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Primary Data Collection and Environmental/Energy Audit of Hot Mix Asphalt Production

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Abstract: The development of the road construction sector determines the consequences on consumption of non-renewable resources, energy expenditure and environmental pollution. Recent sustainability issues have highlighted the importance of efficient design and quality-oriented techniques in this sector, due to the huge amount of materials involved in construction and maintenance activities. Thus, it is necessary to properly quantify the environmental impacts of asphalt mixtures used for pavement construction, considering the whole life cycle of the products. Life cycle assessment (LCA) represents the most appropriate methodological framework for assessing the environmental burdens of a product, from raw material acquisition to final disposal. A common problem for LCA is the lack of primary data useful to calculate the product eco-profile, for a specific production process. In this context, there is generally limited reliable and accurate data regarding the asphalt plant production phase, which represents the most critical phase. Consequently, the aim of this paper is to perform an environmental/energy audit of an asphalt plant and, further, to collect and analyze primary data useful for the definition of the eco-profile of 1 metric ton of hot mix asphalt (HMA), following a "gate to gate" approach, including transport. The asphalt production is examined in a Sicilian batch-mix plant, representing one of the most commonly used for asphalt production in the Italian context. The results are of interest for asphalt mixture producers, contractors, transportation agencies and researchers seeking to quantify asphalt pavement environmental impacts in Italy, based on context-related foreground data.

Keywords: asphalt production; data collection; eco-profile; emissions; energy consumption

1. Introduction

Due to the volumes of materials involved in road and railway construction, the infrastructure sector implies significant consumption of natural resources and critical issues for the environment [1,2]. In the last decade, several researchers have been discussing the critical drawbacks of pavement road construction and maintenance activities related to traditional techniques and procedures, generally involving huge quantities of virgin materials and relevant consumption of fuels [3,4]. In parallel, modern and more efficient sustainable solutions, such as the use of Reclaimed Asphalt Pavements (RAP) or the production of Warm Mix Asphalt (WMA) have been proposed [5,6], for reducing energy and resource consumption, as well as the production of waste materials. As for mechanical performance assessment and comparison, in order to effectively understand sustainability benefits of different solutions and technologies, making reference to scientific, reliable and adaptable approaches is strategical. In this regard, Life Cycle Assessment (LCA) represents an exhaustive and reliable methodology for determining the environmental impacts of several kinds of products or processes, considering their entire life cycle and all the relevant involved elements. Indications for performing an LCA are provided by the International Organization for Standardization (ISO) in its 14040 series publications [7,8].

Applied to asphalt pavements, this analytical approach considers all the relevant phases of the product life cycle, including extraction of raw materials (aggregate and bitumen, mainly), production, construction, use and final recycling (or disposal), assuring a reliable assessment of its environmental impacts and sustainability. In order to understand the sustainability of the current practice and to evaluate possible improvements in processes and technologies, several studies have focused on LCA for pavement construction and maintenance activities in different countries [9–15]. Despite some positive results, the main issue of similar studies is that the related case studies rely on specifically optimized models that cannot be easily applied to other countries and scenarios [16] nor immediately compared [11]. Further, considering asphalt pavements, when "cradle to grave" analyses are performed, the information regarding the product stage is usually based on secondary data, not always perfectly fitting the evaluated geographical and economical context [4]. To overcome this limitation, research is currently oriented toward the development of more solid primary datasets on the materials and components used in road pavements, based on information provided by manufacturing companies [17]. Similar primary data is necessary for assessing, with significant accuracy, the eco-profiles of these materials and components. In this way, reliable and comprehensive datasets will be available for performing complete LCA studies in the construction sector. The primary data collection is indeed the basic step for preparing a reliable life cycle inventory of the product [18,19] taking into account all of the inputs and outputs from the specific manufacturing process. The elaboration of these inputs and outputs will allow a reliable determination of the production impact on several indicators, including greenhouse gas emissions and non-renewable energy use.

Similar research has already collected and analyzed interesting data related to the North American market [17,20] or the North European context [9,21–23], but only a few partial attempts are known for the Italian context [4,24,25], although their focus is not directly on the asphalt plant production phase. Furthermore, according to Santero et al. [11], regional specificity represents a key aspect for improving the reliability of LCAs.

In this regard, the main goals of this study are to perform a preliminary environmental/energy audit of a reference asphalt plant for the Italian context and to collect primary data related to the production process of a hot mix asphalt. The research investigated a particular batch-mix plant, located in Sicily, representative of the most common technology in Italy, to highlight all the materials and energy flows involved in the production process. Such an analysis may represent a useful reference base for asphalt plant owners interested in the evaluation of their plant efficiency and sustainability, for benchmarking purposes. Furthermore, the numerical evidence may be exploited by researchers and analysts aiming to base LCA complete analyses of asphalt pavements on direct primary data for production stages.

In the following paragraphs, first the LCA methodology is discussed, and then details on the data collection for the characterization of the product reference unit are provided and discussed.

2. Methodology

This research focused on the collection of primary data useful for the definition of the eco-profile of an asphalt mixture produced in a Sicilian plant, which is a relevant step according to the LCA methodology, in agreement with the ISO 14040 and ISO 14044 standards [7,8]. In general, LCAs are cradle-to-grave analyses of the environmental impact and include four basic steps:

1. Goal definition and scoping, required for identifying the boundaries of the life-cycle system, the functional unit, the target audience, etc.;
2. Inventory analysis, for the quantification of resource consumption, waste flows and emissions for functional units attributable to the different processes in the life cycle system;
3. Impact assessment, providing useful environmental characterizations, for a better and deeper understanding of the inventory data;

4. Interpretation, stating specific conclusions and recommendations strategical for improving the analysis or evidencing relevant aspects and critical issues for the decision makers.

In this research context, as stated, the analysis is stopped at the factory gates ("gate-to-gate"), as the aim is the collection of accurate primary data in a representative plant and its preliminary environmental/energy audit. In detail, the first two components of the general LCA framework are investigated, i.e., up to the data collection in the inventory analysis. According to the Product Category Rules (PCR) for asphalt mixtures of the National Asphalt Pavement Association [26], 1 metric ton of hot mix asphalt is considered as a declared unit (DU).

In order to have primary data for defining the eco-profile of a hot mix asphalt mixture produced in a representative plant for the Italian context, a batch-mix asphalt plant located in Sicily was selected as reference. The considered batch-mix plant may be considered as an "average technology" in the context of this study, since it is the most common technology for asphalt mixture production in Europe [27] and Italy [28]. Considering in particular Sicily, 26 of the 32 total working plants were batch-mix; among 693 total active asphalt plants in Italy, only 87 were continuous, thus the batch-mix plant represented more than 87% of the industry in 2010, with almost homogeneous situations in each region [28]. Since no significant modification of this scenario has happened in the last decade and no technological innovation is expected in the next 10 years, the technological characteristics as well as the operating conditions of the examined plant refer to an existing large-scale technology in Italy. Further, the recent evolution of the Italian asphalt market—characterized by few novel road projects and mostly by site-specific maintenance and rehabilitation projects—has strongly directed the technological choices towards the batch-mix solution, owing to its adaptability and versatility. Thus, the collected data are technology specific primary data that can be considered representative of the average technology in Italy according to the above percentage (technological representativeness) and can be applied for describing HMA plants located in all the Italian regions (geographical representativeness) in the short-medium term (time-related representativeness).

For determining the system boundaries, first, it is useful to consider the characteristics of a road pavement life cycle. In general, it is possible to identify 5 different phases in an infrastructure life cycle:

1. Material production (including raw material extraction, their transformation and transport to the production plant);
2. Construction (actual construction activities on field);
3. Use (energy consumption and environmental effects due to the actual utilization of the road);
4. Maintenance and rehabilitation (material production, transport, demolition activities, disposal of damaged materials);
5. End-of-life (considering all the final activities for recycling or disposal of the road residual components).

In accordance with the aim of the paper, the research is focused on the "product stage" processes performed in the asphalt plant only, and the related system boundaries can be identified considering the following phases included in the analysis: "A2 Transport" and "A3 Plant production", according to the definition provided in the PCR for asphalt mixtures [25].

3. The Asphalt Plant Studied

The study focused on the production of a traditional hot mix asphalt, using a batch mix plant. This plant was specifically selected since it represents one of the most common facilities used for asphalt mixture production and the resulting primary data may be considered as a benchmark for similar plants. The average production rate of the plant is around 65–75 ton/hour. During a single production cycle (60 seconds long) a batch of 1400 kg of asphalt mixture is produced, and the production temperature is around 165 °C.

In accordance with the system boundary of this research, defined in Section 2, it is reasonable to consider the following different processes for the entire production phase of the asphalt mixture (since the focus of the research is specifically limited to the energy/environmental audit of the batch-mix asphalt plant, production of raw materials is out of boundaries, while their transportation to the plant is included): aggregate transportation from extraction site to production plant; bitumen transportation to the production plant; aggregate movement for cold feeder loading; aggregate preliminary proportioning, blending and heating; dust filtering and filler recovering; aggregate screening and accurate proportioning; bitumen addition; mixing (aggregates, filler, bitumen) and asphalt concrete production. In terms of energy, the following elements are considered: aggregate transportation and storage; aggregate movement to the cold feeder; dryer drum heating; bitumen transportation and storage; bitumen heating; fuel transportation to the plant; energy consumption for equipment and plant working. In Figure 1, a simplified representation of the activities and components included in the production process considered is provided.

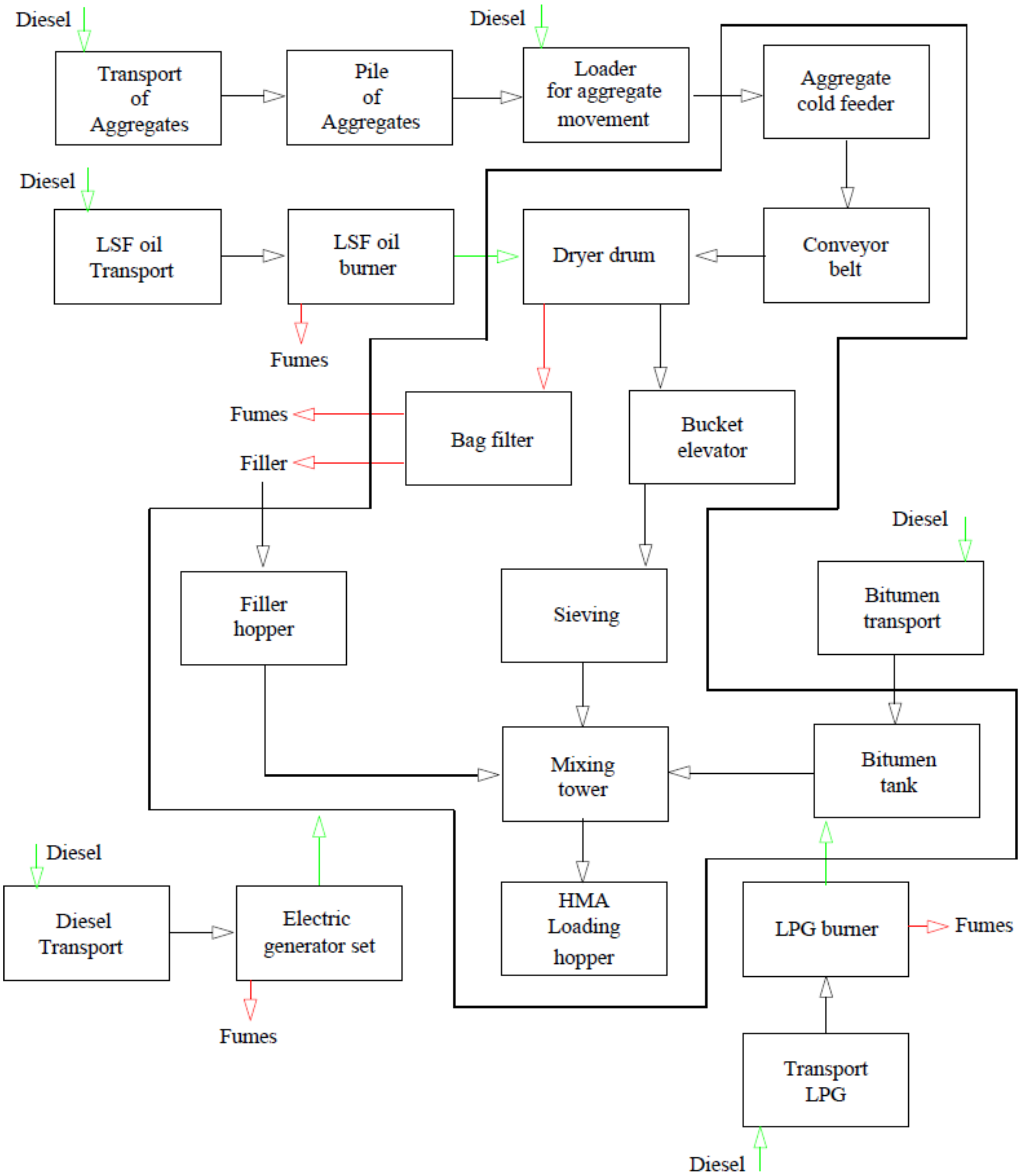

Figure 1. Reference scheme of the considered processes.

The current research analyzed a very commonly produced asphalt mixture for both maintenance and construction activities, suitable for binder course according to Italian standards and technical specifications, the mix design (mutual percentage of components) of which is presented in Table 1. In detail, this mix design requires a separate introduction of four dimensional classes of the same limestone aggregates ("Crushed stone 1.5", "Crushed stone 1.0", "Crushed stone 0.5", "Sand") together with a 50/70 pen grade bitumen; thus, all the processes related to the different classes of aggregate (such as internal transportation, proportioning, preliminary movements by means of conveyor belts, etc.) are considered four times.

Table 1. Asphalt mixture mix design.

Mixture Component	Min–Max Aggregate Diameter (mm)	Nature	%
Crushed stone 1.5	15–20	Limestone	30
Crushed stone 1.0	10–15	Limestone	12
Crushed stone 0.5	5–10	Limestone	10
Sand	0–6	Limestone	45
Filler	—	Limestone	3
Bitumen 50/70	—	—	5.5

It should be noted that the electricity for the entire plant machineries is produced by means of a diesel-based dedicated generating set. The drum mixer is heated using an LSF (Low Sulphur Fuel) oil burner, while the bitumen heating is performed by an LPG (Liquid Petroleum Gas) burner. Aggregate transportation from production site to the asphalt plant is performed using both Euro 4 and Euro 5 diesel trucks, as for bitumen, LPG and LSF oil transportations. Although all materials are produced in Sicily, the production sites for aggregates, bitumen, LSF oil, diesel and LPG are different and located at various distances from the asphalt plant. It should be underlined that, although there is a specific reference plant for each component/fuel, bitumen and diesel are alternatively acquired from two different sites, located in different areas in Sicily, thus both calculations are provided for these materials. The related transportation distances are reported in Table 2. Aggregate loading in the hoppers is performed by means of a diesel wheel loader, operating for all the four classes.

Table 2. Transportation distances for mixture components and fuels.

Element	Distance from Plant (km)
Limestone aggregates	35.0
Bitumen plant #1	152.0
Bitumen plant #2	193.0
LSF oil	152.0
LPG	76.6
Diesel plant #1	47.8
Diesel plant #2	123.0

4. Data Collection and Analysis

The acquired data and all the available information collected in plant have been properly processed to derive the inputs and outputs of the investigated asphalt mixture production process. First, the amount of virgin raw materials needed was computed. According to the optimized recipe of the considered mixture, the quantities of the raw materials involved in the process and related to a functional unit of asphalt concrete are listed in Table 3.

Data concerning energy consumption is also necessary. The overall plant electrical power is around 100 kW. The diesel consumption due to the generating set for the plant working is around 260 kg/day or 0.6 kg/cycle. The consumption of LSF oil for aggregate heating is around 5 ton/day or 12 kg/cycle. Considering LPG for bitumen heating, available measurements prove a consumption of around 375 kg/day or 0.9 kg/cycle. According to the effective production rates of the plant in a single hour, the various consumption values were related to a single cycle and, thus, to the DU. Further, consumption data were processed to determine the required energy for the DU; indeed, knowing the calorific value of each fuel (average values here assumed are in line with the typical calorific values for selected petroleum products [29,30]), the energies in MJ were calculated. All the related results on fuel consumption and energy needs are listed in Table 4. Consumption related to the loader activity for aggregate moving and feeder loading are also provided.

Table 3. Composition of a DU of asphalt mixture (1 ton), according to the mix-design.

Mixture Component	Nature	%	Kg
Crushed stone 1.5	Limestone	30	284
Crushed stone 1.0	Limestone	12	114
Crushed stone 0.5	Limestone	10	95
Sand	Limestone	45	427
Filler	Limestone	3	28
Bitumen 50/70	—	5.5	52

Table 4. Fuel consumption for production of a DU of asphalt mixture in the plant.

Fuel	Function	Consumption (kg)	Calorific Value (MJ/kg)	Energy (MJ)
Diesel	Electric generating set	0.44	42.70	18.78
Diesel	Loader activity	0.19	42.70	8.04
LSF oil	Drum mixer heating	8.42	46.05	387.89
LPG	Bitumen heating	0.63	41.02	25.91

Moreover, specific ammeters installed on the main plant components performed electric current measurements, during production. Knowing the electric current and the working voltage, the electricity power required for 1-hour working was calculated and, then, related to the DU, taking into account the number of cycles per hour and the mass of mixture produced per cycle. The measurements taken in terms of electric current and the related electric power and energy required for a DU are presented in Table 5, with a total energy request for all the plant equipment equal to 4.85 MJ. Owing to the nature of the electricity source, it should further be considered that the electricity generating set has a low efficiency (around 30%), as is common for similar equipment, with huge energy spent due to inefficiency.

Table 5. Electric performance of main plant components: electric current, electric power and energy needs.

Component	Electric Current (A)	Electric Power (kW)	Energy for DU	
			(kWh)	(MJ)
Main blower fan	67	15.4	0.21	0.75
Dryer drum	42	9.7	0.13	0.47
Bucket winch	37	8.5	0.11	0.41
Mixer	45	10.3	0.14	0.50
Drum fan	50	11.5	0.15	0.56
Aggregate pre-batchers (4 items)	16	14.7	0.20	0.71
Bucket elevators (2 items)	16	7.4	0.10	0.36
Other equipment	—	22.54	0.30	1.09
Total	**—**	**100.0**	**1.35**	**4.85**

Other specific emission measurements have enriched the data collection campaign. In detail, direct measures of emission in the atmosphere were performed, in two different locations of the plant: (1) dryer drum heater; (2) bitumen heater. In particular, Table 6 lists the measured values, reported in terms of dust, oxygen, nitrogen and sulphur oxides and, finally, carbon monoxide for the DU. References to the standards on which the measurements are based are provided in the table.

Table 6. Direct measures of emission in atmosphere in two plant locations for the DU.

	Dust		Oxygen (% v/v)	NO_X		SO_X		(CO) (% v/v)
	Con. (mg/Nm^3)	MF (g/h)		Con. (mg/Nm^3)	MF (g/h)	Con. (mg/Nm^3)	MF (g/h)	
Standard	UNI EN 13284-1:2003		ISO 12039:2001	Italian DM 25/08/2000				ISO 12039:2001
Dryer drum heater	0.116	1.935	0.233	0.505	8.437	0.402	6.705	0.046
Bitumen heater	0.0003	0.0001	0.100	0.290	0.083	0.0001	0.000	0.191

Con.: concentration; MF: mass flow; NO_X: nitrogen oxides; SO_x: sulphur oxides; CO: carbon monoxide.

Beyond fuel consumption and emission data, there is another issue to take into account in such an inventory analysis: material and fuel transportation from the production sites. As previously anticipated, the different components are produced in different plants in Sicily; thus, the distance travelled by each component of the mix design and each fuel was calculated, according to provider plant locations (Table 2). Considering transportation, the relevant value for the DU is calculated in "ton-kilometer" (t·km), representing the measure of the required mass of material (in tons) moved for the required distance (in km) for the DU. The acquired and processed data regarding transportation are provided in Table 7 (information regarding the bitumen and diesel plants have to be considered as alternative and not cumulative).

Table 7. Component and fuel production site distance from asphalt plant (km) and ton-kilometer values.

Component/Fuel	Distance from Asphalt Plant (km)	Mass for DU (kg)	Ton-Kilometers for DU (t·km)
Aggregates	35.0	947.9	33.18
Bitumen plant #1	152.0	52.1	7.92
Bitumen plant #2	193.0	52.1	10.06
Diesel plant #1	123.0	0.6	0.08
Diesel plant #2	47.8	0.6	0.03
LSF oil	152.0	8.4	1.28
LPG	76.6	0.6	0.05

5. Discussion and Research Perspectives

All the collected data are real data acquired at the production site, in a real working asphalt plant, representing the state of the art in Sicily and a reliable reference for the Italian context. It should be underlined that the collected and analyzed data are useful as foreground data for developing a dataset for Italy (and southern Italy, mainly) to be used also as a benchmark for similar plants and research. In fact, LCA of asphalt pavements in Italy thus far usually rely, for the product stage, on secondary data only, collected in foreign countries or derived from international databases. This data acquisition campaign and the derived elaborations are effectively representative of a real productive process and can be properly exploited in more comprehensive LCAs of asphalt pavements, assuring a reliable and up-to-date dataset of primary data, improving calculation of emission impacts, and overall solidness of considerations in all the relevant LCA elaborations.

Comparisons of the various inventory analyses among various studies available in the literature are not immediate, especially when related to different regions [11]. In terms of raw material needs for traditional mixtures (without RAP and additives), generally, the component rate and bitumen type and percentage are very similar. Transportation considerations are not so interesting, since they are particularly related to the site-specific configuration. However, the environmental/energy audit performed provided interesting results concerning performance of the plant in terms of required electricity and fuel consumption for drying/heating purposes. The total values results are in line with the existing literature for similar mixtures, despite specific differences in the geographical and technological representativeness of the various studies. Owing to the different contexts and variations in mixtures, there are some differences in the values, especially with foreign scenarios. The investigated plant (that relies on a diesel-based generator set) required a total process energy equal to 432.6 MJ/DU, whereas, e.g., in Mukherjee [17] the mean process energy for USA plants was 349.5 MJ/DU, while in Vidal et al. [15] the total energy request (for a Spanish plant combining continuous and batch-mix sub-plants, with the former widely dominant) was equal to 319.8 MJ/DU. For another Italian plant, the total request was quantified as 388.3 MJ/DU for energy [25]. However, it should be clarified that the differences may be related to different hypotheses and selection criteria of the various studies. First, the geographical representativeness of the data is fundamental. As highlighted in Section 2, the industry asset in the USA is different from the European one; further, in Mukherjee [17], despite the large sample and the outlier deletion, "no distinction is made for different kinds of asphalt plant technologies". Secondly, considering the European context, Vidal et al. [15] do not fully separate the primary data between the continuous and the batch-mix sub-plants. Further, also for European and Italian studies, the scenario may still be heterogeneous, involving different electricity sources or locally convenient fuels that may determine slight variations in plant operational characteristics and efficiency. In some cases, it is not practical to separate fuel uses based on the available information. However, despite the calculation hypotheses, the acceptable consistency in the Italian data is valuable and underlines the role of regional specificity.

The primary data collected for the environmental/energy audit of the plant may be used also for a preliminary discussion of current common practice. It appears that huge quantities of virgin materials are required for producing the DU, and further, the transportation of materials and fuels may also play a fundamental role. The availability of adequate materials closer to the production plant absolutely represents a strategical benefit from an environmental point of view, even due to the reduction in truck travelling distances. Moreover, industry managers, based on this evidence, should move towards more sustainable solutions; they should avoid acquiring raw materials and fuels from plants further away, only relying on their related direct costs, as the eventual environmental drawbacks require significant attention and consideration. The definition of stricter and stronger regulations and policies for preferring locally available and recycled materials would be very effective for increasing the sustainability of the road industry and adopting different mix-designs that may assure equivalent performance in practice. The analysis of the collected data may speed up the definition process of novel mixtures, including innovative, alternative and more easily available products, to limit not only direct transportation costs, but also related emissions and environmental impacts. From this perspective, for instance, the growing trend of recycling asphalt pavement may be considered as more and more convenient, when mixtures including RAP (Reclaimed Asphalt Pavement) are produced in plants directly located on construction sites. Such a choice, can reduce raw material consumption, an issue related to pavement waste disposal, and, further, even reduce impacts related to material transportation: a RAP content of 25% as a substitution of virgin material in asphalt mixture reduces total lifecycle greenhouse gas emissions by 10% [31]. According to the circular economy view, relevant attention should also be paid to construction and demolition waste from roads, which are proved [32] to represent the largest percentage (hundreds of million tons annually, only in EU) and grow faster than other wastes due to the relative short lifetime of roads compared to buildings [33]. In fact, many studies [32,34] suggest that roads are a major driver of resource use, and thus, it is necessary to develop effective recycling techniques and apply policies for environmentally sustainable management of natural resources. Although RAP technology is widely used in various parts of the world, in Italy, so far, the usage or RAP is quite limited (last position in Europe for the RAP reuse): less than 25% is reused on average [35].

Other significant information derives from the analysis of fuel consumption. In general, up to 10 kg of fuel are burned per each ton of HMA mixture produced in the plant, and it is evident how LSF oil may determine the strongest environmental consequences. In this regard, more sustainable production technologies requiring lower mixing temperatures would determine significant savings from this point of view. For example, warm mix asphalt [24,36], which may assure production of equally reliable and adequate mixtures at sensibly lower temperature (around 120 ÷ 135 °C), may represent a more adequate solution when sustainability issues are taken into account. This choice determines remarkable savings in terms of emissions and impacts due to fuel consumption needs for heating aggregates and bitumen, which require relevant contributions in terms of mass and, thus, energy for the DU. Future steps of the research will primarily consist of a more extensive primary data collection campaign, with direct measurements/surveys on other similar plants in Italy. The future parallel results will increase reliability and accuracy of the related dataset and may also be used for statistical analysis and considerations, as already performed for other geographical and productive contexts. Further, relying on this foreground data, overall LCA for asphalt pavements focusing on the entire life cycle will be performed, even considering different production and construction technologies, for sustainability rankings.

6. Conclusions

In this paper, an environmental/energy audit of an Italian batch-mix asphalt plant was performed. In detail, the authors analyzed the production technology and processes in the plant and collected specific reliable primary data in the field. The analysis investigated the inputs and outputs of the production of a traditional HMA mixture, for road pavement construction, to be used for eco-profile calculations and performing more reliable LCAs. After the identification of scope, functional unit and system boundary, based on the acquired data, the materials involved, energy consumption and direct emissions for each different process performed in the plant before practical use were quantified in the field.

The study allowed primary data to be collected that may be used for the calculation of the eco-profile of a traditional HMA mixture, according to the most common production procedure; in particular, such specific data, directly derived from plant measurements and analysis of the productive cycle, can represent a reliable reference and numerical base on which carry out "from cradle to grave" LCAs in the Italian context. Such a solution will provide acceptable and applicable results for Italian stakeholders and decision makers.

Moreover, the provided dataset may serve as a benchmark for other plants and similar research; indeed, these data can be compared with those related to different or modified plant systems and productive procedures for the definition of long-term strategies aiming to improve the entire production process. Similar comparisons may evidence the most critical phases and processes characterized by the major impacts on the environment, providing evidence on solutions that may reduce their influence. These comparisons may drive through more sustainable and efficient technologies and solutions, determining reduced emissions and impacts on environments. Finally, in further steps of this research, it would be worthy to (1) deepen the analysis by completing the LCA and calculating the eco-profile and environmental impacts of a functional unit according to PCR; (2) elaborate the eco-profile of a similar mixture produced in other plants, with different processes, technologies and energy resources.

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References

1. Butt, A.A.; Mirzadeh, I.; Toller, S.; Birgisson, B. Life Cycle Assessment Framework for Asphalt Pavements: Methods to Calculate and Allocate Energy of Binder and Additives. *Int. J. Pavement Eng.* **2014**, *15*, 290–302. [CrossRef]

2. Airò Farulla, C.; Celauro, B.; Celauro, C.; Rosone, M. Field test of lime treatment of clayey soils for railways and road works. *Ing. Ferrov.* **2014**, *69*, 729–752.
3. Lee, J.; Edil, T.; Tinjum, J.; Benson, C. Quantitative assessment of environmental and economic benefits of recycled materials in highway construction. *Transp. Res. Rec. J. Transp. Res. Board* **2010**. [CrossRef]
4. Giani, M.I.; Dotelli, G.; Brandini, N.; Zampori, L. Comparative life cycle assessment of asphalt pavements using reclaimed asphalt, warm mix technology and cold in-place recycling. *Resour. Conserv. Recycl.* **2015**, *104*, 224–238. [CrossRef]
5. Farooq, M.A.; Mir, M.S. Use of Reclaimed Asphalt Pavement (RAP) in Warm Mix Asphalt (WMA) Pavements: A Review. *Innov. Infrastruct. Solut.* **2017**, *2*, 10. [CrossRef]
6. Plati, C. Sustainability Factors in Pavement Materials, Design, and Preservation Strategies: A Literature Review. *Constr. Build. Mater.* **2019**, *211*, 539–555. [CrossRef]
7. International Organization for Standardization. *Environmental Management—Life Cycle Assessment—Principles and Framework*; ISO 14040_2006(E); IOS: Geneva, Switzerland, 2006.
8. International Organization for Standardization. *Environmental Management—Life Cycle Assessment—Requirements and Guidelines*; ISO 14044_2006(E); IOS: Geneva, Switzerland, 2006.
9. Hakkinen, T.; Makela, K. *Environmental Adaptation of Concrete—Environmental Impact of Concrete and Asphalt Pavements*; VTT Research Notes; Espoo: Helsinki, Finland, 1996.
10. Horvart, A.; Hendrickson, C. Comparison of Environmental Implications of Asphalt and Steel-Reinforced Concrete Pavements. *Transp. Res. Rec.* **1998**, *1626*, 105–113.
11. Santero, N.J.; Masanet, E.; Horvart, A. Life-Cycle Assessment of Pavements. Part I: Critical Review. *Resour. Conserv. Recycl.* **2011**, *55*, 801–809. [CrossRef]
12. Santero, N.J.; Masanet, E.; Horvart, A. Life-Cycle Assessment of Pavements. Part II: Filling the Research Gaps. *Resour. Conserv. Recycl.* **2011**, *55*, 810–818. [CrossRef]
13. Celauro, C.; Corriere, F.; Guerrieri, M.; Lo Casto, B. Environmentally appraising different pavement and construction scenarios: A comparative analysis for a typical local road. *Transp. Res. Part D Transp. Environ.* **2015**, *34*, 41–51. [CrossRef]
14. Celauro, C.; Corriere, F.; Guerrieri, M.; Lo Casto, B.; Rizzo, A. Environmental Analysis of Different Construction Techniques and Maintenance Activities for a Typical Local Road. *J. Clean. Prod.* **2017**, *142*, 3482–3489. [CrossRef]
15. Vidal, R.; Moliner, E.; Martinez, G.; Rubio, M.C. Life cycle assessment of hot mix asphalt and zeolite-based warm mix asphalt with reclaimed asphalt pavement. *Resour. Conserv. Recycl.* **2013**, *74*, 101–114. [CrossRef]
16. Huang, Y.; Bird, R.; Bell, M. A Comparative Study of the Emissions by Road Maintenance Works and the Disrupted Traffic Using Life Cycle Assessment and Micro-Simulation. *Transp. Res. Part D* **2009**, *14*, 197–204. [CrossRef]
17. Mukherjee, A. Life Cycle Assessment of Asphalt Mixtures in Support of an Environmental Product Declaration. ISO 14040 Compliant Life Cycle Assessment Study Supporting the National Asphalt Pavement Association, EPD Program for North American Asphalt Mixtures. 2016. Available online: https://www.asphaltpavement.org/PDFs/EPD_Program/LCA_final.pdf (accessed on 14 October 2019).
18. Stripple, H. *Life Cycle Inventory of Asphalt Pavements*; IVL Swedish Environmental Research Institute Ltd.: Stockholm, Sweden, 2005.
19. Tumminia, G.; Guarino, F.; Longo, S.; Ferraro, M.; Cellura, M.; Antonucci, A. Life cycle energy performances and environmental impacts of a prefabricated building module. *Renew. Sustain. Energy Rev.* **2018**, *92*, 272–283. [CrossRef]
20. Mukherjee, A.; Dylla, H. Challenges to using environmental product declarations in communicating LCA results: The case of the asphalt industry. *Transp. Res. Rec. J. Transp. Res. Rec.* **2017**, *2639*, 84–92. [CrossRef]
21. Stripple, H. *Life Cycle Assessment of Road: A Pilot Study for Inventory Analysis*; IVL RAPPORT, 1210; The National Academies of Sciences, Engineering, and Medicine: Washington, DC, USA, 2001.
22. Mroueh, U.M.; Eskola, P.; Laine-Ylijoki, J.; Wellman, K.; Makela, W.; Juvankoski, M.; Ruotoistenmaki, A. *Life Cycle Assessment of Road Construction*; Tielaitoksen selvityksia: Helsinky, Finland, 2000. Available online: https://www.researchgate.net/publication/237683954_Life_cycle_assessment_of_road_construction (accessed on 14 October 2019).

23. Yang, R.; Kang, S.; Ozer, H.; Al-Qadi, I.L. Environmental and economic analyses of recycled asphalt concrete mixtures based on material production and potential performance. *Resour. Conserv. Recycl.* **2015**, *104*, 141–151. [CrossRef]
24. Gulotta, T.M.; Mistretta, M.; Praticò, F.G. A life cycle scenario analysis of different pavement technologies for urban roads. *Sci. Total Environ.* **2019**, *673*, 585–593. [CrossRef]
25. Farina, A.; Zanetti, M.C.; Santagata, E.; Blengini, G.A. Life cycle assessment applied to bituminous mixtures containing recycled materials: Crumb rubber and reclaimed asphalt pavement. *Resour. Conserv. Recycl.* **2017**, *117*, 204–212. [CrossRef]
26. NAPA. *Product Category Rules (PCR) for Asphalt Mixtures*; National Asphalt Paving Association Lanham: Greenbelt, MD, USA, 2017.
27. NAPA; EAPA. *The Asphalt Paving Industry—A Global Perspective: Production, Use, properties, and Occupational Exposure Reduction Technologies and Trends*, 2nd ed.; National Asphalt Paving Association and European Asphalt Pavement Association: Lanham, MD, USA, 2011; ISBN 0-914313-06-1.
28. Ravaioli, S. Impianti d'asfalto: Considerazioni storico-economiche e statistiche del settore. *Rass. Del Bitume* **2010**, *66*, 33–39. (In Italian)
29. MacLeay, I. *Digest of United Kingdom Energy Statistics 2010*; The Stationery Office: London, UK, 2010.
30. IEA. *Energy Statistics Manual*; OECD Publishing: Paris, France, 2004.
31. NAPA. *Black and Green: Sustainable Asphalt, Now and Tomorrow*; Special Report Number 200; National Asphalt Paving Association: Lanham, MD, USA, 2009.
32. Wiedenhofer, D.; Steinberger, J.K.; Eisenmenger, N.; Haas, W. Maintenance and Expansion: Modeling Material Stocks and Flows for Residential Buildings and Transportation Networks in the EU25. *J. Ind. Ecol.* **2015**, *19*, 538–551. [CrossRef]
33. Han, J.; Chen, W.-Q.; Zhang, L.; Liu, G. Uncovering the Spatiotemporal Dynamics of Urban Infrastructure Development: A High Spatial Resolution Material Stock and Flow Analysis. *Environ. Sci. Technol.* **2018**, *52*, 12122–12132. [CrossRef] [PubMed]
34. Miatto, A.; Schandl, H.; Wiedenhofer, D.; Krausmann, F.; Tanikawa, H. Modeling material flows and stocks of the road network in the United States 1905–2015. *Resour. Conserv. Recycl.* **2017**, *127*, 168–178. [CrossRef]
35. Ravaioli, S. DM 69/18—End of Waste per il fresato d'asfalto: Vera opportunità o occasione mancata? *Rass. Del Bitume* **2019**, *91*, 19–26. (In Italian)
36. Zaumanis, M. Warm Mix Asphalt. In *Climate Change, Energy, Sustainability and Pavements*; Gopalakrishnan, K., Steyn, W., Harvey, J., Eds.; Green Energy and Technology; Springer: Berlin/Heidelberg, Germany, 2014.