HMA mixture was lower than that of the unmodified HMA mixture. In this sense, if the raw materials acquisition was lower, the GHG emissions would be lower as well. Similarly, if the HMA mix design incorporated recycled materials, the emissions could be greatly reduced.

Table 4 shows the impact of GHG or global warming as estimated based on the previously detailed information. The GHG emissions are reported in kilograms of equivalent carbon dioxide (kg CO_2e).

Table 4. Design Stage Greenhouse Gas (GHG) Emissions Results.

Category	Material	GHG (kg CO_2e/lane-km)
Polymer-modified HMA layer	Polymer-modified bitumen	11,369
	Coarse aggregate	313
	Intermediate aggregate	234
	Fine aggregate	1109
	HMA plant operation	16,572
	Polymer-modified asphalt (PMA) mix subtotal	29,596
Unmodified HMA layer	Neat bitumen	13,668
	Coarse aggregate	489
	Intermediate aggregate	362
	Fine aggregate	1047
	HMA plant operations	19,285
	Conventional mix subtotal	34,851
Total	Project subtotal	64,448

On the other hand, the total GHG emissions associated with the design and construction stages of the project under observation were estimated as well (Table 5). A summary of the GHG results for the project per functional unit is shown in Figure 4.

Table 5. Total Project GHGs per Functional Unit.

Category	Material	GHG (kg CO_2e/lane-km)
Design (Production)	Polymer-modified HMA layer	29,596
	Unmodified HMA layer	34,851
	Design subtotal	64,448
Construction	Construction subtotal	1333
Total	Project total	65,781

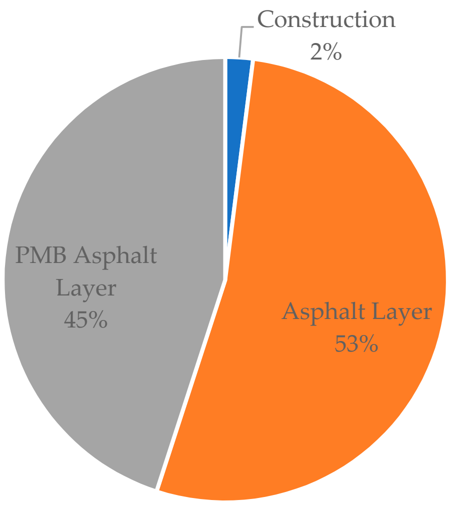

Figure 4. GHG distribution for all processes in road project by percentage.

On the other hand, the aggregates that were used in the design of the two HMA mixtures (with and without polymer) were blended from stockpiles with nominal maximum aggregate size (NMAS) of 19 mm (coarse aggregate), 16 mm (intermediate), and fines. The aggregate materials were modeled based on the processes for crushed gravel production in Ecoinvent 3.0. The activities included extraction, processing, and transportation. To customize the unit processes, the electricity and diesel from the default Ecoinvent 3.0 process were replaced with corresponding regional upstream processes. Likewise, it is important to note that each size may use unique amount of energy to be produced due to different crushing and processing requirements. This is an example of a multiple output process, where raw materials are inputted into a system, processed, and then outputted as various products.

In the case of the HMA plant, the amount of energy was estimated based on an energy model from NAPA that uses the mixing temperature and moisture content as inputs [36]. It was observed that the percentage of energy to operate the plant was very small (1%), compared to the typical percentage (23%). This was due to the use of renewable energy to generate electricity. To estimate the environmental impacts generated by each equipment during the on-site construction process, the fuel consumption and the hours corresponding to each individual equipment were quantified.

Finally, the results of the evaluation showed that the construction of the HMA mix layer generated a carbon footprint of 65.8 kg of CO_2e per lane-km. Of this amount, 2% was contributed by the construction of the roadway, while the remaining amount was contributed by the production processes required to obtain the materials needed for the roadway. The HMA plant operations contributed the largest portion of GHGs (approximately 55%), while asphalt production contributed the second largest (38–39%). On the other hand, transportation represented a smaller portion with a 5–6% GHG contribution. These results show that the production stage is the one that generates the greatest impact. For this reason, special attention must be given to determine possible approaches for GHG reductions.

When evaluating the results obtained with the international studies presented in Table 1, the results are significantly lower in most cases. However, by studying the methodologies that were used in these studies, it is possible to notice that the inventory analysis, the databases, and the software used in modeling vary from one to the other, so it is not possible to make a real comparison of one with the other. Considering the above and also taking into account the particular situation of Costa Rica to have renewable energy sources, it is possible to explain the differences found in the results of this analysis with those that have been made around the world.

4. Conclusions

As part of the project, it was possible to quantify the GHG emissions from the construction project of the La Abundancia–Florencia highway. In summary, the following data were obtained:

- The production and construction stages of the HMA layers generated a carbon footprint of 65.781 kg of CO_2e per lane-km.
- The production stage of polymer-modified HMA layer presented a contribution of 29.596 kg of CO_2e per lane-km, while the unmodified HMA layer contributed 34.851 kg of CO_2e per lane-km. The unmodified HMA layer was thicker and used more asphalt content.
- Aggregate production contributed approximately 6% of total GHGs, which was similar to the transport contribution (close to 6%).
- Considering production and construction stages only, the production stage contributed approximately 98% of the total GHGs in this project, while the construction stage contributed only 2% of the total GHGs.

Based on the results of the case study, the following conclusions and recommendations arise:

- The percentage of energy required to operate the components of the HMA plant is small (1%). This is because Costa Rica uses renewable energy to generate electricity. Therefore, GHG emissions due to electricity generation (kg of CO_2e per lane-km) in Costa Rica are low.
- It is recommended to increase the efficiency of asphalt mixing equipment and techniques of construction. The use of raw materials with lower emissions (e.g., Recycled Asphalt Pavement RAP) can result in reducing energy use and corresponding emissions.

Finally, several recommendations can be drawn from this study, in order to reduce GHG emissions. For example, since the production stage is the one with the higher carbon footprint, there are several points that can be improved to make the process more efficient, such as to define the most efficient route for material transportation, to check the conditions of the trucks to ensure that no additional gasoline is required, and so on. Given the fact that these recommendations seem simple, the authors consider that a deeper analysis must be performed to find better ways to reduce the carbon footprint related to pavement road construction.

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