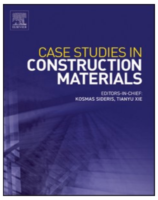
Case Studies in Construction Materials 21 (2024) e03669

Contents lists available at ScienceDirect

Case Studies in Construction Materials

journal homepage: www.elsevier.com/locate/cscm



Case study of a batch asphalt mix plant: Energy consumption and emission allocation based on primary data

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ARTICLE INFO

Keywords:
asphalt batch mix plant
asphalt mixture production
energy consumption
energy monitoring
global warming potential
life cycle assessment
manufacturing phase
sustainable infrastructure

ABSTRACT

Determining the environmental impact of asphalt mixtures is crucial for sustainable infrastructure development. A dominant factor in the ecological performance of the building material is the heating process in the dryer drum of an asphalt mix plant. Since it depends on various parameters, large scattering can be observed. While most Product Category Rules (PCRs) only consider the mean consumption over a whole production year in Module A3 according EN 15804, and consequently assign the same value to each ton asphalt mixture produced, the advantages of some asphalt mix designs remain unconsidered. Based on primary data of a batch asphalt mix plant, this case study investigated the impact of production amount, asphalt mixture temperature, number of dryer drum starts and the addition of reclaimed asphalt pavement (RAP) on the energy consumption of asphalt mixture production. By applying Linear Discriminant Analysis (LDA), it was demonstrated that it is not possible to precisely determine the energy consumption in the dryer drum based on the available data. Thus, further parameters are necessary for a fully-fledged prediction model. Nevertheless, the finding of this study showed the significant impact of the daily production volume, which results in 22 % less fuel consumption for high production volumes compared to low volumes. When the production temperature is lowered from 186 °C to 162 °C, further fuel savings of up to 9 % can be achieved. Considering the Global Warming Potential (GWP), the highest saving potential (27 %) in the drying and heating process can be achieved by operating the dryer exclusively with natural gas instead of heating oil.

1. Introduction

Climate change stands as one of humanity's most urgent challenges in the present era. It denotes prolonged alterations in worldwide and regional weather patterns and temperatures, chiefly propelled by human endeavors like the combustion of fossil fuels and reliance on non-renewable resources. The ramifications of climate change extend broadly, encompassing escalating sea levels,

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Abbreviations: EPD, Environmental Product Declaration; EDA, Exploratory Data Analysis; GWP, Global Warming Potential; GPP, Green Public Procurement; IQR, Interquartile Range; LCA, Life Cycle Assessment; LDA, Linear Discriminant Analysis; LHV, Lower Heating Value; PmB, Polymer-modified Bitumen; PCR, Product Category Rule; RAP, Reclaimed Asphalt Pavement.

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https://doi.org/10.1016/j.cscm.2024.e03669
Received 3 July 2024; Received in revised form 14 August 2024; Accepted 21 August 2024

more frequent and severe weather events, and disturbances to ecosystems [1]. To address climate change effectively, the actions of every individual are crucial - whether private persons or large corporations. However, to enable sustainable decision making, a consisting assessment of the environmental impacts of various actions is crucial for prioritizing effective strategies to mitigate climate change [2].

Green public procurement (GPP) is gaining worldwide momentum and is seen as a promising leverage to support sustainable development [3–5]. It is a voluntary instrument for boosting a resource-efficient economy and relies on verifiable, justifiable and ambitious environmental criteria for products and services that consider the whole life cycle on a scientific evidence base [2]. In order to compare the environmental impacts of products or services, GPP relies on a combination of life cycle assessment (LCA) and ecolabels [6,7]. While the LCA, which is standardized in ISO 14040 [8] and ISO 14044 [9], is used to estimate the environmental impacts of a product throughout its life cycle, labeling is used to provide a quick and easy comparison of results. One of the most promising ecolabels are type III environmental declarations, also known as environmental product declarations (EPDs), which are standardized in ISO 14025 [10] and ISO 21930 [11]. The idea behind EPDs is to group products with the same or similar usage into categories, for which specific regulations regarding the conduction of LCA, so called product category rules (PCRs), are set. Consequently, the life cycle of each product can be considered more individually and the room for interpretation shrinks to obtain more comparable results of the environmental impacts of products. Program operators are responsible for the development of a PCR. They are also supervising and coordinating the type III environmental declaration program and, finally, verify the EPD [12]. Since numerous program operators exist already and there are no guidelines regarding the coordination of such PCRs among each other, the comparability of the resulting EPDs remains in doubt if they are not harmonized.

Also in the asphalt pavement sector, various program operators have already published specific PCRs of asphalt pavements [13–18]. Since there is still no core-PCR, corresponding differences can be observed regarding impact categories, cut-off criteria, underlying databases, allocation methods and other LCA-based assumptions [4,6,19–21]. A further distinction in the respective PCRs can be found in the life cycle stages to be considered, including the manufacturing phase, Module A3 according to EN 15804 [22]. This module includes the production of auxiliary and operating materials or pre-products, the manufacturing of products or co-products and the manufacturing of packaging [22]. Probably the most discussed issue regarding this module is the allocation of the used energy per produced ton of asphalt mixture. The reason for this is the high scattering of energy consumption in the production of asphalt mixtures. The scattering is due to a wide range of influencing factors (e.g. asphalt mix design, plant operating parameters or ambient conditions etc.) and the inaccurate documentation of the plant's energy consumption. When comparing existing PCRs [13–18] regarding energy allocation of the heating process in the dryer drum, three approaches can be distinguished:

- Relating the total energy consumption to the total production quantity of asphalt mixture over a specified period of time (e.g. one year) and assign the same energy consumption to each asphalt mix design [13,14,18].
- Determining the theoretical consumption of an asphalt mix by model calculations based on a wide range of input parameters [13,16].
- Determining the energy consumption of a specific asphalt mixture on the basis of on-site measurements [16].

Recognizing that other life cycle phases, such as the provision of raw materials (Module A1) or the use phase (Module B) has a significantly impact on the environment throughout the entire life cycle of asphalt pavements, this study focuses exclusively on the manufacturing phase (Module A3) [23–25]. Several LCA studies of asphalt pavements have already been conducted and shown the significant impact of the manufacturing phase, which mainly depends on the fuel consumption of the dryer drum [24,26–29]. Therefore, there is great interest in determining the influencing parameters in order to reduce its consumption and its associated emissions. Various parameters (e.g. aggregates moisture and storage, asphalt mixture temperature, asphalt mix plant efficiency, adding reclaimed asphalt pavement (RAP) etc.) have been identified and investigated, based on thermodynamical models or on-site measurements under specific conditions [24,30–35]. Although these studies are scientifically plausible, they are most common based on a theoretical approach and do not reflect actual consumptions. In order to mitigate the research gap between theoretical and real fuel consumption, this study follows a novel attempt to describe this energy consumption by using exploratory data analysis (EDA) and linear discriminant analysis (LDA), which are exclusively based on primary data.

Hence, this study investigates several impact parameters on the energy consumption of the asphalt mixture production, with the following objectives: (i) identifying parameters with a significant impact on the energy consumption of asphalt mixture production, (ii) providing an allocation method based on primary data to quantify such impacts in order to evaluate the environmental impacts of asphalt mix design more specifically, (iii) giving a recommendation for further consideration of allocation methods in Module A3 in PCRs.

2. Methods

The focus of this paper is set on the various impact parameters that might affect the energy consumption of asphalt mixture production. In the first part, the influence of the available parameters is examined and quantified using a combination of allocation method and the grouping of the data. Subsequently, it is examined whether the findings are reasonable and applicable in general, i.e. whether the given parameters in the provided data are sufficient to describe the consumption behavior of the dryer drum accurately.

Secondly, to provide a holistic view of environmental impact of the asphalt mixture production and especially to demonstrate the relevance of the more specific consideration in Module A3, the findings are embedded in an LCA. For better illustration, the applied methodologies and research objectives have been graphically summarized in Fig. 1.

2.1. Batch asphalt mix plant

The analysis is based on two production years of a batch asphalt mix plant, which is situated in an urban area of a central European country. The plant covers a wide range of products (e.g. cold mix asphalt and hot mix asphalt) and can operate the dryer drum with both natural gas and heating oil. Depending on the intended RAP content of the respective asphalt mix designs, RAP can be added in the middle of the drying drum via center inlet or directly into the mixer. Fresh mineral aggregates are stored in an elevated storage silo. From there, the aggregates are directly fed into the drying drum via electrically powered underground conveyor belts. During peak production periods, when the capacity of the high silo storages is not sufficient, aggregates are also stored like RAP in uncovered areas. To load these materials into the cold feeders or RAP bins, diesel-powered wheel loaders are used. Since the plant supplies both, large construction sites such as highways and small construction sites such as private garage entrances, only in a small number of cases a large quantity of the same asphalt mixture is mixed continuously.

The collected data were automatically derived from the asphalt mixing plant operating system and include production volume, components statistics, batch statistics, fuel consumption (natural gas and heating oil) and operating data (asphalt mixture temperature, drum starts etc.). The operating data and the fuel consumption were recorded hourly, all other remaining data were recorded on a second-by-second basis at the time of the event.

2.2. Data handling

The data read out includes a total of 349 production days over a period of two years. The fuel consumption of the drying drum is directly related to the drying and heating process of the aggregates. For practical reasons, the hourly energy consumption was added up for each day and related to the daily production volume, even though a certain amount of information is lost by aggregating the data and inaccuracies could arise (e.g. when the aggregates are dried but not mixed until the next day).

In order to make a statement about specific asphalt mix designs or asphalt mixture groups, an allocation method needs to be defined which allocates the daily energy consumption to a representative production day of such mixtures. Based on an empirical parameter study, which is not discussed in this paper, a representative production day for a specific asphalt mix design was defined as a day on which the cumulative mass of a specific asphalt mixture design accounts for at least 70 m% of the total mass of all asphalt mixtures produced on that day. This threshold value was defined to represent a category to be analyzed with sufficient quality on the one hand and not to discard too many data points on the other hand.

2.3. Linear discriminant analysis - LDA

The energy consumption of asphalt mixture production depends on a combination of various parameter. While some of these parameters have been recorded and can be used for further data analysis, some remain unconsidered. To investigate the impact of all available data at the same time, LDA was applied. It is a commonly applied method in multivariate data analysis, e.g. for dimensionality reduction problems as a preprocessing step for machine learning and pattern classification applications. The main idea of dimensionality reduction is to transform data from a high-dimensional space onto a low-dimensional space, while retaining meaningful properties of the data. In principle, this can be achieved either by following a supervised or an unsupervised approach. While unsupervised approaches, like the principal component analysis (PCA), are not provided with the desired results during the training of the learning algorithm, supervised approaches like the LDA, do include the desired results in the input data [36].

LDA and PCA are closely related to each other since both are based on a linear combination of weighted variables. While PCA reduces the dimensionality of the original dataset by maximizing the variance in the data, LDA maximizes the separability. Mathematically speaking, this is achieved by maximizing the ratio of "between class variance" (difference between means of classes) to "within class variance" (difference between mean and the samples of each sample of each class). The resulting combination, also called linear discriminants, are used for classification and cannot be linked back to the input parameters [36].

In total six features (listed in Table 1) are considered in the LDA to describe the dependent, which is the daily fuel consumption. It needs to be noted that all seven parameters are related to a daily production day. Since it can already be assumed that it will not be

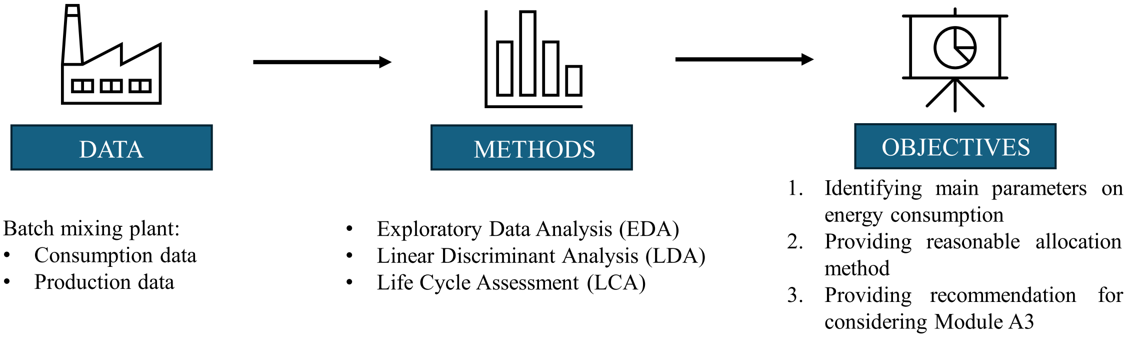

Fig. 1. Flow chart - Methods and research objectives.

possible to determine the exact energy consumption based on the existing parameters, the analysis should be used to determine whether it is possible to differentiate between the classes low, medium, and high energy consumption. To achieve as even a distribution of the data volume as possible, the classification is based on the 33 % and 66 % quantile of daily energy consumption, resulting 68.17 kWh/t and 78.03 kWh/t asphalt mixture.

The entire computation of the LDA has been conducted by using the Scikit-learn module v1.3.0 in Python 3.11.2 [37]. For training and validation of the model, the dataset was split randomly into a train and test set in the ratio 80:20 and was standardized by subtracting the mean of training samples to the sample and dividing it through the standard deviation of the training samples. The LDA was conducted by using the maximum number permissible of linear discriminants of two components, which results from the number of classes minus one, and using singular value decomposition as a solver.

2.4. Life cycle assessment - LCA

In order to assess the environmental impact of the asphalt mixture production and to demonstrate the relevance of the allocation method in asphalt mixture production in consideration of the whole manufacturing phase (Module A3) according EN 15804 [22], an LCA according to ISO 14040/44 [8,9] is conducted. Material and energy consumption associated with the infrastructure (e.g. production, maintenance and end of life of asphalt mix plant, vehicles, roads, pipelines etc.) are not considered within this LCA. As a functional unit, 1 metric ton (1000 kg) of asphalt mixture is used. Although EN 15804 includes multiple environmental indicators, this paper considers only GWP_{TOTAL} [kg CO_2-eq.] as environmental indicator.

3. Results and discussion

The following energy sources are used by the investigated plant for the production of asphalt mixture: Electricity, natural gas, heating oil and diesel. To make the analysis comparable, all fuels are related to the lower heating value (LHV) in kWh, converted as stated in Table 2. However, it must be taken into account that the consumption of the individual energy sources is essential for the LCA and not the total energy consumption.

3.1. Fuel consumption of the dryer drum

As stated in Section 2.1, the dryer drum can be operated with both natural gas and heating oil and consequently, the fuel consumption needed to be converted into the lower heating value (LHV) of the respective fuel. The LHV has been chosen over the higher heating value (HHV), since it was assumed that the energy conversion process does not include the condensation of water vapor and consequently represents a more accurate measure of the usable energy content. Fig. 2 presents the fuel consumption of the dryer drum as a function of the daily produced amount of asphalt mixture. It can be observed that there are high fluctuations in the consumption, especially at low daily production volumes. Based on the low coefficient of determination R^2, it can be assumed that beside the production volume, the fuel consumption of the drying process depends on further parameters (e.g. asphalt mix design, asphalt mixture temperature, RAP addition, amount of dryer drum starting processes, amount of different asphalt mix designs mixed per day, aggregate moisture etc.) than just the production volume.

To better illustrate the energy consumption vs. production volume of Fig. 2, the data points are assigned to one of the four defined categories based on the daily production volume: <=250 t, >250–500 t, >500–750 t and >750 t of asphalt mixture produced per day. The boundaries of the categories were chosen so that there is a representative number of data points in each group. The results are represented as boxplots in Fig. 3. For the sake of good legibility, the ordinate is limited to 160 kWh fuel consumption per ton of asphalt mixture and the outliers above this value are no longer displayed. This also applies for all of the following figures. The results clearly show the significant impact of the daily production volume. The more asphalt mixture is produced per day, the more efficient is the energy consumption and the lower the scatter. While the interquartile range ($IQR = Q_{75} - Q_{25}$) of the relative energy consumption on production days below a production volume of 250 t asphalt mixture is 36 kWh/t, the range for the other categories is between 11 and 16 kWh/t. It is also notable that there is a significant difference between mean value (101 kWh/t) and median (84 kWh/t) of the relative energy consumption in the below 250 t daily production category, which does not apply in the other categories. The respective mean value of the relative energy consumption of the category “>250 – 500”, “>500 – 750” and “>750” is 76, 70 and 66 kWh/t. If all data points are considered without further subdivisions, a mean energy consumption of 77 kWh/t of asphalt mixture is obtained.

Table 1
Considered features in LDA related to one production day.

Features	Unit
Production volume	t
Asphalt mixture temperature	°C
Number of dryer drum starting processes	-
Number of different asphalt mix designs produced	-
Ratio PmB to total used binder	m%
Ratio of asphalt mixture containing RAP to total production volume	m%

Table 2
Overview of the energy sources used in asphalt production and its properties [38].

Energy source	LHV	GWP_{TOTAL} [CO_2-eq./kWh]
Natural gas	10.18 kWh/m^3	0.249
Heating oil	9.89 kWh/l	0.344
Diesel	9.80 kWh/l	0.332
Electricity	-	0.226

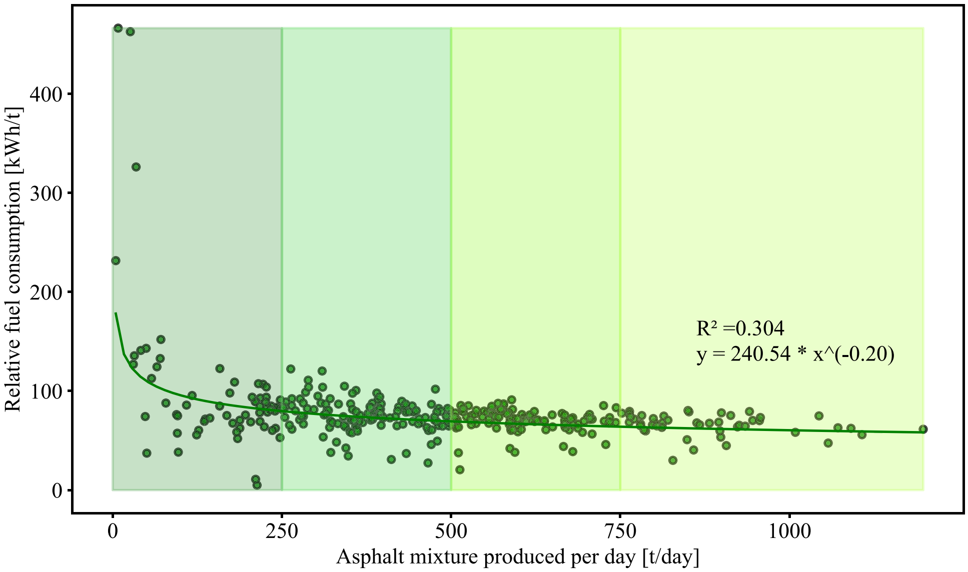

Fig. 2. Scatter plot - fuel consumption per produced ton asphalt mixture.

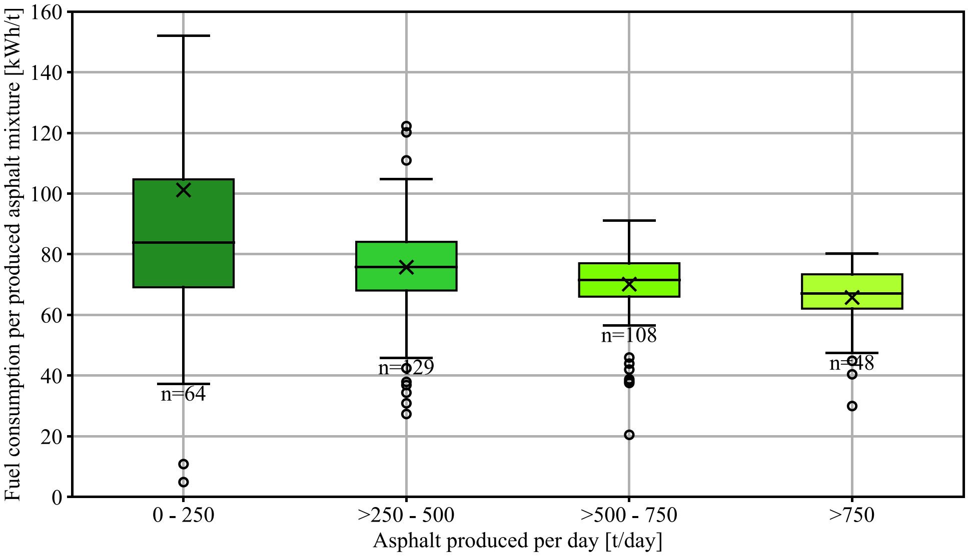

Fig. 3. Boxplot - fuel consumption per produced ton asphalt mixture.

3.1.1. Asphalt mixture temperature

The main goal of this study is to allocate the actual energy consumption to a specific asphalt mix design based on primary data. An asphalt mix design specifies which components make up the asphalt mixture and thus determines for example the required asphalt mixture temperature. As there are not enough data points obtained by applying the 70 % threshold method defined in Section 2.2, the energy consumption of an individual mix could not be investigated. For this reason, the asphalt mixture temperature had to be considered as a proxy for different mix designs. The temperature was measured for each batch of asphalt mixture in the mixer, directly before loading the truck. No other temperatures were recorded by the plant. However, it must be considered that although the asphalt mixture temperature is specified by the asphalt mix design, certain temperature fluctuations are still to be expected due to the individual operation of the plant.

To consider the production temperature, the asphalt mixture temperatures of the individual batches that were mixed on one day, were weighted according to their mass, totaled and averaged by the daily production quantity. To determine its impact on energy consumption, the daily average temperature of the produced asphalt mixtures was related to the daily energy consumption. Over the entire investigated period of two years, a mean value of 176°C is obtained per production day. Since only 3.2 % of all production days have an average asphalt mixture temperature lower than 150°C (lower limit for hot mix asphalt (HMA) [39]), a classification into HMA, warm mix asphalt (WMA) and cold mix asphalt (CMA) was not considered as reasonable.

Nevertheless, to investigate the impact of temperature and still consider the impact of the production volume, the production days have been grouped into days "<=180°C" and ">180°C" average mixing temperature throughout the day. The threshold of 180°C was chosen since the median of all average asphalt mixture per production day is 179.49 °C to guarantee enough datapoints per each category. The temperature threshold is also sensible, since asphalt mixtures with unmodified bituminous binders are commonly produced at temperatures below 180 °C and mixtures with polymer modified binders at temperature at or above 180 °C. For a better documentation, Table 3 contains the actual temperature of the considered classes. Additionally, it also contains the difference of the temperature ΔT between the two classes, which is roughly around 20°C.

Fig. 4 presents the relative fuel consumption per asphalt mixture based on the previously mentioned classifications. As in Fig. 3, category "<250" still shows strong scattering despite the additional temperature parameter. Especially for production days with an average mixture temperature below 180°C, big differences between mean value (117 kWh/t) and median (84 kWh/t) can be noticed. According to the mean values of category "<250", asphalt mixtures with lower temperatures consume more energy than the ones with higher temperatures (82 kWh/t). This indicates that either the production volume has a greater influence than the temperature and cannot be recognized due to the rough grouping of 0–250 t per day, or that no statements can be made for production volumes below 250 t, as other parameters have a stronger impact in this classification. In the other classifications, asphalt mixtures produced with lower temperature obtain a lower energy consumption. When comparing the remaining three classifications, an increasing difference between the mean value of average mixture temperature below 180°C and above 180°C (">250 - <500": 74 kWh/t and 77 kWh/t; ">500 - <750": 68 kWh/t and 72 kWh/t; ">750": 64 kWh/t and 70 kWh/t) can be observed. For a more accurate quantification of the impact of the temperature, a finer classification needs to be made, which, however, builds on an even larger amount of data that is not available at this time.

Based on the 70 % threshold method mentioned in Section 2.2, six representative production days of CMA have been indicated over the investigation period of two years. Although, by definition, CMA is mixed cold, the average asphalt mixture temperature during these six days was 112°C per production day. For all six data points, it was ensured that the average temperature was not formed by the arithmetic mean with an HMA. According to the plant operator, the temperature was necessary to ensure that the aggregates are mixed in a dry state with the binder. In order to enable a comparison of CMA with the remaining hot asphalt mixtures, the production volume of the remaining asphalt mixtures is limited to the smallest and largest production amount of the representative production days of CMA, resulting from 412 to 513 t per day. This classification of the remaining hot asphalt mixture results in an average temperature of 178°C per day. The relative fuel consumption of both categories is shown in Fig. 5. It can be observed that the temperature difference of approximately 65°C has a significant influence on the energy consumption. Comparing both mean values of the respective classifications (73 kWh/t and 40 kWh/t) results in a difference of −33 kWh/t or −45 %, which indicates that temperature reduction has a high potential in saving energy. Nevertheless, it needs to be considered that the calculations of CMA are based on only six datapoints. In upcoming studies, the findings need to be verified on a larger dataset.

Another parameter that should have been investigated in this study is the content of PmB. As it requires a higher temperature during processing than unmodified bitumen, a high ratio of asphalt mixtures with PmB results in higher energy consumption. This was proven in a previous case study conducted on another batch asphalt mix plant [40]. Based on the defined allocation method in Section 2.2, not enough data for representative PmB-days could be derived for this plant to run meaningful analyses.

3.1.2. Addition of RAP

Another parameter, which is not necessarily related to the asphalt mixture temperature, but in most cases to the outlet temperature of the drying drum, is the addition of RAP. When RAP is added in a cold (ambient temperature) and wet state directly to the mixer, a drop in temperature of the preheated fresh aggregates and bitumen is the consequence. To compensate for such temperature losses in the mixer and to ensure a homogeneous mixing process, the aggregates in the drum are heated to a higher temperature than usually. If

Table 3
Average asphalt mixture temperature of the defined classes.

production volume [t/day]	Temperature class	≤180 °C [°C]	>180 °C [°C]	ΔT [°C]
<=250		170	190	20
>250–500		165	187	22
>500–750		164	188	24
>750		162	186	23

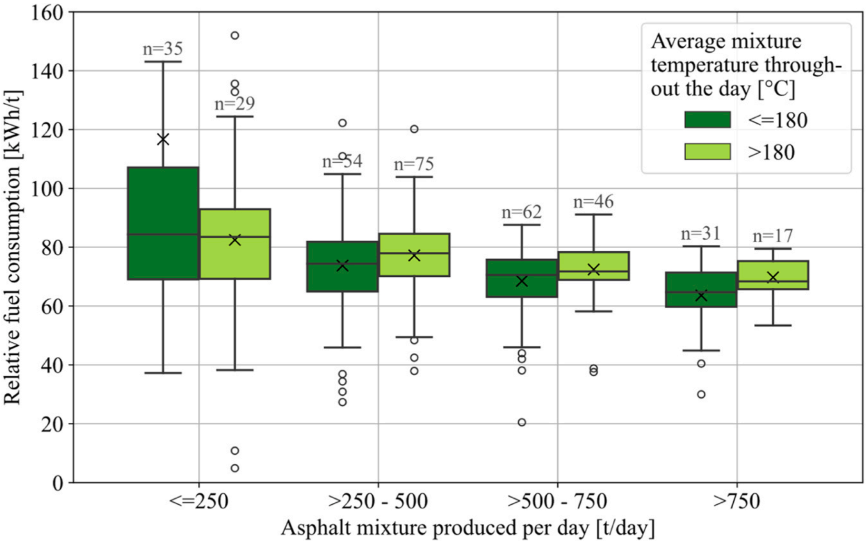

Fig. 4. Boxplot - fuel consumption per produced asphalt mixture as a result of asphalt mixture temperature.

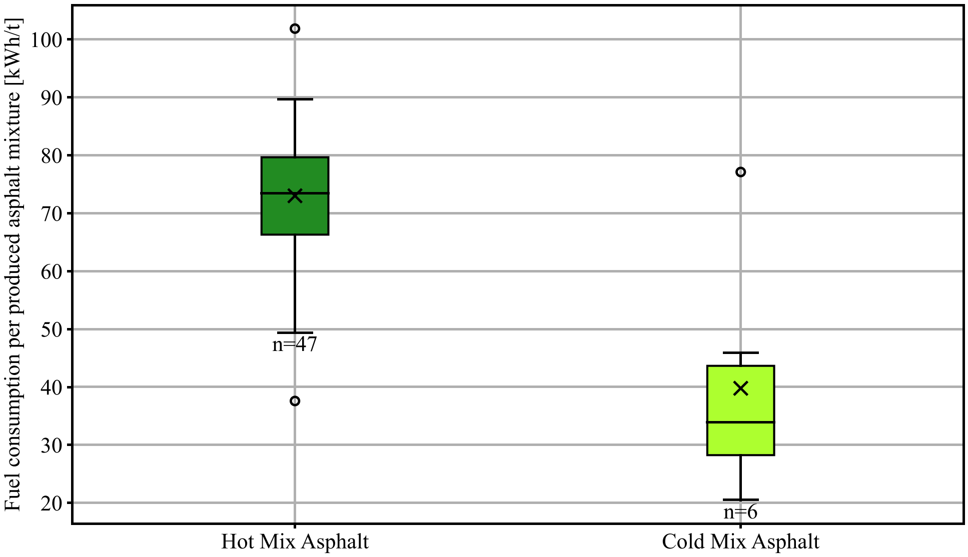

Fig. 5. Boxplot - fuel consumption of CMA and HMA.

asphalt mixtures with a higher RAP content are produced (usually more than 20 % according to the plant operator), the RAP is added to the drum via center-inlet ring and heated with the virgin mineral aggregates. In order to investigate the impact of adding RAP, a methodology needed to be established to determine if a production can either be considered as a representative RAP- or no-RAP-day. As several asphalt mixtures with different contents of RAP ranging from 10 m % to 40 m% are mixed within one day and the number of data is limited, it was not possible to distinguish between the quantity of RAP added and the addition method. Therefore, it was only possible to distinguish whether an asphalt mix contained RAP or not. If the ratio between the sum of the daily production quantities of asphalt mixtures containing RAP and the daily production quantity is ≥70 %, the day was assigned as a representative RAP-day. The determination of a representative no-RAP-day is carried out analogously with the asphalt mixtures without RAP content. The rest of the data is neglected for this analysis.

Fig. 6 presents the relative fuel consumption in consideration of the production volume and the addition of RAP. As expected, an additional energy demand to produce RAP containing asphalt mixtures is required. What is also noticeable are the high fluctuation in energy consumption of asphalt mixtures without RAP, which do not only apply at low production volumes as usual. This can be reasoned by the fact, that CMA was mixed within the range of category “>250–500” and “>500–750” t of asphalt mixture per production day. In general, it can be observed that there are only a few data points from representative non-RAP days available based on the chosen allocation method, which makes the results less meaningful, as outliers have an increased impact. Although it makes no

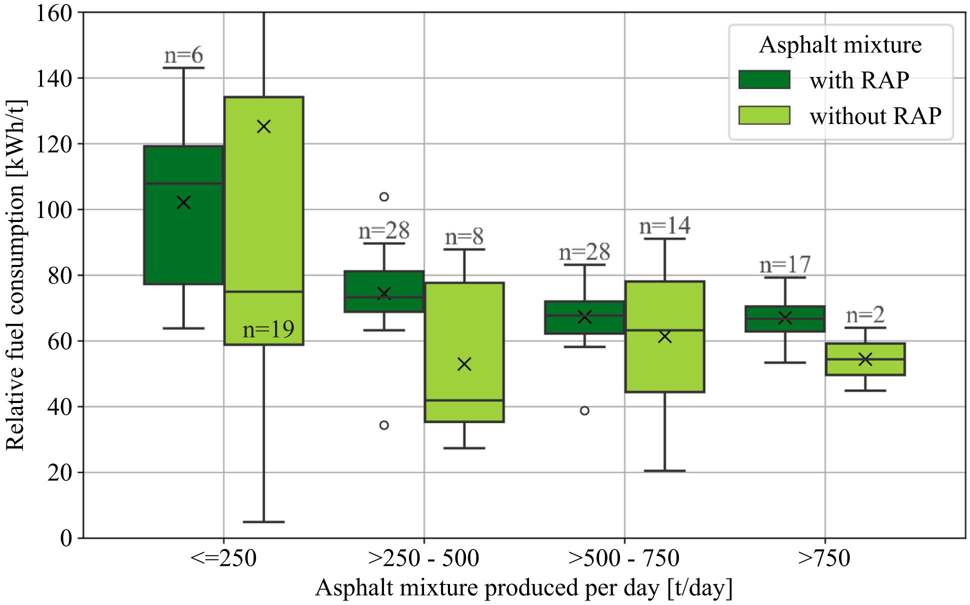

Fig. 6. Boxplot - fuel consumption of asphalt mixtures with and without RAP.

sense to quantify the energy differences between the individual categories due to the large scattering, Fig. 6 nevertheless qualitatively confirms, that the addition of RAP results in an additional energy consumption in the manufacturing process. However, this should not detract from the positive characteristics of RAP, namely that its use saves a significant amount of upstream energy in the provision of raw materials (Module A1).

3.1.3. Dryer drum starting process

In general, it can be assumed that a production process that is as continuous and evenly as possible has a positive effect on energy consumption. To evaluate the asphalt mixture production process, the number of dryer drum starts were taken into account. These are recorded by the operating system of the plant. However, it needs to be noted, that a dryer drum start does not always necessarily have to be associated with the reheating of a cold drum, but only the activation or reactivation of the burner. As it can be anticipated that for larger production volumes also several starting processes are to be expected, the production volume is considered additionally to take the production volume per burner start into account. Thus, the following groups have been formed: <=25 t, >25–50 t, >50–100 t,

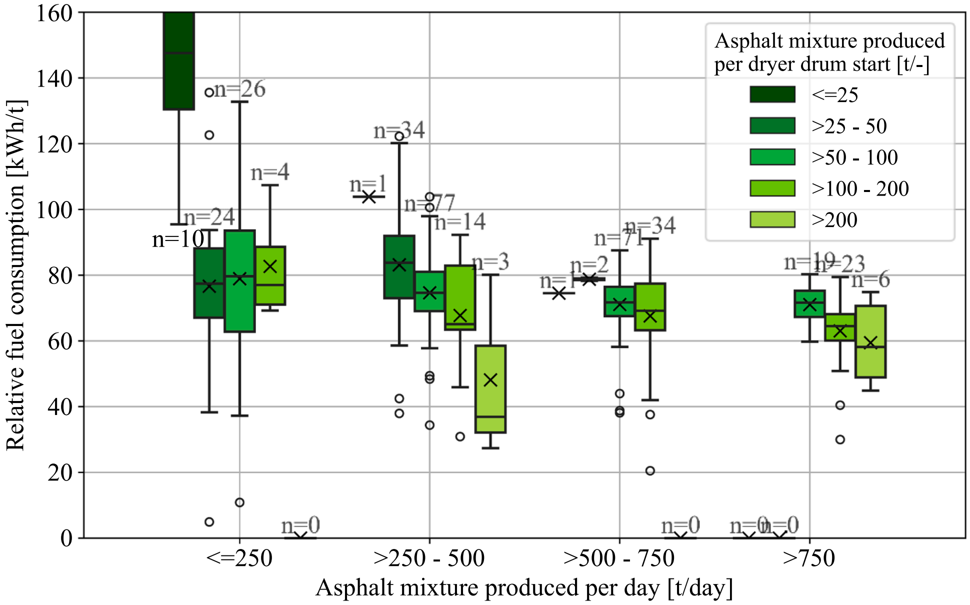

Fig. 7. Boxplot: fuel consumption per asphalt mixture as result of the number of dryer drum starts.

>100–200 t and >200 t of asphalt mixture produced per dryer drum start. The fuel consumption of the respective groups in relation to the daily production volume is presented in Fig. 7. Similar to the analysis, where the impact of the production volume has been investigated exclusively (shown in Fig. 3), the results show that higher production volumes ensure a more efficient manufacturing process. The main thought to relate the asphalt mixture produced per dryer drum start and additionally considering the daily production volume, was to retain the information, whether a heating process is carried out just once or more often. In general, it can be assumed that the more often such a process takes place, the more likely it is that the drum has not cooled down completely and therefore less energy is required to heat and dry the aggregates. When looking at the category >50–100 t of asphalt mixture produced per dryer drum start, which is the category with the highest amount of datapoints in all groups, this assumption can be confirmed. At a total production volume of less than 250 t of the respective group, the mean energy consumption is 79 kWh/t. With an increase in the production volume, the fuel consumption decreases slightly, resulting 75 kWh/t for >250–500 t, 71 kWh/t for >500–750 t and 71 kWh/t for >750 t production volume. This may be related to the fact that with larger production volumes the standstill time of the drum is shorter and consequently the cool down process is limited. A similar observation can be found with a production of >100–200 ton per dryer drum starts, whereby relatively few data points are available for the low production volumes. Fig. 7 illustrates once again the strong impact of the production volumes and the difficulty of determining the energy consumption for small amounts.

3.1.4. Linear discriminant analysis – LDA

To consider all available parameters simultaneously, an LDA was conducted to analyze all available data in one model and enable a two-dimensional visualization of the data. The results of the dimensionality reduction method can be seen in Fig. 8, where the color represent the intended classes (low, medium high) modelled by the algorithm based on the training set and the position of the markers reflects validation of the class using the test set. It can be observed that although the model assigns a large proportion of the data points correctly, there is still a certain degree of uncertainty. When observing the classes from low to medium and medium to high consumption, relatively little differentiation can be observed, which was also to be expected due to the smooth transitions between the classes at 68 and 78 kWh/t. More surprising is that also low and high consumption class are not well distinguished by the model. Although there is an energy difference of at least 9.9 kWh/t between the two classes, the model was not able to distinguish between low or high consumption (e.g. one point with high consumption is in the low consumption area and four points with low consumption are in the high consumption area). This can be either explained by a too small dataset or by the used feature in the model. If the second reason applies, this indicates that based on the recorded data (listed in Table 1) it is not possible to determine the energy consumption of asphalt mixture production without the inclusion of other relevant parameters (e.g. moisture in mineral aggregates and RAP) that are not measured by the production plant at this time.

3.2. Electricity consumption

The main focus in this paper is set in the energy consumption of the dryer drum, since it has the most significant impact on the environment in the manufacturing phase. When all energy consumptions are distributed equally to the total production volume, the ratio of electricity to fuel consumption of the drying drum is approximately 1:9. In order to not exceed the scope of this study, the electricity consumption is allocated evenly to the production amount and no further allocation methods were applied. Therefore, a relative energy consumption of 8.7 kWh/t asphalt mixture is employed regarding electricity consumption.

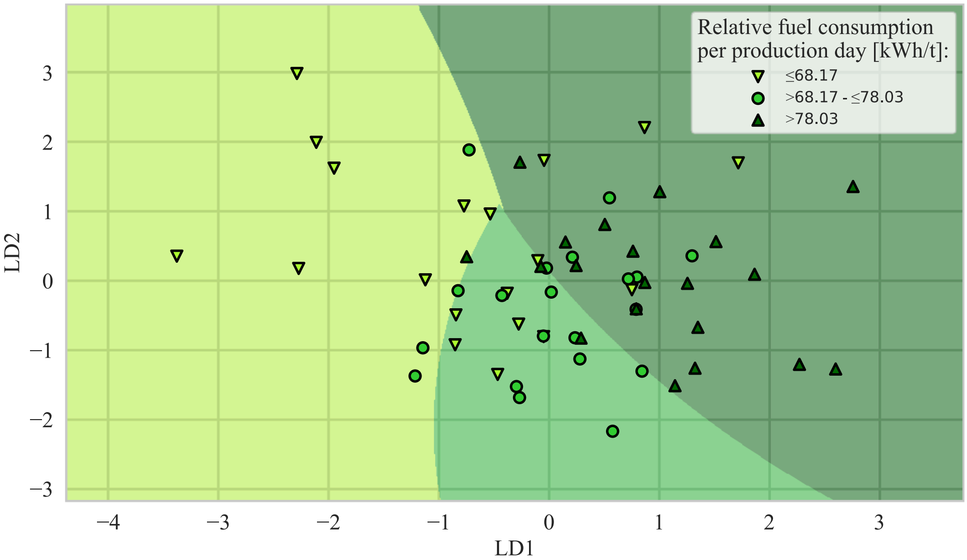

Fig. 8. Scatter plot - LDA of low, medium and high fuel consumption.

3.3. Fuel consumption of the wheel loaders

The consumption data of the wheel loaders were not recorded by an operating system. Only the time of refueling was documented manually. Therefore, the only possible and reasonable option to allocate the fuel consumption of the wheel loader to asphalt mixture is to relate the total energy consumption over a longer period of time to the produced amount of asphalt mixture and to distribute it equally to each asphalt mix design, resulting 0.08 l Diesel or 0.72 kWh per ton asphalt mixture.

3.4. LCA of Module A3

To raise awareness of the environmental impact of the energy consumption, an LCA of the manufacturing phase (Module A3) was conducted. The entire impact assessment is based on the inventory presented in Table 2. The energy consumption of the manufacturing phase of asphalt mixtures results from the electricity consumption of the plant, fuel consumption of the wheel loaders and the fuel consumption of the dryer drum.

No distinctions were made when allocating the electricity consumption of the plant and the diesel consumption of the wheel loaders to asphalt mixture production Consequently, a GWP of 2.0 and 0.2 kg CO_2-eq. is assigned to each ton produced asphalt mixture, respectively.

Section 3.1.3 presents the impact of several parameters on the energy consumption of the dryer drum. Although the tendency of all parameters is evident from the results, a meaningful quantification cannot be made for each grouping due to the insufficient amount of data. Consequently, the scenarios of distinguishing asphalt mixture with or without RAP content and the production amount per dryer drum starts has been omitted. Table 4 shows the energy consumption and the associated GWP of the production volumes with and without the additional consideration of a daily average mixture temperature above and below 180°C. As there are particularly high outliers at small production volumes, which have a significant impact on mean value, the median was used for production days $\leq$250 t of asphalt mixtures. When looking at the results of the different fuels, it becomes clear that the choice of fuel has the greatest influence in terms of GWP, especially at low production volumes. While the difference for natural gas and heating oil at production days $\leq$250 t of asphalt mixture is 8.0 kg CO_2-eq./t, it decreases to 6.3 kg CO_2-eq./t for production days of >750 t. Also, when considering the production volume exclusively, a significant impact can be observed. When comparing the lowest and highest production groupings, there is a difference of 4.5 kg CO_2-eq./t for natural gas and 6.4 kg CO_2-eq./t for heating oil. When additionally the impact of the temperature is considered, differences between −0.54 and +0.99 kg CO_2-eq./t can be observed when operating with natural gas, and −0.75 and 1.36 kg CO_2-eq./t with heating oil. As a comparison, when allocating the energy consumption equally to each produced ton asphalt mixture, depending on operating with natural gas and heating oil, a GWP of 19.2 kg CO_2-eq./t and 26.6 kg CO_2-eq./t can be obtained, respectively.

If the emissions of the three main consumptions that make up the manufacturing phase are considered simultaneously, assuming that each asphalt mixtures consumes the same amount of energy, the GWP results to 21.5 kg CO_2-eq./t for operating the drum with natural gas and 28.8 kg CO_2-eq./t for heating oil, respectively. The majority of these emissions are attributable to the drying and heating process, accounting 90 % and 92 % respectively. For this reason, significant changes in the GWP can be observed when the fuel consumption of the drying drum is considered more individually. For example, when taking into account the daily production volume, differences of 13.4 % in GWP can be detected for natural gas as a fuel, and 13.8 % for heating oil. When the daily average asphalt mixture is considered additionally, the differences in GWP increase to 15.9 % and 16.4 %, respectively.

4. Conclusion & outlook

The energy consumption of the manufacturing process of asphalt mixtures has a significant impact on the environment and depends on multiple parameters. Based on an allocation method on primary data of a batch asphalt mix plant, the influence of several impacts on the energy consumption have been investigated. In order to illustrate the relevance of the findings, an LCA of the manufacturing phase was carried out. The results of this case study can be summarized as follows:

- Several impact parameters on the energy consumption like production volume, asphalt mixture temperature, addition of RAP and the amount of dryer drum starting processes are shown, of which the production volume has the largest impact. Other significant parameters, such as moisture content in mineral aggregates and RAP, could not be investigated due to the lack of sensors in the plant, which may explain the high scatter in the results.
- Based on the conducted LCA, the largest savings potential lies in the fuel and the production volume. Since the GWP of heating oil is 38 % higher than natural gas, a significant amount of greenhouse gas can already be saved by using an efficient fuel source. Additionally, with high production volumes (>750 t/day), 22 % fuel savings per ton asphalt mixture can be obtained in comparison to low production volumes ($\leq$250 t/day). Asphalt mixture temperature differences of around 20°C did not show a strong impact. Nevertheless, CMA with a production temperature of approximately 110°C results in a high energy saving potential of roughly 80 %, compared to HMA produced at approximately 180°C.
- LDA was applied by considering all provided parameters simultaneously to examine if a distinction in low, medium or high consumption is possible. Based on the developed model and provided data, it is not possible to determine the fuel consumption of the dryer drum. Consequently, in order to describe the consumption behavior of the drying and heating process more accurately, a larger database with more parameters is required.

Table 4
GWP of various drying and heating scenarios.

Production volume [t/day]	Energy consumption [kWh/t]		Natural gas [kg CO_2-eq./t]		Heating oil [kg CO_2-eq./t]	
	Without further subdivision	≤ 180 °C/ > 180 °C	Without further subdivision	≤ 180 °C/ > 180 °C	Without further subdivision	≤ 180 °C/ > 180 °C
≤250*	83.9	+0.41 −0.42	20.9	+0.10 −0.10	28.9	+0.14 −0.14
>250–500	75.7	−2.01 +1.44	18.9	−0.50 +0.36	26.1	−0.69 +0.50
>500–750	70.2	−1.66 +2.24	17.5	−0.41 +0.56	24.1	−0.57 +0.77
>750	65.8	−2.17 +3.96	16.4	−0.54 +0.99	22.6	−0.75 +1.36

* Instead of using the mean value. the median has been considered.

- The allocation method presented with a 70 % threshold criterion showed sensible results. Even if the annual average takes into account all effects (lower temperature in production, roofing of the aggregates etc.), which is most common approach in current PCRs, the findings of this study show that product-specific distinctions make sense. Consequently, the possibility of such distinctions should be provided in module A3 if it is in the client's interest. However, it must be taken into account that a large amount of data is required for this and consequently some regulations like a minimum number of representative production days must be defined for the respective asphalt mixture or asphalt mixture group to implement the method in a PCR.

In general, it should be noted that the results only reflect the manufacturing phase and not the entire life cycle. Therefore, as other modules (e.g. provision of raw materials, transportation, etc.) or other parameters (e.g. performance, service life, usage, etc.) have a significant influence on the environmental impact of asphalt pavements, it is not possible to make generally applicable statements based on an isolated consideration of the manufacturing phase. This case study investigates several parameters that have been recorded in normal operation of an asphalt mix plant. In order to further confirm the results and give general validity, the amount of data needs to be increased and the method needs to be applied to several other asphalt mix plants. Additionally, to enable a more accurate prediction of the energy consumption, other parameters (e.g. outlet temperature, aggregate moisture, etc.) need to be considered.

CRediT authorship contribution statement

Paul Schönauer: Writing – original draft, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Michael R. Gruber:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization. **Bernhard Hofko:** Writing – review & editing, Supervision, Resources, Project administration, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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