Article

CO₂ Emissions Comparisons on Cementous Sustainable Flooring Options: Modeling and Evaluation

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ABSTRACT: CO₂ and greenhouse gas emissions have become a major environmental issue worldwide, and emissions have spiked faster than most could ever imagine. The issues have made it crucial to find financially feasible and long-term, use-efficient solutions that fulfill industrial needs. As society so much depends on the current industry outputs, we need to reduce emissions coming from those industrial facilities and premises where people shop and buy services and assets on a daily basis. These emissions need to be reduced on a global scale, and here, concrete as a building material comes into play as one of the most used materials, especially on industrial floors. A typical solution is a sturdy base slab with a use case-specific coating on it. The base slab is expected to last the whole life of the building, whereas the coating might be considered consumable and refurbished/fixed as a maintenance job many times before the building itself is demolished. In heavy use cases, the maintenance cycle might be fast, which reduces the usable time of the building and generates downtimes for business. The coating decisions have a major impact on the building's lifetime emissions, which is the key focus of this study, too. Bad decisions can introduce unnecessary microplastics and nano dust particles to work environments and also generate restructuring needs of the operational activities. In the worst case, operations have to be shut down. Luckily, there are options, and emissions can be reduced in many ways. By using long-term and durable cementitious mix-based dry shake coatings, one can reduce top coating-based emissions, and by decreasing the amount of used reinforcement components in the base slab, an extra positive impact can be achieved. With a base slab, also more environmentally friendly low-carbon cement formulations can be considered, like fly ash or GGBS (ground granulated blast furnace slag) based formulas, which we discuss in detail and analyses traditional options compared to modern CEM3a and CEM3b versions. For the top coating, emissions are generated in the construction and maintenance phases. To find different options with cross implications on lifetime emissions, our study analyzes CO₂ emissions sources for several concrete mixes, which are then paired with floor-top coatings based on Cementous mix or epoxy coating. We have pinpointed the potential for reducing the building's floor-based lifetime CO₂ emissions. The analysis is based on the impacts of the base slab and floor coating selection combinations. As a de facto comparison element, we used a 100 percent virgin Portland cement-based mix. The Portland cement was compared to CEM3a and CEM3b mixes. On the top surface of the floor, traditional epoxy base floor coating was compared to a modern dry shake-based option. In the analysis, the dry-shake-based floor showed major benefits. Emissions were drastically reduced, fewer maintenance downtimes were needed, and the general life expectancy was a lot longer for the dry shake option.

Keywords: CO₂; Emission; Dry shake; Circularity; Digitalization; Emission reduction; Long term sustainable; Sustainability; Epoxy; Concrete; Economical; Ecological; Modern building materials
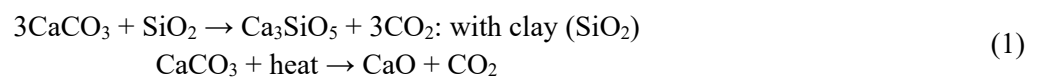
1. Introduction

Climate change is a current issue causing a lot of problematic consequences but also boosting interest in designing modern, novel, financially feasible [1] and industry-changing solutions [2,3]. In the digitalized era [4], we have achieved a lot in assets management [5], had new ways to be able to utilize crowd resources [6], do economical and ecological waste and emissions reduction [7,8], and more sustainable supply chains and their evaluation [9], in general, and university—industry collaboration for more sustainable solutions [10,11], development in textile industry [12] and, e.g.,

in recycling too [13]. But on the other hand, e.g., food production is endangered by shifting weather patterns and rising sea levels, causing floods, *etc*. Without fast actions, better formalization of innovation fronts [14], and novel & less emissions-making solutions to our lifestyles, emissions, and waste makings [15,16], these impacts will be devastating and global in scope and unprecedented in scale [17–22]. As expected, the importance of environmental issues in society [23], the role of companies of all sizes, including micro, SMEs [24], and large companies alike, is growing, and more actions are also taken and still need to be taken into consideration within the construction industry. Concrete is the world's most widely used building material [25], thus at the heart of the environmental debate. Concrete production is the third largest producer of CO_2 emissions globally and we need to find new ways to reduce these emissions in global scale [26].

Concrete-related CO_2 emissions mostly come from the cement industry's cement-making process, when raw materials are converted to Portland cement, or so-called ordinary Portland cement (OPC). The traditional OPC cement is the major global standard cement product made from a limestone and clay mixture. This mixture is pyrolysed in a hot kiln at temperatures around 1450 °C. The kiln-heated product/powder is blended with case-specific additives [27,28] to achieve the desired product structure. Considering the CO_2 emissions in the global clinker production, projected to reach over 5 billion tons by 2030, the typical chemical reactions go as follows:

Equation (1). Typical cement CO_2 emissions source from a chemical reactions point of view.

$$3CaCO_3 + SiO_2 \rightarrow Ca_3SiO_5 + 3CO_2: \text{with clay (}SiO_2\text{)}$$
$$CaCO_3 + \text{heat} \rightarrow CaO + CO_2$$

(1)

The general view is that the CO_2 emissions produced in this production process are in the range of 0.5–0.9 kg per 1 kg of produced clinker produced [29–31]. Basically, all commercial buildings like to utilize and need durable and high-strength floors for their operation's, including modern sustainable and long-term use designed warehouses [32]. These facilities producers are seeking options to help them to reduce buildings-related emissions in addition to the operations related emissions and professional concentration in sustainability operations issues [33,34]. At the same time, when we try to solve our global food insecurity issues [17], we could be seeking symbiotic solutiosn to utilize food production side stresms for more sustainable concrete mizs [35]. But in short, from an emissions perceptive, it is just the current basic reality that concrete cannot be produced without cement, and the cement industry alone produces three times more CO_2 emissions than, for example, the aviation industry [36]. It has been represented that cement produces eight percent of the world's CO_2 emissions on a yearly basis [37]. As cement production is vast, emission reductions in concrete production can achieve significant results in global climate change mitigation activities. Also, in a bigger picture, heat and power creation-related emissions should be taken into account [38], the solution development should consider both, the sharing of the archived gains but also the pains [39] and in addition of the material efficiency and low-carbon products to be able to reduce product-driven emissions, in a big picture [40].

The goal of the study was to compare different concrete based flooring options with different lifetime CO_2 emission rates, including floor renewal into the life cycle CO_2 emissions rates. As for performance and de-facto industry standard comparison items, we also added epoxy-based flooring [41] as an option to give a clear impression of how different options and widely used typical plastics based solution, do actually compare to each other, from sustainability and emissions points of view. The study was made as this is one of the first studies on the area of comparing multiple different flooring options, where sustainable concrete floor topping is put against high industry-used epoxy options, even though it is well known in the industry that this surface option might need special treatment, e.g., anti-slippery purposes [42,43] and especially a heavy use (a lot of movement on top of the surface) will make the epoxy option to be damaged easily and in quite fast phase too, in addition to making a specially strong ponding epoxy floor, on top of a base concrete slab, one might need expensive special epoxy resins [44,45].

2. Research Methodology, Objectives and Limitations

For realistic concrete floor emissions production in the floor's lifetime, the authors have created a model to calculate the CO_2 emissions of concrete floor construction for industrial purposes. The goal was to compare created CO_2 emissions from two different floor toppings: epoxy and case company's specific mineral and cement mix-based dry shake hard topping.

The analysis focused on a concrete floor for industrial warehouses, large halls, and similar spaces. For this purpose, the model uses 10,000 m^2 as a fixed parameter, which makes results comparison and scaling to, e.g., larger spaces with simple multipliers an easy task. Analysis includes three different concrete mixes CEM1, CEM3a, and CEM3b, which are presented in Table 1. These mixes are analyzed together with two different coating options: epoxy coating and the

mentioned special coating, which, for simplicity purposes, will now be referred to as dry shake-based coating in the following chapters. For calculations, CO_2 emissions from energy usage and transportation were excluded. This decision was made due to their CO_2 emissions to be immaterial/negligible compared to CO_2 emissions from cement production [46]. Additionally, the estimated CO_2 emissions from energy usage and transportation are very similar for the investigated options. The costs of these solutions have also been excluded. However, the greener and less polluting options tend to be currently a bit more expensive, and thus the transition into those takes time. On another hand, legislation, sustainability related positive brand effects, and changes in industrial sustainability trends [47] can outweigh the cost matters. The article uses a narrative literature review and Excel-based scenario modeling as its methodology.

Table 1. Typical cement descriptions and emission rates are based on sources [48,49].

	Portland/CEM1	CEM3a	CEM3b
Cement description	A "pure" cement, Ordinary Portland cement	A blend of traditional cement 30 percent of fly ash	A blend of traditional cement 50 percent of GGBS
CO_2 emissions	295 kg CO_2/m^3	245 kg CO_2/m^3	175 kg CO_2/m^3

3. Theory and Background

With a study of current literature, a researcher can "acquire an understanding of what has already been done, how it has been researched, and what the key issues are" [50]. Theory and background also help to introduce the study's contributions and justify its approaches, research methods, tools, questions, and methods [51].

As a methodology, a narrative literature review summarizes previously published information on a topic of interest. It focuses on concepts, theories, research methods, and research outcomes [52]. It is developed to provide a concise overview of a certain issue in a relatively short period [53,54]. Narrative reviews often serve as an applicable starting point for future research developments, and it has been found helpful in determining and refining research questions or hypotheses [55]. The narrative literature review was conducted with a snowballing method, where information is collected by including relevant articles selected from a reference list of a certain starting set of articles. In short, in the snowballing method, a starting set of articles is used as a selection pool for other articles, as other relevant articles are searched from the reference list of the starting set of papers by reviewing their content and potential contribution to the ongoing research [56].

4. Research Specific Supportive Literature

For industrial floors, certain unique requirements can be present, as the floor surface needs to be, e.g., dust-free and easy to clean, but most importantly, heavily durable. Usually, all industrial floors are made from concrete, but it is enhanced with different methods to retain its precedence over time [57]. This report focuses on analyzing the environmental impacts of three different concrete floor options with the case company's specific mineral and cement mix, hard topping, and epoxy coating. Thus, only these are briefly introduced. About ten billion cubic meters of concrete are used in the world every year. The environmental impacts are due to the vast amounts of concrete produced. On the other hand, it enables, among other things, the production of emission-free energy from wind, hydro, and nuclear power plants, as well as the construction of safe, long-lasting, and valuable housing and other buildings. And the concrete and cement industries have not been inactive in terms of emission reductions. The sector's climate emissions have been reduced by almost 25 percent over the past decade compared to the 1990 reference year [12].

Epoxy resins are classified as plastic; like other plastics, they are made from oil [57]. As epoxy resin is made from fossil fuel resources, thus the production of epoxy resin causes a lot of CO_2 emissions [58]. Additionally, epoxy resins are challenging to recycle as commonly it is used only in small amounts, such as adhesives or coatings. Currently, recycling a layer of coating is not feasible, either technologically or economically [59].

5. Modeling and Scenario Analysis

Due to the vast amount of CO_2 emissions in the concrete industry, the target is to analyze how the selected concrete base and topping affect the CO_2 emissions. There are different solutions to build the floor, but there are construction standards that serve certain density and strength requirements. These standards limit the number of different options for construction. Additional industrial floor requirements, like previously mentioned dust-free, durable, and long-lasting, set their own option limits. Taking these properties into account, our study analyzed how different concrete slab and

surface coating combinations produce CO_2 emissions with either of the top surface materials: epoxy coating or dry shake-based coating.

Concrete slab options are presented in Table 1 in the first chapter. These were chosen for the analysis as the requirement for concrete is globally so vast, and there is just not enough slag to produce less emissive concrete slabs for everyone, to fulfill all global demand. Due to this, the article analyzes Portland/CEM1 concrete slab pairing with a less pollutive coating option. Currently, epoxy coating is widely used in the industrial sector; thus, it was a natural and optional choice for the analysis. Additionally, the studied dry shake option promises a lot in paper and, as such, wanted to be compared to the epoxy coating option. This analysis gives insight into how these coating options may affect whole floors CO_2 emissions. Epoxy coating might be an easy and affordable option, but it will require maintenance activities. Cost-wise, CEM3b concrete slab with epoxy coating could be utilized in industrial halls that have low utilization rates and do not see the use of heavy vehicles. In short, CO_2 emissions can vary a lot, and the target was to model these variances in an analytical way.

6. Industrial Floor Structure

Industrial floors are often constructed, as presented in Figure 1. On top of the soil, there is mounting and leveling gravel to create a flat base for the concrete slab and layers on top of the gravel. Our study focuses on calculating the CO_2 emissions for the concrete slab and the thin top surface layer on top of the base slab. Concrete acts as a base layer in this study as it is the most common industrial flooring option. Concrete is commonly confused with one of its constituents, cement. However, cement is the most important constituent as it is part of "the glue" that holds the other materials together. Concrete is made by mixing cement, other cementitious materials, water, fine aggregates, and coarse aggregates together. Coarse aggregate may also include admixtures, reinforcement, fibers, or pigments [60].
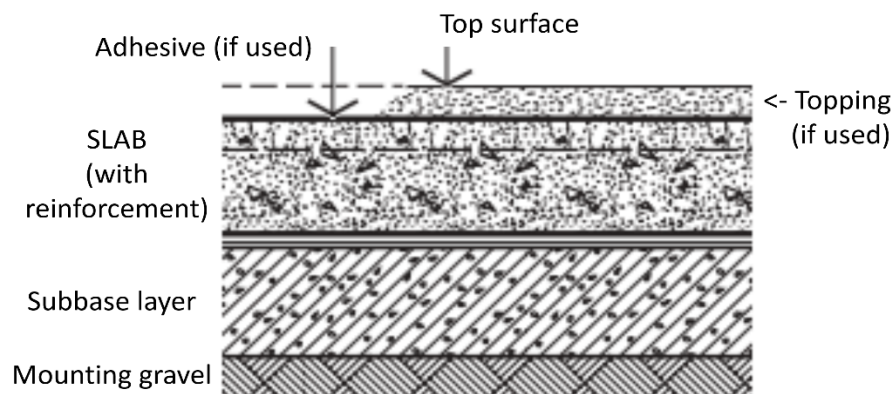

Figure 1. Cross section of a concrete floor structure.

Reducing CO_2 emissions is possible by replacing Portland cement with other materials such as GGBS, fly ash, micro-silica, glass, limestone powder, and chimney clay [61]. Here, GGBS (Ground Granulated Blast-furnace Slag) is a cementitious material whose main use is in concrete and is a by-product of the blast furnaces used to make iron [62]. These blast furnaces operate at temperatures of about 1500 °C and are fed with a carefully controlled mixture of iron ore, coke, and limestone. The iron ore is reduced to iron, and the remaining materials form a slag that floats on top of the iron. This slag is periodically tapped off as a molten liquid. In case it will be used for making GGBS, it has to be rapidly quenched in large volumes of water. The quenching optimizes the cementitious properties and produces granules similar to coarse sand. This 'granulated' slag is then dried and ground to a fine powder. Although normally designated as 'GGBS', it can also be referred to as 'GGBFS' or 'slag cement'.

The strength development of these sustainable concrete mixes tends to be slower than CEM I or CEM II types of cements. This means a longer mold release time or, heat treatment, or accelerator recovery [63]. A report by BIBM suggests, as a rule of thumb, that substituting 50 percent of cement with GGBS equals 40 percent less CO_2 emissions, and substituting 30 percent of cement with PFA equals 20 percent less CO_2 emissions [61]. In Finland, the construction industry has not been aggressive with the implementation of concrete mix products, as the first CEM type III cement did not enter the market until 2021 [63]. There are different types of concrete mixes, of which Portland/CEM1, CEM3a, and CEM3b are analyzed in this report. Portland/CEM1 is the common cement type widely used in the construction industry.

Floor coatings have traditionally been used in secondary spaces, such as engine rooms or spaces where the functional characteristics of the floor play a much more important role than the appearance. A traditional example would

be an industrial hall. In these locations, the floor coating is usually installed directly on top of the concrete base. The coatings are relatively thin and align with the shape of its platform, in which case the concrete base flatness requirements will put some pressure on base slab producers. Also, paint-like coatings, including epoxy-based coating, tend to highlight the defects of the concrete base. To achieve a flat and desired outlook, the casting and surface treatment of the underlying concrete base must be done with particular care and in favorable conditions. As poorly done leveling work may ruin the floor, in some cases, screeds are also used [64]. However, screeds are not included in this report's CO_2 calculations.

Polymer coatings are liquid coatings that utilize epoxy, polyurethane, and acrylic polymer or a cement polymer blend as a binder. The polymer mass consists of two or more distinct phases: a polymer that acts as a binder and a granular component as an aggregate. The aggregate may be natural, quartz, or a wear-resistant mineral such as corundum. Coated floors are concrete floors where the surface has been created as a polymer product to improve the durability and properties of the floor. Polymer mass coating provides a durable, seamless floor. Types of coatings include cement polymer mass, abrasive mass, self-leveling compound, and solvent-free coating. This article analyzes ground epoxy mass as a polymer coating product as it is one of the industrial halls' most durable and frequently utilized polymer products. Ground epoxy coating is suitable for medium and heavy use; see the example in Figure 2. Medium refers to regular walking, repetitive truck traffic, and occasional plastic wheeled carts, and heavy refers to continuous truck traffic, carts with hard plastic wheels, and occasional knocks [65].
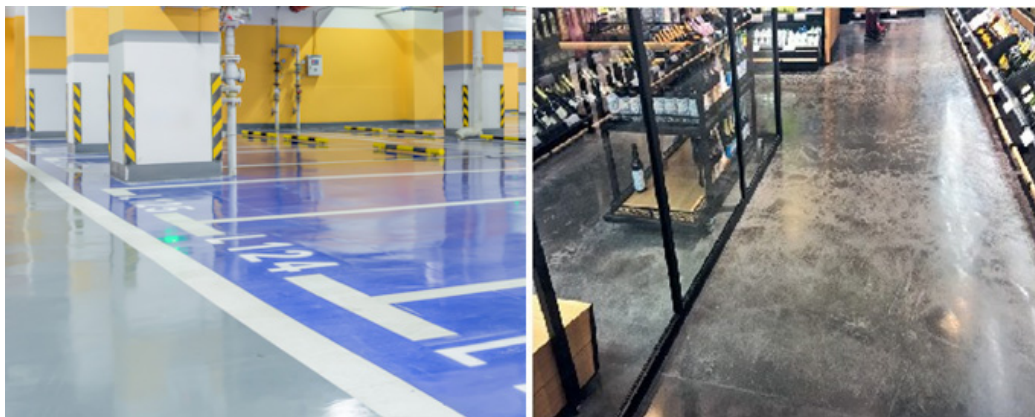

Figure 2. (**Left**): An example of an epoxy coating in a public space (Image by evening_tao on Freepik) and (**Right**): An example of a dry shake-based floor in a public space.

A dry shake is a concrete product without any water. It includes cement and a variety of hard aggregates. A dry shake is applied on top of the fresh concrete base, and it absorbs the water required from the underlying concrete mass. Dry shake can be applied to the concrete base in several different ways. Traditional method utilizes a sled, which is pushed on the casting surface, and the dry shake drains from the sled to the concrete base. In small locations, the dry shake can be applied by hand tossing and leveling. In larger construction sites, the contractors have a spreader attached to the reach stacker, see Figure 3. The advantage of this method is that the dry shake can be applied to the concrete base earlier, thus ensuring enough water for the cement reaction. With manual hand tossing methods, the dry shake cannot be applied before the concrete base has hardened enough that it allows walking on top of it, and thus, it creates a risk that the concrete has dried too much. Finally, a dry shake is ground on top of the concrete base, creating a homogeneous structure; thus, some may suggest that it is not a separate coating product [66]. Figure 3 includes an example cross-section of a dry shake hardener floor. Figure 2 includes an example of a dry shake-based floor in a public space.

The study's dry shake-based floor topping provides strong and nearly maintenance-free floor solutions for industrial purposes. Dry shake-based floor topping is made of Portland (CEM1) cement, also including hard and coarse aggregates, polypropylene microfibers, and additives. During installation, nano-silica is applied, which creates a surface that is denser and harder and improves bonding. Plastic shrinkage and delamination can be minimized with polypropylene fibers and the case company's installation method, which can enhance glossier finish creation together. With a durable and smooth surface, there is less forklift tire wear, and the floor is easier to maintain in its lifetime.
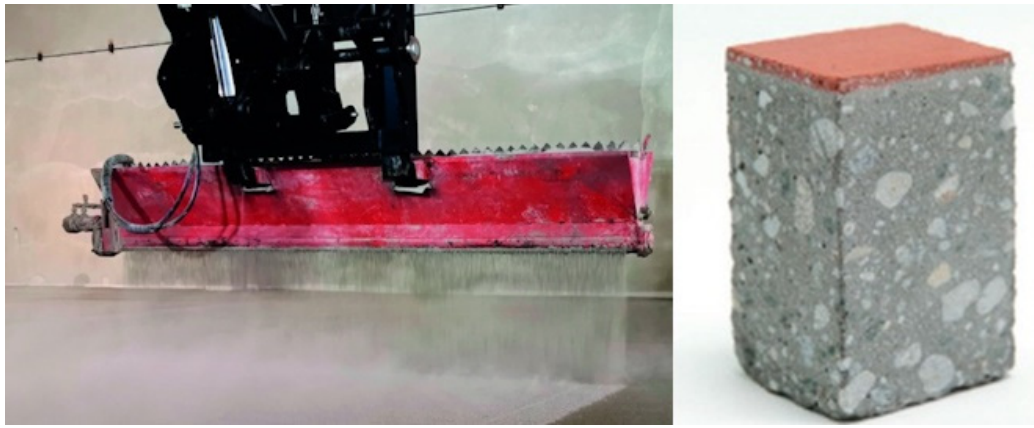
Figure 3. (**Left**): dry shake topping spreader applying dry shake and (**Right**): an example of a dry shake hardener floor in a public space.

7. Carbon Emission Factors for Cement and Concrete

Carbon emission factors collection was challenged by mixed CO_2 emission data available for both cement and concrete. Data was provided in mixed units such as kg CO_2/kg, kg CO_2/tn, and kg CO_2/m^3. Average CO_2 emissions for cement in the UK changed from 668 kg/tn (Weighted average) of all cementitious in UK (includes CEM 1, 2, 3, 4 cements and GGBS and fly ash) to 820 kg/tn (Weighted average) of all factory-made cement in the UK and different mixes for concrete change from 72.5 kg/tn to 157 kg/tn. For CEM1 Portland cement, the values were between 860 kg CO_2/tn and 910 kg CO_2/tn, CEM3a between 480 kg CO_2/tn and 594 kg CO_2/tn, and for CEM3b between 232 kg CO_2/tn and 362 kg CO_2/tn [49,67–70]. For simplicity, in the model, it was decided to use Concrete Centre's values [49] for ground floors as those are suitable for industrial flooring as they are already reinforced with steel, and the values were already in cubic meters. CEM1 concrete 295 kg CO_2/m^3, CEM3a 245 kg CO_2/m^3 and CEM3b 175 kg CO_2/m^3.

The difference between cement and concrete emissions levels relates to the fact that concrete includes only about 10 percent cement, other materials are air, water, fine aggregate, and coarse aggregate. As concrete includes mainly, about 70 percent, fine and coarse aggregates such as sand, crushed rock, stone, and gravel, which CO_2 emissions are immaterial/negligible, thus the total CO_2 emission level decreases [49].

8. Introducing the Model

The following introduces the model to calculate CO_2 emissions in an industrial floor context. The model for CO_2 emissions includes the initial construction of an industrial hall floor, and the maintenance time emissions are calculated based on the data gathered from research phase literature review sources and company interviews. Parameters that were received from the company or were given to limit the number of changeable parameters are the following: Size of industrial floor 10,000 m^2; Depth of the concrete slab 12 cm; Concrete weight 2500 kg/m^3; Time period up to 50 years; An epoxy surface maintenance period every four, six, or eight years and an epoxy surface maintenance cycle related exchange amount need set to 30 percent.

The area to be covered is 10,000 m^2 and the concrete element weight is estimated at 2500 kg per m^3 and slab thickness at 12 cm. The epoxy coating requires maintenance from time to time and it is suggested that the floor should be maintained every ten years [57]. The model uses a more careful maintenance period of eight years instead of 10 years. Re-grounding requires, at minimum, removing at least 0.5 mm of coating with a grinding machine. In typical industry cases tough, surface is damaged deeper than just barely half a mm.

To get back to the original surface quality level, most used passageway areas have to be removed completely, and less utilized but, e.g., chemically/mechanically damaged areas have to be ground up to a level where good base coating with tight contact to the base slab is encountered. For this particular model, a typical industrial case of removal of around 30% of the original mass of epoxy was estimated to cover all resurfacing needs. Averaged out for the whole surface, it would equal 0.9 mm in depth in this model.

Based on these parameters, the concrete requirement is 1200 m^3 to cover the floor area. CO_2 emissions for steel reinforced concrete suitable for ground floors are 175–295 kg/m^3, depending on the concrete quality, as shown in Table 2. As Table 2 shows, CO_2 emissions from concrete deviate from 210 tn to 354 tn. These concrete bases are applied with both topping options to analyze CO_2 emissions from two different floor options with three different concrete base options.

Table 2. CO_2 emission from different concrete mixes.

	Portland/CEM1	CEM3a	CEMb
CO_2 emission factor (kg CO_2/m^3)	295	245	175
Concrete weight (kg/m³)	2500	2500	2500
CO_2 emission factor (kg CO_2/kg)	0.118	0.098	0.070
Concrete requirement (m³)	1200	1200	1200
Concrete CO_2 (kg)	354,000	294,000	210,000

To ensure a durable industrial floor, a recommended coating thickness is at least three mm. Based on research, 3 mm layer requires 5.4 kg per m^2 of epoxy [57]. In the model, the thickness of the epoxy floor coating is a changeable parameter, and thus the requirement for a one mm layer needed to be calculated. Based on the calculation, the requirement for one mm layer of epoxy floor coating is 1.8 kg/m^2. As the area to be covered is 10,000 m^2, the CO_2 emissions are 102.6 tn, as the above Table 3 shows. The requirement of the dry shake is five kg/m^2, of which cement is 35 percent, 1.75 kg/m^2. Considering that the emission factor for CEM1 cement is 0.91 kg CO_2/kg, the case company's specific mineral and cement mix causes CO_2 emissions of 15.9 tn, as shown in the above Table 4. Other dry shake-based floor topping materials have not been included in the analysis as their emissions are immaterial/negligible compared to everything else.

Table 3. CO_2e from epoxy coating.

CO_2 emission factor (kg CO_2/kg)	1.90
Epoxy requirement for initial coating	5.40 kg/m^2
CO_2 epoxy coating	10.26 kg/m^2
CO_2e (kg) for total floor area	102,600

Table 4. CO_2e from dry shake floor coating.

Cement emission factor (kg CO_2/kg)	0.91
Cement requirement	1.75 kg/m^2
CO_2 cement	1.59 kg/m^2
CO_2e (kg) for total floor area	15,925

Figure 4 shows CO_2 emissions for both toppings, epoxy coating, and case company's dry shake-based floor coating with different concrete base options, Portland/CEM1, CEM3a, and CEM3b. It shows that the CO_2 emissions are higher for epoxy than for the case company's dry shake-based floor coating, and it also shows that CO_2 emissions decrease when the concrete base includes more fly ash or GGBS instead of cement, meaning CEM3a or CEM3b is used instead of Portland/CEM1. The total CO_2 emissions can be affected in different ways depending on the requirements for the industrial floor in question. A simple way is to use less pollutive coating, such as the modeled dry shake-based floor coating, instead of epoxy coating. Even bigger effect is achievable, in the total CO_2 emissions viewpoint, by utilizing concrete mixes that use secondary source cementitious materials, like is the case with CEM3 cements.
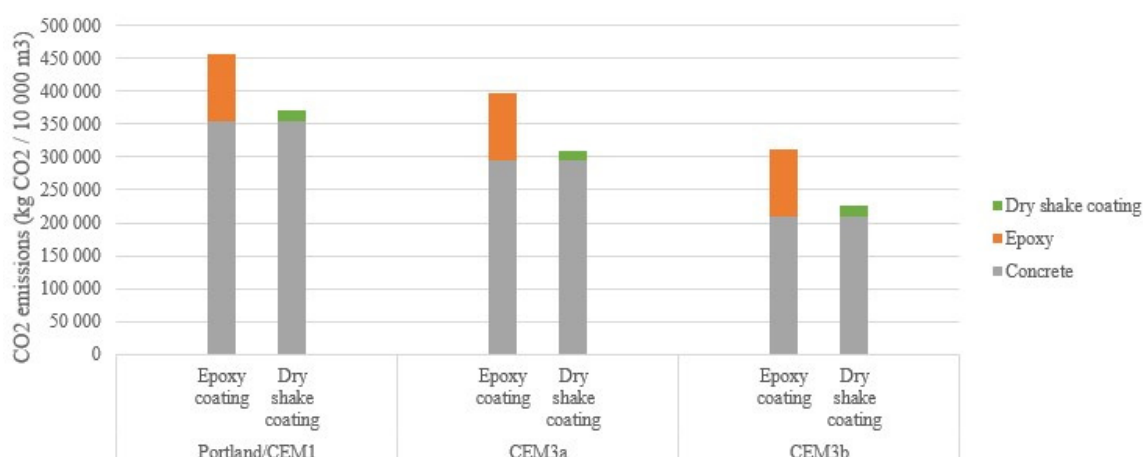
Figure 4. CO_2 emissions for different industrial floors (excl. maintenance).

Maintaining the floor requires the removal of the whole surface, averaging 0.9 mm of the surface coating. After that, a new one mm layer of epoxy floor coating is added, which requires 1.8 kg of epoxy floor coating per m^2. Table 5

shows that each maintenance round causes 34.2 tn CO_2 emissions, and within a 50-year timeline, the floor requires maintenance six times in this 50 years' time, which means a total of 205.2 tn CO_2 emissions for the given timeline. The model did not include the emissions from energy usage of the grinding machine as it is not considered a major source of CO_2 emissions, compared to the used and needed epoxy-related emissions.

Table 5. CO_2 emissions from maintenance with 8-year maintenance period.

Maintenance Period	Eight Years
Epoxy requirement for maintenance	1.8 kg/m^2
CO_2 emissions for epoxy coating in maintenance	3.42 kg CO_2/m^2
CO_2 (kg) for a total floor area of 10,000 m^2	34,200
Maintenance times during a period	6.0
CO_2 emissions (kg) for total floor area (during lifetime)	205,200

9. Results and Analysis

The following analyses model-based results for the CO_2 emissions for different industrial floor solutions. We also present the findings based on the model and the differences between the compared solutions. The analysis is concluded by describing the most favorable solutions based on low CO_2 emissions. Figure 5 shows how different concrete options add up as CO_2 emissions within an eight-year maintenance period for the epoxy surface. Black lines represent floors with epoxy coating and green lines floors with the modeled dry shake-based floor topping. Grey bars represent CO_2 emissions for each maintenance round. When the maintenance period is decreased to six or four years, the total CO_2 emissions increase as there are more maintenance rounds during the floor's lifetime, as presented in Figures 6 and 7.
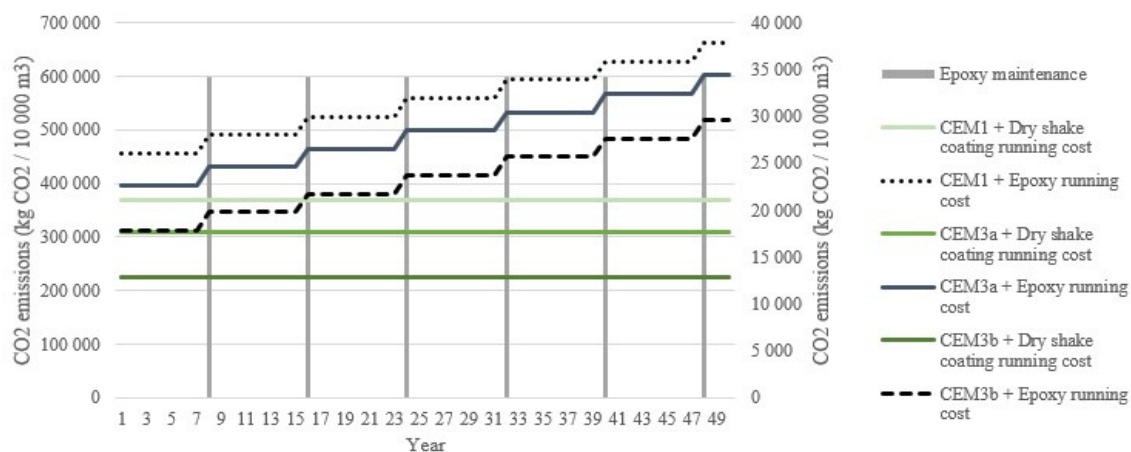

Figure 5. Comparison of CO_2 emissions from Case Company's dry shake-based floor topping and Epoxy coating with 8-year maintenance period.
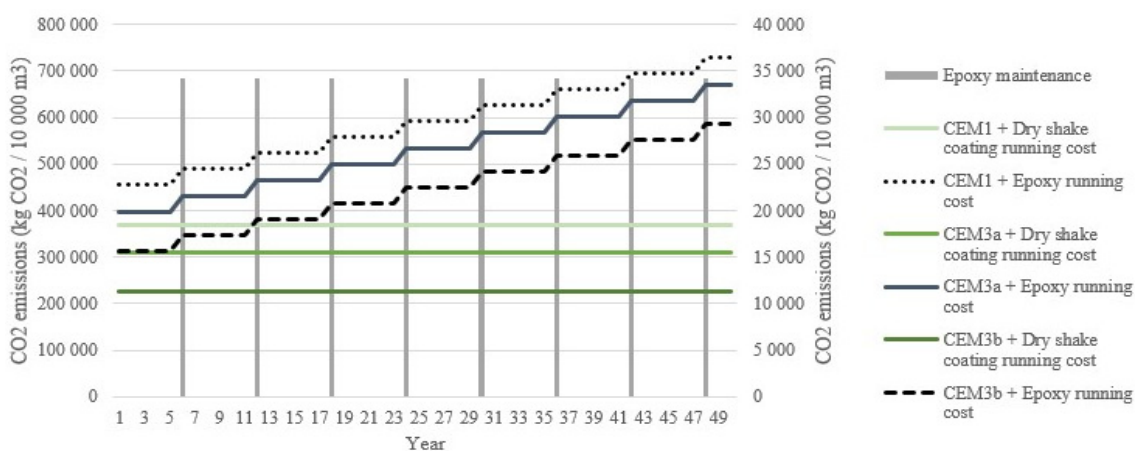

Figure 6. Comparison of CO_2 emissions from Case Company's dry shake-based floor topping and Epoxy coating with 6-year maintenance period.
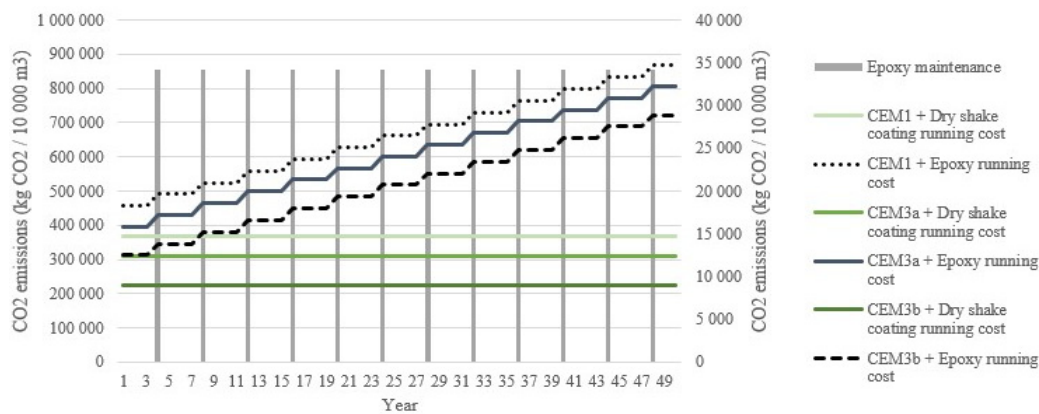
Figure 7. Comparison of CO_2 emissions from Case Company's dry shake-based floor topping and Epoxy coating with 4-year maintenance period.

10. Deeper Look to the Modeled Results

As shown in the previous Figure 4, the base slab causes most of the CO_2 emissions of the modelled floor. With the Portland/CEM1 base slab, the CO_2 emissions are the highest, causing 350 tn CO_2 emissions when the floor base is created. If CEM3a is used, a mix that includes 30 percent of fly ash, the CO_2 emissions decrease by more than 50 tn to 294 tn. If CEM3b is used, a mix that includes 50 percent GGBS, the CO_2 emissions are substantially lower than with CEM1, at 210 tn. When coating options are included in the analysis, the difference becomes even larger. Figure 4 also shows that the epoxy floor coating causes 102.6 tn CO_2 emissions when the floor is initially covered, whereas the dry shake-based floor topping causes only 15.89 tn CO_2 emissions when the concrete is coated. When these CO_2 emissions are added on top of the CO_2 emissions from the concrete base, the most polluting option, Portland/CEM1 concrete base with epoxy coating, causes a total of 456.6 tn of CO_2 emissions, and the most sustainable option, CEM3b with the modeled dry shake-based floor topping, only about half of the previously mentioned most polluting option, resulting just 225.9 tn of emissions. Figure 4 shows that the total CO2 emissions are higher for an epoxy coating with CEM3a slab than the dry shake-based floor topping option with Portland/CEM1 base slab. Additionally, Epoxy coating with CEM3b has about as high CO_2 emissions as the modeled dry shake-based floor topping with CEM3a. Notice, that these CO_2 emissions represent the emissions that are already realized when the floor is initially constructed and thus do not include CO_2 emissions from maintaining the floor within its lifetime.

With lifetime modeling, the epoxy coating option becomes less sustainable with time. When the floor maintenance is included in the analysis, each maintenance round causes 35 tn CO_2 emissions (Table 5). In the model, analyses of CO_2 emissions for the epoxy coating maintenance cycle were made for 8-, 6- and 4- years' time cycles. The modeled dry shake-based floor topping does not require any surface grinding and resurfacing maintenance. Figure 5 reveals that at the end of the 50-year time frame, the total CO_2 emissions for epoxy floors with CEM1 to CEM3b bases is from 518 tn to 662 tn, with an epoxy coating maintenance cycle of 8 years. Figure 5 also shows that the only case where epoxy coating does fewer emissions than dry shake-based floor is the case with CEM3b concrete base slab, and this only happens when compared to the most emissive (worst case) dry shake-based floor topping option with Portland/CEM1 concrete base, and only in the beginning of the process, before any maintenance is done. However, after the second maintenance round, 16 years after construction, the epoxy option exceeded the CO_2 emissions, compared to the dry shake floor topping floor, as the dry shake-based floor topping did not cause any CO_2 emissions after it was initially constructed.

When maintenance is required every six years, the CO_2 emissions will of course, get higher, as there will be additional maintenance rounds. Figure 6 reveals that at the end of the 50-year time frame, the total CO_2 emissions for epoxy floors with different concrete bases change from 586 tn to 730 tn. Epoxy coating with CEM3b concrete layer becomes more polluting than the modeled dry shake-based floor topping option with Portland/CEM1 concrete base, once again, after the second maintenance round, which is already happening in year 12. When maintenance is done every four years, the break-even point with the dry shake-based floor topping is already at eight years. After that, the epoxy coating, even with CEM3b base slab, generates more CO_2 emissions. The total CO_2 emissions deviate from 723 tn to 867 tn, as shown in Figure 7.

Table 6 shows total CO_2 emissions from the entire 50-year time frame for all product combinations. It also shows how the maintenance periods affect the amount of CO_2 emissions. It reveals that within the 50-year time frame, dry

shake-based option will always be more sustainable, causing less CO_2 emissions than an epoxy coating, especially thanks to its expected maintenance-free lifetime of 50 years.

Table 6. The total CO_2 emissions from a 50-year time frame.

	Epoxy Coating			Dry Shake-Based Coating		
	Portland/CEM1	CEM3a	CEM3b	Portland/CEM1	CEM3a	CEM3b
Four years	867 tn	807 tn	723 tn			
Six years	730 tn	670 tn	586 tn			
Eight years	662 tn	602 tn	518 tn			
No maintenance				370 tn	310 tn	226 tn

The analysis highlighted the main aspects of the model calculations. However, the fact that cannot be underlined enough is that due to the maintenance, the dry shake-based option gets lower CO_2 emission values with all concrete mixtures in the long-term, which is especially important, as there is no CEM3 available for everyone.

11. Analysis and Discussion

In the model, the industrial floor with different two different coatings, (1) epoxy coating and (2) modeled case company's dry shake-based floor topping, were compared. Results showed that the dry shake-based floor topping was always a less polluting option compared to epoxy coating, when lifetime maintenance was taken into account. However, a substantial part of the CO_2 emissions from industrial floor construction was generated by the concrete base. When CO_2 emissions from maintaining the industrial floor were included, the model showed big benefits for the modeled dry shake-based floor topping. This model included fixed parameters such as the size of the industrial floor, base floor slab thickness, epoxy layer thickness, epoxy floor coating maintenance requirement, CO_2 emissions of epoxy floor coating, epoxy surface for removal, CO_2 emissions of cement and concrete, and the requirement for the modeled dry shake-based floor topping. Changes in any of these parameters would affect the model calculations.

Additionally, the model excluded cement transportation (factory to construction site) related emissions, and emissions from energy usage from grinding the concrete floor before applying the top coating. However, adding these CO_2 emissions would most probably increase the CO_2 emissions in total, but the emissions would be almost the same for both epoxy coating and the modeled dry shake-based floor topping, within a negligible error margin. As a future development item, the CO_2 emission model could be developed to include more fine details, but with current knowledge, it is not expected to change the big picture.

12. Conclusions

The motivation for this study is the fact that the construction industry is currently burdening the environment with a vast amount of concrete production [71–75], which could be eased up, with prover awareness additions [7]. However, concrete is durable and thus a natural choice for construction and, also not easy to replace. All this means that we need to seek every potential option to decarbonize cement and concrete production [76]. But at the same time, we do have some societal and industry barriers to being sustainable in concrete-related constructions [77–79]. Even though there are good options for making concrete less environmentally harmful [80,81], the construction industry bases building block elements [82,83]. Additionally, on top of concrete slab emissions, one of the most common coating options, epoxy resins, adds their own extra CO_2 emission burden. Epoxy resin production uses fossil fuel bases as the main base element, and recycling epoxy resin coatings is currently considered technically extremely challenging or non-feasible effort to be done and economically non-viable option to be taken, in case there are no major substitutions given for doing that. From these viewpoints, the study has calculated the CO_2 emissions for different concrete and epoxy coating options, looking for solutions that would be less emission-prone, that the most traditional ones, mostly in use at the moment.

The study has presented model-based emissions for different concrete mixes, which are made from the traditional 100 percent Portland cement, CEM3a, and CEM3b options. The CO_2 emissions from these concrete mixes as part of industrial floor total emissions were compared and analyzed. Additionally, the study compared traditional epoxy coating with the more recent and modern novel dry shake-based option as base slab floor coating options. CO_2 emissions for these were collected and a model was created to calculate and compare different options emission rates for multiple different time frames. First, an initial model was created, which was then completed with more detailed data, such as information regarding the maintenance needs, intervals, and assumptions for maintenance depths on those floor coating

options. Also, the emissions rates for the epoxy coating option were added, too. After model enhancements, the results were calculated and analyzed to understand further where the underlying realities are in initial and time dimension-related emission rates.

Results show that the concrete-based dry shake option, when compared to epoxy resin, using the exact same base slab, is always a more ecologically friendly option than epoxy coating due to higher CO_2 emissions per unit and more frequent maintenance needs in the case of the epoxy-coated floors. In floor construction, most CO_2 emissions come from the base slab [84], since the required huge amounts of concrete on it, when compared to sleek and slim coatings on top of the tight base slab. The CO_2 emissions could be lowered by increasing the amount of fly ash or GGBS in the concrete mix. However, as the global required amounts of concrete are huge and thus cause the main part of the CO_2 emissions, but at the same time, there just is not enough more sustainable base slab mixes available for everyone, it is evident that CO_2 reductions should be looked from many different angles and other locations too. More attention is needed to be given to the coating selection and its environmental impacts, while at the same time, we keep studying yet new sustainable concrete mixes for the base slabs [85–87]. The choice between these two coating options is a mix of multiple variables-based optimization solutions. It will definitely be based on the properties required for the floor to offer for the intended use purposes. In case the heavy use requirements, such as truck traffic, a lot of warehouse & logistics items storage carts with hard wheels, and occasional hard knocks and hit damages expected to happen [34], one should look at the dry shake-based options, with any preferred concrete mix based base slab, as these are likely the preferred solutions. It all boils done to the fact that the dry shake-based coating is harder than epoxy, and it has been shown to be overall less pollutive and also requires less maintenance, even in heavy use cases, and the hardness of the surface can even be enhanced with special surface hardening chemicals [88]. On the other hand, in light use cases, such as regular walking and just occasional plastic wheeled carts movements, maybe the epoxy coating could be seen as a compromise with CEM3b concrete mix to lower the CO_2 emissions, which are going to be negatively affected, because of the petroleum-based raw materials, used in floor epoxy mixes.

A recent model calculates CO_2 emissions for three different types of concrete mixes and for two different floor coating options. Set of new novel sustainable concrete mix solutions, e.g., those which utilize different society waste streams [89], crack preventive solutions [90], recycled aggregate concrete mixes [91], and organic materials like sawdust mixed options [92]. In addition to the base slab sustainable mixes, studying new coating options would be an interesting addition to future models, as would be wider range of fleet level analysis on transportation and sutainable concrete products management solutions too [93,94]. In the details enhancements front, our study did exclude some minuscule emission sources, and emissions which would be basically the same for all the compared cases. These excluded sources, e.g., CO_2 emissions from transport and energy usage, were known to be basically the same for all options compared, but that might not be the case if the model were extended with extraordinary cases. So, suppose a total overall covering CO_2 emissions calculations are needed, or the model is made to include special kinds of base slabs and/or coating options. In that case, these emissions sources should also be included in the analysis process. One example of current technology development is autonomous vehicles [95], which could be optimized to move in special ways, with special coatings, and as such, also made less destructive for those special top-coated floor surfaces. Lastly, we suggest developing the model to compare the economic impacts too, e.g., to include the prices of the different solutions in the analysis and see how the newest technologies like artificial intelligence (AI) [96–98] utilized in traditional industries like the construction industry, could change the emissions and cost structures.

Author Contributions

Conceptualization, P.K. and A.H.; Methodology, P.K. and A.H.; Software, P.K. and A.H.; Validation, G.Á.C. and A.H.; Formal Analysis, P.K.; Investigation, P.K.; Resources, A.H.; Data Curation, P.K.; Writing—Original Draft Preparation, P.K.; Writing—Review & Editing, P.K. and A.H.; Visualization, P.K.; Supervision, A.H.; Project Administration, A.H.; Funding Acquisition, A.H.

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