

Article

# Carbon Emissions of Construction Processes on Urban Construction Sites

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**Abstract:** For Europe to achieve “climate neutrality” by 2050, emissions from all economic sectors must be reduced to the absolute minimum. In addition to changes in raw material extraction and building material production, the construction industry must embrace emission-free construction sites. The present paper suggests a method to calculate carbon emissions on construction sites by defining all fuel-consuming processes while relying on established European standards. A set of system boundaries is defined to single out emissions that occur in the construction industry sphere. These definitions are essential to calculate savings through the entire construction process. This method is subsequently used to assess the carbon balance of four exemplary construction sites in Austria, which cover the total span of the construction life cycle. Results show that the largest share of emissions is attributed to transport during the construction of new buildings, followed by emissions from demolition and building processes.

**Keywords:** construction processes; carbon neutrality; sustainable construction methods; sustainable building construction; life cycle assessment; construction site operation; construction equipment



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## 1. Introduction

Recently there has been significant progress in energy-efficient construction processes, ecological building materials, and recycling. Nevertheless, the environmental impact of construction activity has hardly ever been considered in the literature. This research paper aims to identify all, directly and indirectly, generated CO<sub>2</sub>-equivalent (an artificial unit that accounts for the global warming potential of any desired compound of substances by converting the substances' resulting global warming potential into a mass of carbon dioxide that has an equal global warming potential as the compound) (CO<sub>2</sub>eq) emissions on urban construction sites and shows the methods, technologies, and framework conditions for their substitution or compensation. These conditions include reduced CO<sub>2</sub>eq emissions through shorter construction time and optimization of the process chain with lean management and CO<sub>2</sub>eq credits using construction resources. The construction processes are subdivided to balance the emissions. The authors assigned diesel and electricity consumption, transport kilometers, and other emission sources to the respective process steps. The results further show that emissions depend on additional factors, such as the construction methods used, the size of the machinery, the site's location, and logistics. Four exemplary construction sites (building construction, road construction, renovation, and demolition) are defined for the balancing. Their emissions are calculated with the help of a tool developed in the project using the ecoinvent database [1].

The research identifies several opportunities and obstacles in the context of carbon neutral construction site management. Due to the climate targets set by the European Union [2] to increase the share of renewable energy sources in electricity to over 80% by 2050, local energy providers will supply many construction sites with renewable electricity in the future. The reduction of waste can potentially mitigate existing emissions through new digital technologies, such as the digital twin, which represents a virtual representation of

buildings over their life cycle [3,4], predictive construction site process simulations, and lean construction organization. The ongoing development of alternative energy sources and related drive systems could replace liquid fossil fuels and provide an alternative to battery-powered construction equipment [5]. A volatile electric construction equipment market further illustrates the rapid development of low emission drive technologies for construction equipment.

Another contributing factor to introducing carbon neutral construction processes is the expected implementation of carbon dioxide taxation in Austria [6]. In this context, taxing CO<sub>2</sub>eq-intensive processes or favoring carbon neutral construction site activities can be done through a standardized methodology for recording the CO<sub>2</sub>eq balance of a construction site. Further development is a standardized emission certificate for construction sites—a transparent tool to compare construction sites with each other for the end customer. Subsequently, policymakers will be called upon to set limits for the permissibility of climate compatibility or to open funding pots for low-emission construction sites.

### 1.1. Related Work

Monitoring CO<sub>2</sub>eq emissions at construction sites has been the subject of several previous studies [7–10]. In Austria, the researchers of the RUMBA project (“Richtlinien für umweltfreundliche Baustellen-Abwicklung”; Engl.: “guidelines for environmentally friendly site management”) developed guidelines for an environmentally friendly construction site [11], including site management guidelines and proposed measures to reduce pollutants and CO<sub>2</sub>eq emissions. The steps are evaluated according to the type of construction site, while their effectiveness and costs are examined based on case studies. Furthermore, the Austrian Federal Environment Agency published a document on air pollution reduction on construction sites. The document mainly focuses on organizational measures and ecological construction tenders [12]. Another milestone for carbon neutral construction site management was set in Switzerland with the carbon neutral construction of the Umweltarena Spreitenbach in 2010 [13]. Recently, the methods for measuring and assessing the carbon footprint of construction sites have increasingly become the focus of international research teams [9,14].

Other studies look at the emission balance of individual aspects of construction, for example, the production of asphalt surfaces [15]. In their research, Hong et al. [16] propose identifying CO<sub>2</sub>eq emissions using a machine-learning-based algorithm, which estimates exhaust emissions and energy consumption on construction sites in real time. Simonen et al. provide detailed benchmarks for the amount of embodied carbon of buildings (also: “grey energy,” all carbon emissions necessary to construct buildings, including upstream processes of building materials) of various types and sizes in the United States [16], while another worldwide meta-study shows similar values for embodied emissions [17].

In contrast to the presented research, the present paper aims to identify possible system boundaries for all CO<sub>2</sub>eq on-site emissions and related key processes and parameters. Additionally, the study seeks to answer the CO<sub>2</sub>eq contribution of the construction stage compared to other life cycle phases of a building.

#### 1.1.1. System Boundaries

The selection of proper system boundaries is essential for every life cycle assessment’s (LCA) success and quality. The choice to involve or leave out key system pieces can influence results unlike any other component of the study’s methodology.

Previous research attempts to balance carbon dioxide emissions from construction activities have identified multiple approaches. However, many draw incomplete system boundaries since on-site assembly works are left out [8]. The use of different systems proves insufficient due to the risk of so-called environmental burden shifting or the relocation of emissions in various stages of the life cycle of an interconnected system or a different impact category [18]. Therefore, it is essential to view the whole system, single out the most significant emitters, and minimize the effects of burden shifting from one stage of

the building process to another. On the other hand, including all of the upstream flows is barely possible, as Nässén et al. [19] suggest, since the number of material flows grows exponentially with the number of upstream levels.

Other LCA studies discuss emissions from material production, including transport of raw materials, transport of building materials to the site, transportation of workers to the site, and the construction process directly [20]. In some studies, the operation of the building is also included [21], which moves the focus away from construction, leads to a more comprehensive analysis of the system, and further clarifies the impact of construction processes on the object's life cycle. Yang et al. [22] divide the emissions mentioned above into direct carbon dioxide emissions from burning fuel in machinery engines and indirect emissions from the production of electricity used on site.

### 1.1.2. Reduction Potentials on Site

The reduction of carbon emissions over the life cycle of a building can take place in three main areas: in the planning phase (choice of materials), during on-site activities (including demolition), and during the operation phase of the building. Because the highest emissions occur during the building operation [23], planning is of great importance, as pointed out by several authors [24–26]. Acquaye [10] further suggests that good design practices cut indirect (upstream) emissions by 20% [10]. In contrast to the research presented above, this paper focuses on the construction phase and on-site activities with the respective reduction potentials. The potential impact on other phases is discussed briefly.

The impact of improved working efficiency on the emission balance is another finding. Along with reducing fuel use and directly saving emissions, the reduction of idling time has a positive effect on extending the life of engines. Increasing productivity and reducing idling time can be achieved through taking effective measures in the planning stage [27]. Additionally, prefabrication substantially lowers on-site emissions by cutting construction waste by 52% for residential buildings and avoiding transportation [28].

Regarding road construction, Karlsson et al. found that changes in asphalt production and pavement could reduce up to 35% of greenhouse gas (GHG) emissions, leading to a drop in asphalt emissions by over 60%. Lower temperatures in asphalt paving could reduce emissions by another 12% by 2025. Furthermore, electrified construction machinery and crushing plants, along with carbon capture and storage in the cement industry, could lead to a 25% reduction in CO<sub>2</sub>eq emissions by 2030, and the scenario of electrification of cement and steel production could rise to 35% by 2045.

The authors point out that most articles focus on the material production and design phase. Research does not give specific reduction potentials for construction sites themselves. Introducing a rigorous integrated planning process is inevitable regarding the possible improvements for on-site execution. Together with improved interaction between the project's primary stakeholders, better mobilization of the project and a lean approach to coordinate the different disciplines on the site could lead to a surge in productivity by up to 50% [29]. However, if and to what extent this would translate to a reduction of emissions is uncertain.

### 1.1.3. Results

In a previously conducted highway tunnel study [21], casting and lining, rock support, and road work were detected as the processes with the highest emissions during construction. Per meter tunnel, off-road machinery emits 57–60 t, material 24–52 t, and transportation less than 1.5 t CO<sub>2</sub>eq. The relative distribution of GHG emissions from materials and energies in tunneling shows that electricity use is the most significant contributor, accounting for 52–69% of all CO<sub>2</sub>eq emissions, followed by 25–31% from cement production. In total numbers, the CO<sub>2</sub>eq emissions per lane and meter tunnel are between 20.5 and 28.4 t CO<sub>2</sub>eq. In a study about a tunnel project in China [30], 60% of CO<sub>2</sub>eq emissions were assigned to material production, 18–25% to off-road machinery, and 12% to transportation.

A study about finished road projects involving asphalt and concrete roads [20] shows that asphalt roads produce about 2.5 times more CO<sub>2</sub>eq emissions than concrete roads of the same dimension (500 vs. 1250 t CO<sub>2</sub>eq per lane per km road). The reason is that the high energy required to heat the asphalt before paving is the most significant contributor to higher CO<sub>2</sub>eq emissions compared to other contributors for the concrete variant, steel, and concrete production.

Hong et al. [8] discovered that of the whole CO<sub>2</sub>eq footprint from their case study project, a residential complex, about 95% of all CO<sub>2</sub>eq emissions came from building material production, 3.6% from material transportation from and to the site, and only 1.9% were directly produced on site. From these direct on-site emissions, over 79% of CO<sub>2</sub>eq emissions stemmed from on-site electricity use, compared to just 11% from construction machines and 3.5% from (on-site) transportation. In their analysis of on-site carbon emissions, Zhang and Wang [31] also recognized the largest share (85–98%) to stem from on-site electricity use. The disproportionately high emissions from electricity use in Chinese studies are probably due to China's increased share of coal power plants—more than 50% [32]—and a high carbon impact of electricity use in relation to European countries.

A similar study [33] was completed, in which the CO<sub>2</sub>eq emitted only during on-site activities and transportation was evaluated. The study concluded that fuel for transportation and fuel and electricity used on site were the sole sources of CO<sub>2</sub>eq emissions and simultaneously an efficient way to measure carbon dioxide emissions. Accordingly, the type of building material and transportation distances were identified as the most critical parameters for the number of emissions.

A previous article by Weigert et al. suggested various methods to reduce carbon on-site emissions [34]. This list is updated here, while more exact data are provided for the extent of reduction. Initial results from the research on which the study is based, together with the evaluation of sample construction sites and an opinion survey, show the most significant CO<sub>2</sub>eq emissions on a construction site. These arise from electricity and diesel consumption by large construction equipment and transport, representing areas with the most potential for savings. One possibility of evaluation would be to relate the CO<sub>2</sub>eq emissions to the site dimensions and construction time by linking the construction methods and the resource use of construction equipment and personnel with the quantities and the construction time. This idea calls for construction operations research and the creation of a corresponding LCA database.

### *1.2. The Goal of the Research*

The article represents a part of a research project that aims to lay a foundation for carbon neutral construction sites. The research process contains three steps to reach this goal: the CO<sub>2</sub>eq evaluation of existing on-site processes, the exploration of possible reductions of GHG emissions, and the deployment of measures to real construction sites to verify the reductions. These steps go along with the economic implications of measures and a forecasted timetable to reach carbon neutral construction sites.

This article specifically addresses the first step where data from construction sites are analyzed to calculate CO<sub>2</sub>eq emissions a posteriori, and through inductive research methods standards such as system boundaries, a calculation method for direct and indirect CO<sub>2</sub>eq emissions from on-site construction processes is developed. These standards should avoid burden shifting for every construction process. Another goal of the research is to determine critical construction processes by applying the suggested method to four different use cases and comparing the collected data. The results should highlight the CO<sub>2</sub>eq contribution of the construction stage compared to other life cycle stages.

## **2. Methods**

To address the questions above, the authors examined four different construction sites, balanced them a posteriori, and evaluated the impact on the construction processes as well as on the other stages of the life cycle. A workflow diagram showing how the

authors calculated emissions is presented in Section 2.2. A significant challenge is to single out construction processes from the whole life cycle while suppressing the other phases without neglecting their mutual impact on construction processes.

Four exemplary construction sites (“Use Cases”) are examined. One of them is a newly built, “classic” Viennese ten-story residential building complex with 200 units. The second is the restoration of an existing residential building complex also located in the city of Vienna. The third sample site is an asphalt road construction in an urban environment. The fourth is the deconstruction and demolition of a large office block outside Vienna.

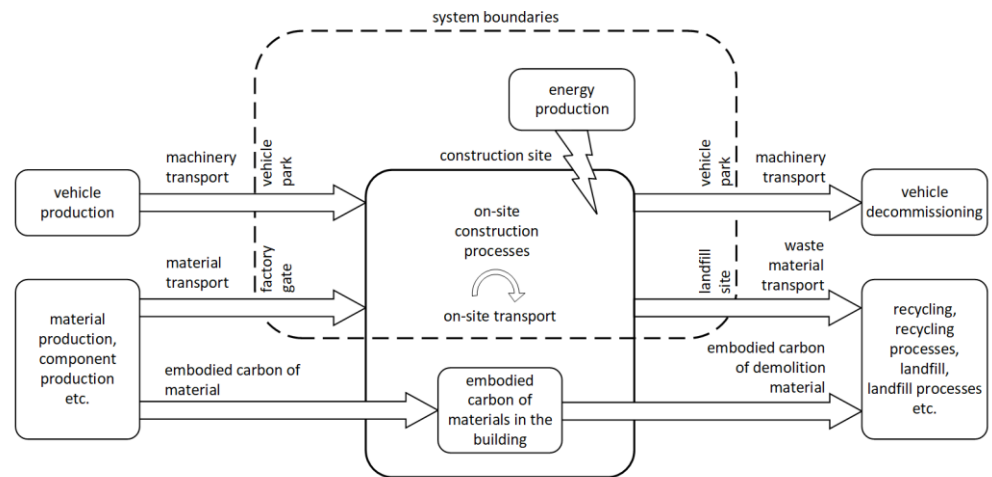
Emissions originating from construction machinery are estimated by the usage time from on-site records (diaries of construction progress) and the assumption of average fuel consumption based on the engine’s power. In his doctoral thesis, C. Winkler [35] provides the engine power and fuel consumption ratio per hour. Data for electricity consumption stems from electricity bills provided by the contractors. The conversion of both to CO<sub>2</sub>eq was made using the ecoinvent database [1], applying the electricity mix for the Austrian electricity market.

### 2.1. System Boundaries

The system boundaries are an adjusted version of the balancing method suggested in EN 15804 [36]. The selected system shows the maximum impact, and changes within those processes maximize the balance to emphasize on-site construction processes. Most off-site processes are left out of the system to reduce the “background noise,” which is not relevant to the scope of this research. For this purpose, construction materials, components, and machinery supply chains are not considered part of the system.

The system includes all processes on site, all transports of the materials and components from the factory gate or, if an intermediary is involved, the place of the last storage location of the materials used and transports from construction machinery from the vehicle park to the construction site and back. Individual transport of construction personnel is not part of the system. Emissions from upstream processes, such as extraction of materials, prefabrication of components in a plant, or processes that involve handling raw materials, are also excluded from the system. An exception is any electric energy consumed during construction: emissions from energy production are part of the system because they are vital to the construction process. This approach is highly justified because reducing primary energy consumption is one of the most efficient ways to reduce carbon on-site emissions.

According to EN 15804 [36], the measure of distance applied should always be from the factory gate to the construction site for transporting building materials, machinery, and components. However, the research team deviated from this recommendation because this would shift the scope of the study to optimizing global logistics rather than construction sites and water down the results obtained for construction-relevant processes. Similarly, transport from the construction site is limited to the place of the first treatment or storage facility, for example, a landfill site. Figure 1 gives a detailed overview of the system boundaries.

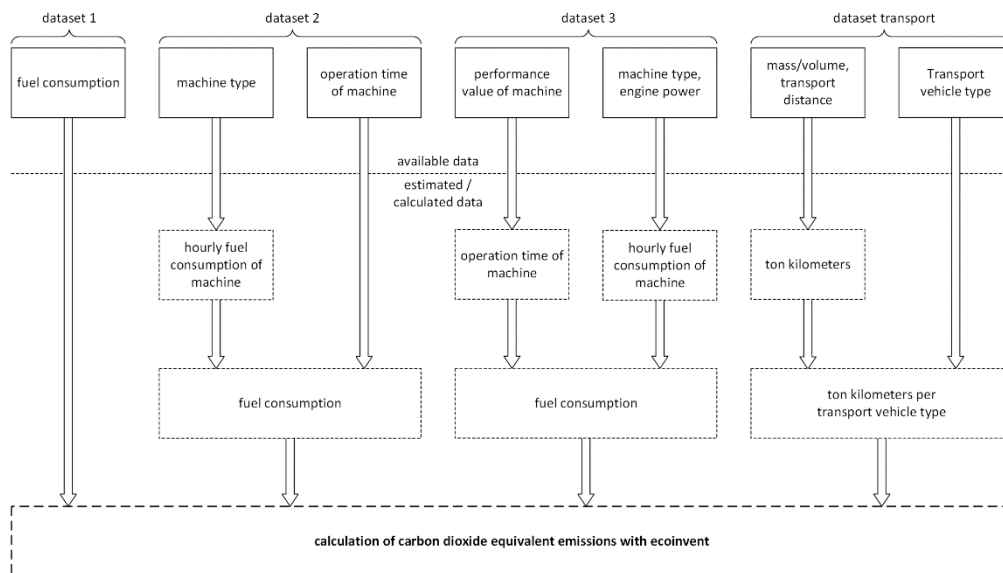


**Figure 1.** System boundaries.

2.2. Process

Different datasets needed to calculate CO<sub>2</sub>eq are available on various construction sites. The quality of this estimation is determined by the quality of the underlying data, which varies over the Use Cases and types of machinery.

Our “dataset 1” comprises the available amount of consumed fuel (specifically diesel, electricity, or other energy carriers). This kind of dataset allows for the fastest and most accurate calculations of CO<sub>2</sub>eq emissions. If electricity was used on the construction site, data for electricity consumption is obtainable through energy bills, and resulting CO<sub>2</sub>eq emissions could be calculated. Diesel bills were available for only one site but were incomplete, so diesel consumption is calculated for all sites as described below and in Figure 2.



**Figure 2.** Process diagram for estimating CO<sub>2</sub>eq emissions.

For some cases, data for operation time were available (“dataset 2”). With knowledge of the machine’s type and its respective operation time, the hourly fuel consumption can be calculated using prior assessments by C. Winkler [35] and multiplied by the operation time to obtain total fuel consumption and resulting CO<sub>2</sub>eq emissions.

In some cases, the operational time also is estimated by assuming performance values for the machinery and applying these to the units of the contract documents or the billing (whichever is available, “dataset 3”). This dataset is generally avoided within the project since it has the most underlying assumptions. It is used only to calculate emissions from the excavation in Use Case 1.

If the type and power of the construction machinery used had not been available, this would also have had to be assumed. The whole work preparation for the construction site would have had to be recreated and recalculated. However, this is not the case for the presented use cases.

The total mass of the transported goods (material, components, machinery, waste) is multiplied by the transport distance to calculate the emissions of transport to and from the construction site. Ton kilometers (tkm) can be converted to CO<sub>2</sub>eq using the ecoinvent database [1]. Information about the size of the transport vehicles that were used, which significantly impacted emissions, was either available or, in some cases, estimated. In this study, no distinction is made between transports that were likely limited by mass (for example, soil) and those that were likely limited by the volume of the transport vehicle (for example, thermal insulation) since the underlying data in ecoinvent assumes a moderate loading level. Additionally, empty trips are included in the ecoinvent dataset and were not considered. Figure 2 gives a detailed overview of the emission estimation process for the various datasets used for machinery and transport.

Emissions are categorized using the classification suggested in EN 15804 [36]. A German version of the standard is used, while the names of the categories are translated into English for this article.

### 3. Use Cases

Altogether, the research looks at four different realized construction projects. The projects are of typical size for local circumstances in Vienna. Together, Use Cases 1, 3, and 4 offer all relevant construction processes of a building’s life cycle: construction of the building, renovation and restructuring, and finally, demolition of the building. The renovation of a currently constructed building will not occur until at least 20 years from now, and demolition will likely take place in 50–100 years or more, timeframes in which construction methods will most probably drastically change. Additionally, the renovated building is a brick construction, and the newly constructed and the demolished buildings are reinforced concrete structures. Since the construction sites mentioned above for a single building occur in different time periods, the use cases focus on the status quo to show room for improvement in further research.

The data for energy consumption and CO<sub>2</sub>eq emissions are processed as suggested in Section 2.2, displayed in Figure 2. Numbers were normalized to 1 m<sup>2</sup> gross floor area (GFA) for buildings or 1 m<sup>2</sup> asphalted surface, respectively, comparing different structures and stages of the life cycle convenient.

#### 3.1. Use Case 1—New Construction of a Residential Building

The first use case is defined as a ten-story building (8 above ground, two underground) constructed as a reinforced concrete structure (about one half in situ concrete and the other half precast concrete) with 2000 m<sup>2</sup> constructed area, 17,000 m<sup>2</sup> gross floor area containing 200 flats, 150 car parking spaces, and 300 bicycle parking spaces. Construction used 1750 m of bored piles and 5300 m<sup>2</sup> of sheet pile wall. Up to 14 construction containers and two cranes were used at a time. Overall, nearly 40 kilotons of material and machinery were moved in the construction, which took 24 months, with a total cost estimated at € 20 million.

The main emitters on site were earthwork, heating, cooling, ventilation, and IT (construction container), followed by installing products in the building (construction machinery). As shown in Table 1, 63% of the on-site emissions originate from electricity consumption and only 37% from burning diesel. This difference occurs mainly due to

the high consumption of cranes and construction containers. More than 77% of CO<sub>2</sub>eq emissions can be assigned to transporting goods and materials (Table 2). The total emissions for this use case sum up to 41.03 kg CO<sub>2</sub>eq/m<sup>2</sup> GFA.

**Table 1.** Process types on site of Use Case 1 and respective CO<sub>2</sub>eq emissions per m<sup>2</sup> gross floor area (GFA).

| Process Type  | kg CO <sub>2</sub> eq Emission<br>Per m <sup>2</sup> GFA |
|---|--|
| earth and asphaltting work  | 3.32   |
| transport within the site   | 0.04   |
| auxiliary work  | 0.10   |
| on-site product manufacturing and conversion                                | 0.37   |
| heating, cooling, ventilation, and IT systems during the construction phase | 3.05   |
| installation of products into the building                                  | 2.43   |
| <b>sum of processes on site</b>   | <b>9.31</b>  |

**Table 2.** Transport processes of Use Case 1, ton-kilometers, and respective CO<sub>2</sub>eq emissions per m<sup>2</sup> GFA.

| Transported Good   | Ton Kilometers<br>Per m <sup>2</sup> GFA | kg CO <sub>2</sub> eq Emissions<br>Per m <sup>2</sup> GFA |
|--|--|---|
| transport of building materials and products   | 116.20                                   | 16.21   |
| delivery and removal of construction equipment (cranes, scaffolding materials, etc.) | 7.26                                     | 0.75  |
| removal of waste and excavated soil  | 88.64                                    | 14.77   |
| <b>sum of the transport processes</b>  | <b>212.10</b>                            | <b>31.73</b>  |

### 3.2. Use Case 2—Road Infrastructure

As part of a sizeable urban high-rise construction project, 4700 m<sup>2</sup> of asphalt surface were constructed. The asphaltting work is further singled out to focus on the infrastructure construction of this project. Two asphalt pavers and two compaction rollers worked for four days and installed 3200 tons of bituminous material. The most energy-intensive processes were the heating and the compression of the asphalt, as shown in Table 3. Transports, primarily building materials, caused 42% of total emissions (Table 4).

**Table 3.** Process types on site of Use Case 2 and respective CO<sub>2</sub>eq emissions per m<sup>2</sup> GFA.

| Process Type  | kg CO <sub>2</sub> eq Emission<br>Per m <sup>2</sup> GFA |
|---|--|
| earth and asphaltting work  | 0.96   |
| transport within the site   | 0.00   |
| auxiliary work  | 0.00   |
| on-site product manufacturing and conversion                                | 0.00   |
| heating, cooling, ventilation, and IT systems during the construction phase | 0.00   |
| installation of products into the building                                  | 0.02   |
| <b>sum of processes on site</b>   | <b>0.98</b>  |



**Table 4.** Transport processes of Use Case 2, ton-kilometers, and respective CO<sub>2</sub>eq emissions per m<sup>2</sup> asphalted surface.

| Transported Good   | Ton Kilometers                        | kg CO <sub>2</sub> eq Emission        |
|--|---------------------------------------|---------------------------------------|
|  | Per m <sup>2</sup><br>Asphalt Surface | Per m <sup>2</sup><br>Asphalt Surface |
| transport of building materials and products   | 3.46                                  | 0.57                                  |
| delivery and removal of construction equipment (cranes, scaffolding materials, etc.) | 0.70                                  | 0.12                                  |
| removal of waste and excavated soil  | 0.08                                  | 0.01                                  |
| <b>sum of the transport processes</b>  | <b>4.24</b>                           | <b>0.70</b>                           |

There was no relevant electric energy consumption on site, and all machines ran on diesel. Total emissions for the asphalt surface construction were 1.59 kg CO<sub>2</sub>eq/m<sup>2</sup> road.

### 3.3. Use Case 3—Renovation and Restructuring

The purpose of this renovation of a Viennese residential complex was, first and foremost, the thermal rehabilitation of the building. There were also some modifications to the building and (sheet) metalwork. Still, the main result was the refurbishment of the facades by applying additional thermal insulation and replacing the old windows with new ones. Some earth and landscaping work also incurred and was carried out by diesel-propelled machines, but the central portion of the work was small-scale and carried out by electrical devices. The renovated building has seven aboveground floors, a floor area of 1600 m<sup>2</sup>, and a gross floor area of 1200 m<sup>2</sup>.

Consequently, 81% of the emissions induced by on-site activity originated from electricity consumption and only 19% from the burning of diesel. During the renovation, 2.62 kg CO<sub>2</sub>eq/m<sup>2</sup> GFA of the renovated building was emitted, with on-site processes and transports accounting for 50% each (Tables 5 and 6).

**Table 5.** Process types on site of Use Case 3 and respective CO<sub>2</sub>eq emissions per m<sup>2</sup> GFA.

| Process Type  | kg CO <sub>2</sub> eq Emissions<br>Per m <sup>2</sup> GFA |
|---|---|
| earth and asphaltting work  | 0.17  |
| transport within the site   | 0.20  |
| auxiliary work  | 0.00  |
| on-site product manufacturing and conversion                                | 0.00  |
| heating, cooling, ventilation, and IT systems during the construction phase | 0.67  |
| installation of products into the building                                  | 0.27  |
| <b>sum of processes on site</b>   | <b>1.31</b>   |

**Table 6.** Transport processes of Use Case 3, ton-kilometers, and respective CO<sub>2</sub>eq emissions per m<sup>2</sup> GFA.

| Transported Good   | Ton Kilometers<br>Per m <sup>2</sup> GFA | kg CO <sub>2</sub> eq Emissions<br>Per m <sup>2</sup> GFA |
|--|--|---|
| transport of building materials and products   | 4.05                                     | 0.69  |
| delivery and removal of construction equipment (cranes, scaffolding materials, etc.) | 2.21                                     | 0.36  |
| removal of waste and excavated soil  | 1.47                                     | 0.26  |
| <b>sum of the transport processes</b>  | <b>7.73</b>                              | <b>1.31</b>   |

### 3.4. Use Case 4—Demolition

For the fourth use case, the demolition of multiple tracts of an office building in a small town near the city of Vienna was examined. The developed system did not consider the dismantling and removal of the pollutants since the study focuses on construction processes. The demolished building was made of a solid reinforced concrete construction with vertical insulation and partly an additional bricklayer to the wall mount. The building had two floors above ground with no cellars. Some of the outside facilities (asphalted surfaces) were torn down. The demolition material was processed on-site by a crusher with a sieving plant. Holes in the ground had to be refilled, for which filling material had to be carried to the site. However, these transports cannot be fully added to the balance because the transport vehicles were sent in a triangular route and drove hardly any empty distances. The demolished buildings had a total gross floor area of 10,000 m<sup>2</sup>, and they amounted to a gross volume of 43,000 m<sup>3</sup>.

Because dismantling, urban mining, and pollutant removal were not considered, no electrical energy was used within the proposed system. All excavators, graders, and crushers ran on diesel. Excavators caused the highest on-site emissions during demolition work (Table 7). Transport emissions (rubble, machinery, and the delivery of filling material, Table 8) made up about a quarter of the overall emissions of the demolition process, which amounted to 23.90 kg CO<sub>2</sub>eq/m<sup>2</sup> GFA of the demolished building.

**Table 7.** Process types on site of Use Case 4 and respective CO<sub>2</sub>eq emissions per m<sup>2</sup> GFA of the demolished building.

| Process Type                    | kg CO <sub>2</sub> eq Emission Per m <sup>2</sup> GFA |
|---------------------------------|---|
| earth and asphaltting work      | 0.11  |
| demolition work                 | 16.35   |
| material processing             | 1.28  |
| <b>sum of processes on site</b> | <b>17.74</b>  |

**Table 8.** Transport processes of Use Case 4, ton-kilometers, and respective CO<sub>2</sub>eq emissions per m<sup>2</sup> GFA of the demolished building.

| Transported Good   | Ton Kilometers Per m <sup>2</sup> GFA | kg CO <sub>2</sub> eq Emissions Per m <sup>2</sup> GFA |
|--|---------------------------------------|--|
| transport of building materials and products (filling material)                      | 5.66                                  | 0.51   |
| delivery and removal of construction equipment (cranes, scaffolding materials, etc.) | 6.90                                  | 0.63   |
| removal of demolition/waste  | 39.93                                 | 5.01   |
| <b>sum of the transport processes</b>  | <b>52.49</b>                          | <b>6.15</b>  |

## 4. Results

The research team tried to determine the system boundaries to establish a logical method to focus the balance on the construction process. By cutting off most upstream logistic processes, only transports within the sphere of the construction sector are considered in the balance. Transports from the factory gate or the vehicle park to the construction site and back are within construction companies' or subcontractors' disposition. At the same time, the upstream logistics are not—unless only “local” material is purchased, which would shift the system's focus away from the construction process toward economic issues. Although it is an upstream process, adding electricity production to the system is inevitable: while electrification is a viable strategy to create local carbon neutrality and, with an unlimited supply of green electricity, even global carbon neutrality, as long as coal, gas, and oil are burnt to produce electricity, the production of electricity needs to be part of the balance to create a simple system for balancing.

The embodied carbon of material and construction components is notably left out of the system, as shown by the flows of embodied carbon outside of the system boundaries in Figure 1. Within the research team, there has been a thorough discussion about whether or not embodied carbon of construction materials and components should be added to the system. The final argument for excluding it is that the research focused on the construction processes, not the building with its overall life cycle. Section 3.1 shows that CO<sub>2</sub>eq emissions from embodied carbon are one order of magnitude higher than those caused by the construction processes. Adding them to the construction-related findings and conclusions would therefore distort the results.

#### 4.1. Use Case Results

The emissions from the various use cases show CO<sub>2</sub>eq emissions of more than 41 kg/m<sup>2</sup> GFA for newly constructed buildings, below 1 kg/m<sup>2</sup> for asphalted surfaces, 2.6 kg/m<sup>2</sup> GFA for refurbishment, and almost 24 kg/m<sup>2</sup> GFA for the demolition. The renovation is comparable only to a limited extent because, in contrast to the new construction and the demolition, it is not reinforced concrete but a brick structure. Nevertheless, the ton-kilometers per m<sup>2</sup> GFA show that the amount of moved material (7.7 tkm/m<sup>2</sup> GFA) is significantly lower than that of the new construction (212.1 tkm/m<sup>2</sup> GFA) or the demolition (52.5 tkm/m<sup>2</sup> GFA). This result can be used as a strong argument for refurbishment rather than new construction and brick construction over reinforced concrete because it is easier to re-design the layout.

It is worth mentioning that in the Use Case of the newly constructed building, transports make out over 75% of CO<sub>2</sub>eq emissions. In contrast, the transportation and on-site process emissions for other use cases are evenly distributed or favor the processes on-site in the demolition use case. This is mainly due to a relatively simple excavation process (as the most significant contributor of on-site emissions) compared to the challenging process of tearing down the enforced concrete structure. In contrast, the transport process remains the same.

The use cases presented in this paper are merely modeled examples. Therefore, due to a lack of sample size, inductive conclusions for emission values cannot be drawn. Emission values depend heavily on transport distances, soil properties, and other factors. These use cases serve as demonstration objects only to apply the proposed balancing system and get a grip on the magnitudes of a building's life cycle emissions.

#### 4.2. Comparison of the Stages of the Life Cycle

According to prior research [16], embodied carbon of multi-family residential buildings is between 341–631 kg CO<sub>2</sub>eq/m<sup>2</sup> GFA for 50% of 77 examined buildings with a median of 438 kg/m<sup>2</sup>. Of these values, 67 include structure and foundation. Of these data points, 32 include exterior facilities as well. Another assessment displays the embodied carbon with the number of stories. No significant correlation between the number of stories and the embodied carbon per m<sup>2</sup> GFA is apparent. Only the variance of the data points shrinks with a higher number of floors. The values for buildings with 7–14 floors (regardless of their type of usage) are similar, with a median of 418 kg/m<sup>2</sup>.

Considering Use Case 1, 41 kg CO<sub>2</sub>eq/m<sup>2</sup> GFA results in 6–12% for the construction processes of a new building (5–9% for transport, 1–3% for on-site processes) of the total embodied carbon determined by Simonen et al. [16]. Röck et al. [17] specify the operational carbon for “new standard” buildings as 3.3–13.3 kg CO<sub>2</sub>eq/m<sup>2</sup>/a. Assuming the lifespan of a residential building of 100 years, emissions from operation over the life cycle of the building range in the magnitude of their embodied carbon, while emissions from construction processes range at least one scale below them. Emissions from the use case of the renovation site (2.6 kg CO<sub>2</sub>eq/m<sup>2</sup> GFA) were below yearly emissions from building operation. Demolition work (in this use case: 23.9 kg CO<sub>2</sub>eq/m<sup>2</sup> GFA) makes up slightly more than half of the emissions from the construction of the building.

The lifespan of a building is one of the most critical parameters for the average yearly CO<sub>2</sub>eq emissions. Therefore, building renovation should be preferred over new construction to avoid emissions, especially if building materials cannot be re-integrated in a circular economy.

## 5. Discussion

The environmental product declarations and building assessments deal with multiple life cycle phases of a product or building. In contrast, the discussed construction process analysis deals only with on-site emissions. Different life cycle phases are considered depending on whether the construction site is a new building, a renovation, or a demolition. Incorporating the mentioned site evaluations in the life cycle phases should be considered for further standardization. Notably, it should be ensured that suggested measures lead to a reduction in GHG emissions and not just a shift to other life cycle phases of a building, for example, into prefabrication. Since converting the life cycle inventory into the impact assessment is done via the emission factors for the impact categories, considering different boundaries and processes can lead to diverging results. Further research needs to ensure that uniform impact categories or emission factors are used for evaluation. This article is a step towards carbon neutrality in the construction industry. It explicitly highlights methods of balancing construction processes and thus serves as a puzzle piece within the complex of a carbon neutral construction industry.

Transportation has a significant influence on the total emissions in the construction phase. A large-scale evaluation of construction sites could be used to establish an expected value and calculation method for transportation in the construction sector. At the same time, databases with emission benchmarks for standard processes need to be developed to complete the a priori evaluation method. In a further step, these benchmarks should be extended to embodied carbon. Furthermore, emissions from building-induced (or reduced) traffic on a corridor level should be regarded as needed to create a holistic approach to the entire lifecycle of buildings and structures.

The resulting GHG emission values for existing and newly developed technologies should also be determined. A standardized data collection system for a simplified GHG emission calculation must be designed to support the implementation of an emission-free construction site. This would allow the parties involved in the construction to record the resulting GHG emissions and implement measures for their reduction. In addition, verification of advanced tools, assessment methodologies, and organizational and technical measures must be validated based on actual construction sites. This should further determine the practical suitability of new types of construction machinery and methods in an interdisciplinary environment with manufacturers, contractors, and users, together with the help of expert interviews and measurements, if applicable. Further, a holistic digital data collection procedure and calculation procedure of site-related GHG emissions should be developed regarding potential carbon dioxide taxation. The suggested measures could be further supported by synergy effects among emission reduction measures, digitalization, and construction operations.

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