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The Ecological Footprint of Construction Materials—A Standardized Approach from Hungary

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Abstract: Due to the large volume and mass of materials used, the construction industry is one of the sectors with the highest environmental impact. However, to provide good quality, affordable, and low-energy housing, the business case must be maintained. Accordingly, we aimed to develop and test a calculator to measure the ecological footprint of the embodied carbon in materials used in construction projects in a standardized way, without the need for environmental or even civil engineering expertise, and thus in a way that is accessible to SMEs. The novelty of our research is that although there are calculators for measuring the environmental impact (e.g., carbon footprint) of the construction industry, and there is a methodology for calculating the ecological footprint of construction, there is no free, easy-to-use, online calculator for calculating the ecological footprint of embodied carbon in materials available to all enterprises. In other words, this approach extends our previously developed corporate ecological footprint calculator with the environmental impacts of material usage. The study summarises the baseline research for an ecological footprint calculator, tested on two new condominium buildings and the energy renovation of five condominium buildings, built with a prefabricated technology typical in Hungary and other post-socialist countries. Based on our results and in accordance with former literature sources, most of the ecological footprint of new construction projects is determined by materials with high mass and volume, in particular, concrete, steel, and masonry; so it is not necessary to take into account all construction materials in a calculator in a detailed way. We also conclude that renovation and ongoing maintenance, as well as preservation, are recommended for structurally sound buildings, as embodied carbon in materials in the case of an energy upgrade of an existing condominium building has an environmental impact of 0.3–0.8 global hectares per dwelling, depending on the technical content, while in the construction of a new building, this value is between 10.49–14.22 global hectares. Our results can help investors and clients in their decisions, and policymakers in determining urban development directions.

Keywords: ecological footprint; dwellings; construction; methodology

Citation: Szigeti, C.; Major, Z.; Szabó, D.R.; Szennay, Á. The Ecological Footprint of Construction Materials—A Standardized Approach from Hungary. *Resources* **2023**, *12*, 15. https://doi.org/10.3390/resources12010015

Academic Editor: Kazuyo Matsubae

Received: 30 October 2022
Revised: 23 December 2022
Accepted: 4 January 2023
Published: 10 January 2023

1. Introduction

The impact of mankind on planet Earth is becoming increasingly significant, as shown by the fact that research suggests that anthropogenic mass reached living biomass by 2020 [1]. Accordingly, since 2000 [2], researchers have been proposing the introduction of a new geological epoch, the Anthropocene which, according to various criteria, began in 1610 or 1964 [3].

Current climate and energy crises show that action on sustainability is inevitable. The IPCC [4] has developed 50 scenarios to limit global warming to 1.5 °C above pre-industrial levels. However, experts warn that these scenarios rely too much on measures such as carbon dioxide removal (CDR), and their analysis suggests that only half of the IPCC scenarios are likely to be sufficient to curb global warming; in other words, "deep societal and economic transformations are needed that are aligned with the UN Sustainable Development Goals" [5].

The role of the construction industry in achieving the SDGs is multi-layered. On the one hand, the objective is to provide decent and affordable housing for people in buildings with the highest possible energy efficiency. On the other hand, with the use of cement and concrete, the latter being considered particularly harmful in terms of CO_2 emissions, the environmental impact of the construction industry is significant (e.g., [6–8]). At the same time, the construction industry is a major employer in all countries, so reducing the volume of development would have negative economic effects, especially on blue-collar jobs. This is proven by the fact that small- and medium-sized enterprises (SMEs), which account for the vast majority of enterprises in the 27 member states of the European Union (EU27), employ two-thirds of the workforce [9], and are the third most common SME activity in the EU27, with more than 3.5 million SMEs in the construction sector [10]. In our previous research [11–14], we developed a general ecological footprint calculator to determine the ecological footprint of SMEs. The research presented here is a continuation of that, dealing with the specific ecological footprint calculation issues of a material-intensive industry.

2. Theoretical Framework

In this chapter, we first briefly introduce the concept of ecological footprint, and then review the main characteristics of the Hungarian housing stock, with a special focus on the socio-economic significance of the energy upgrade projects we have studied. The chapter concludes with a summary of the literature on the environmental impacts of the construction industry.

2.1. Concept of Ecological Footprint

In addition to financial metrics, analysts and decision-makers can also use physical metrics to monitor the performance of an organization [15]. One of the most common indicators is the ecological footprint (EF) [16]. The Global Footprint Network (GFN) conceptualizes the EF indicator as comprising five land use categories: (1) cropland, (2) grazing land, (3) forest land (forest land provides for two services: the forest product footprint and carbon footprint), (4) fishing grounds, and (5) built-up land. Total consumption is measured by land use and then expressed in global hectares (gha) using equivalence factors (EQFs)—globally comparable, standardized hectares with world average productivity. This conversion figure is used as a tool to compare, for example, pasture and arable land. For a country, the comparison should be made using the yield factors (YF) by measuring the differences between different crop areas. This can be used to compare the productivity of arable land among countries [17]. There are two basic methodological approaches to calculating the ecological footprint. The top-down (or composite) approach is based on national footprint accounts broken down into smaller geographical areas provided by the GFN. The bottom-up (or component-based) approach uses individual, local data for a community to quantify consumption [18]. In addition to global and individual applications, ecological footprint calculations have focused on country-level assessments [17,19]. Later, approaches were developed to calculate EF at the regional [20] or even organizational level. The principles of corporate EF calculations were developed by Chambers et al. in 2000 [21]. Wackernagel and Beyers have further developed a methodology for calculating the ecological footprint of enterprises [22]. Their results show that significant progress can be made towards eco-efficiency. Among the corporate applications of ecological footprint calculation, general [12] and sectoral [23–25] approaches are also found. The ecological footprint indicator can also be used to inform policy decisions, including in key areas such as Housing Sector Policy [26].

2.2. Housing in Hungary

According to the latest data from 2016, 66.32% of the housing stock in Hungary was built between 1946 and 1990, during the socialist era [27]. While at the first post-World War II census 2.5 million housing units were registered in Hungary, the number of dwellings increased by 10% every 10 years between 1960 and the late 1980s [28]. This is caused by three factors: (1) fewer dwellings were built in the 1930s and 1940s than before; (2) a large part of the housing stock was damaged or destroyed during the Second World War; and (3) the economic restructuring led to a large increase in the urban population and thus in the demand for urban housing [29].

The large-scale housing shortage in the socialist countries of Central and Eastern Europe was solved by large-scale housing estates [30]. Following the central, Soviet trend, countries of the Eastern Bloc first adopted the more ornate, so-called socialist realistic architecture built with traditional technology, and after 1954, with the cheaper, industrialized prefabricated technology [31]. In the 1950s, housing estates were built using mechanized, typically block and cast technology, the first of which was delivered in the capital in 1954 [32]. Due to capacity constraints in the technology, the decision was made to adopt the technology of the Soviet housing factories, and by that, a significant amount of housing was built in the late 1960s and early 1970s using newly acquired prefabricated technology [29].

It is important to point out that the schematic size of housing estates, often beyond human scale in the case of prefabricated housing technology, has been solved by architects and builders by landscaping the surrounding area and using open-air architecture [33]. As a legacy of the socialist era, 14% of the housing stock in 2016 was prefabricated housing, but this proportion is significantly higher in the capital and rural industrial cities [34]. But if we take only resided dwellings into consideration, 745 thousand of the 3854 thousand dwellings were built with prefabricated technology (19.32%). All of them were built between 1961 and 2000, but approximately 40% of resided dwellings built in 1971 and 1990 used these technologies (see Figure 1).

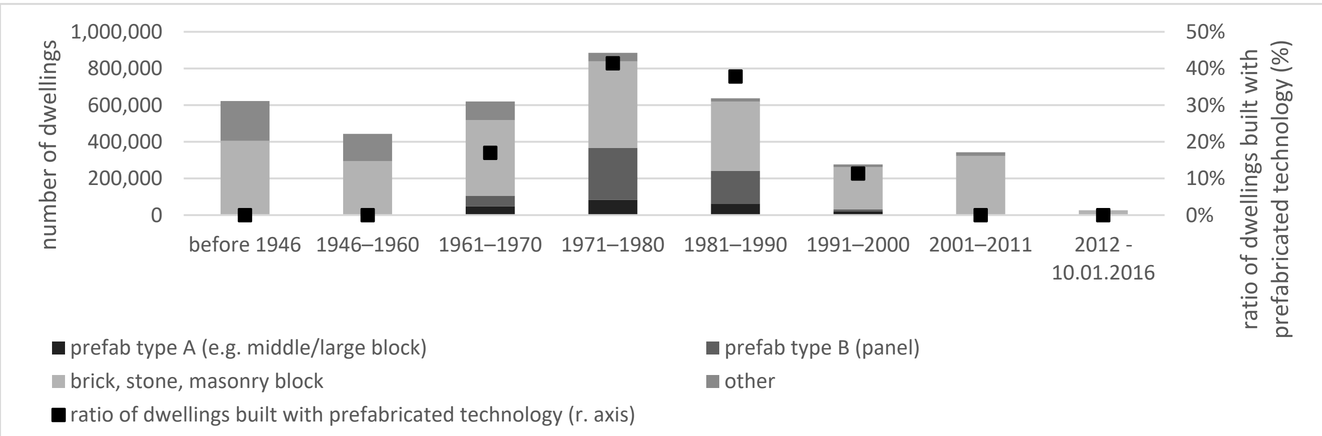

Figure 1. The number of resided dwellings based on their building technology and year of building.

Block construction technology allowed for faster and more economical construction of buildings up to five stories high, compared with the use of traditional small masonry units. The size of the blocks can vary; we can distinguish small block, medium block, and large block constructions. A characteristic feature of prefabricated blocks is that the vertical and horizontal load bearing and space-confining structures of the building are made of large prefabricated, sheet-like panel elements, which allows both the production and assembly to be mechanized. The solution reduces the proportion of monolithic structures used on-site, thus minimizing on-site formwork, concreting, and scaffolding. The efficiency of the technology was enhanced by the simplification of logistics for typically greenfield projects, while the building of public utilities increased the cost of the projects.

Since the 1990s, however, the era of prefabricated housing technology in Hungary has come to an end [29]. Although no housing estates have been demolished and very few new housings have been built since using the above technology [35], a significant proportion of the population still lives there, and the general attractiveness of housing estates is declining—the proportion of people living in housing estates as a proportion of the total population fell from 20% to 17% [29] between 1996 and 2016 [27]. However, it is important to note that this is not a typical Hungarian phenomenon. Central and Eastern European (CEE) cities generally have a short tradition of urban regeneration. After the collapse of the centrally planned land management model, urban land began to be treated as a scarce and valuable resource that needed to be efficiently (re)allocated [36]. However, there are significant differences between housing estates—the aging, low-skilled population of 1950s estates were replaced by younger, more educated residents after the 1989 regime change, while 1980s estates have maintained some of their original higher prestige since then [37].

The doors and windows as well as building services of prefabricated buildings were typically designed for a 30-year lifespan, which justifies their upgrade [32]. Major upgrade projects started in 2000, under various financing structures; and by 2017, almost half of the housing stock in residential buildings was involved. However, these upgrades have been limited to improve the quality of the housing, mainly aesthetically and energetically, and not to renew the environment or institutions [35]. Industry experts suggest that these renovations can lead to significant savings in heating costs of between 50 and 85%, depending on the scale of the upgrade [38,39]. This could even lead to an increase in demand for these apartments if the high energy prices predictedat the time of writing persist in the longer term.

2.3. Using the EF Concept in the Construction Industry

The construction industry is one of the largest consumers of natural resources and is responsible for significant CO_2 emissions on the planet [40]. One of the tools to combat climate change is to reduce carbon emissions from the construction industry. These efforts include the green building concept itself, various certification schemes, and sustainable building materials [41]. Although the direct footprint of the construction industry is relatively small. Results show that the share of operational energy in the life-cycle energy use of buildings is significant (80–90%), followed by the share of installed energy (10–20%) [42]. These figures increase significantly when the carbon embodied in materials, operations, and asset use is taken into account, with over half of the country's carbon footprint directly or indirectly related to the construction and use of infrastructure assets, according to a UK study [43]. Although the drive to reduce carbon emissions from buildings is well-known and widely accepted, it is proving difficult to achieve. Opportunities to reduce the carbon footprint are being explored in a variety of ways, for example, using innovative materials [44–46].

Another way to achieve a more sustainable construction industry is to better measure the impact of existing technologies. Several tools have been developed to facilitate this. For example, the use of building information modeling (BIM) creates opportunities to optimize projects [47–49] and reduce carbon emissions [50–53]. There have been several initiatives to measure carbon dioxide or carbon dioxide equivalents in the construction industry. Carbon calculators can be divided into two methodological groups. In one approach, users prepare their assessment by manually entering each item or material used into a spreadsheet, and the tool then assigns a carbon emission factor to that item. The second approach takes an existing data set, which can be in the form of a quantity inventory or BIM data, and automatically assigns an emission to each item [43]. Many construction companies disclose mainly those carbon emissions over which they have full control and information, which means that the chance of further reductions in emissions could be threatened [41]. While some tools are sector-specific and as such require specific datasets, others, such as the Atkins Carbon Critical Knowledgebase, can be used across all sectors. Most tools use the Inventory of Carbon and Energy (ICE) database, which is a freely available embodied carbon and energy database for construction materials [54]. The database was updated in 2019, meaning that it is likely to be the 'go-to' database for the construction industry for many years to come. There are tools that allow users to select the national database that best suits their needs [43]. Some surveys show that current digital tools have achieved the automation of carbon footprint (CF) computation, but the level of development is still far from "smart" or "intelligent". The tools cannot be easily adapted and transferred to other digital approaches [55]. In our view, it may be useful to separate calculators according to their target audience and purpose of use. Specific, detailed, and specialized solutions such as Simapro or Ecoinvent are primarily intended for professional purposes, while free, less sophisticated solutions, usually based on ICE, are less accurate but are available to a wider audience.

Environmental impact estimates can go beyond CF calculations, with various research groups calculating them [56,57]. Environmental performance is assessed using global warming potential (GWP), fossil resource scarcity (FRS), mineral resource scarcity (MRS), and water footprint (WF) (blue water consumption); cumulative energy demand (CED) using energy performance [58], material, energy and climate footprint [45]. Pulselli et al. developed the Emergy Investment Ratio (EIR) as a synthetic indicator of sustainability for construction applications [59]. As an early application of EF in construction, Li et al. developed a model to assess the ecological efficiency of urban residential buildings [60]. A detailed computational model of the ecological footprint of residential buildings under construction in Spain was developed by Solís-Guzmán et al. [61]. Both methods only considered the ecological footprint during construction. Bastianoni et al. use the EF indicator to calculate the environmental impact of building construction by studying and comparing two building types in Italy. In the calculations for some residential buildings, the EF excludes indirectly occupied land, construction, and demolition waste landfills, and demolition energy [62]. As a result, the calculated total EF may contain some inaccuracy. Ruiz-Pérez et al. analyzed a computer tool that allows the assessment of the ecological footprint of the rehabilitation of residential buildings in Andalusia. To correctly evaluate the ecological footprint generated by the renovation of buildings, 50 residential typologies were analyzed. They carried out a study of five types of buildings, comparing their impact in terms of EF according to whether these typologies were renovated or maintained without any intervention [63]. The life cycle ecological footprint (LCEF) is a further development of this method to assess the environmental impacts of construction materials [40]. The use of an ecological footprint indicator is considered a good solution because it also sets an upper limit to growth, unlike other calculators [64].

The novelty of our research is that although there are calculators for measuring the environmental impact (carbon footprint) of the construction industry, and there is a methodology for calculating the ecological footprint of construction, there is not yet a free online construction footprint calculator available to any enterprise. This is particularly important for SMEs, where there are often not enough resources to carry out specific calculations.

To validate the results, a literature review was carried out of academic work on EF in residential buildings. In our experience, relatively few comprehensive calculations have been published on the topic; published studies tend to focus on larger spatial units, and the number of individual building-level analyses is low. However, this field is a strong focus of the research group of Universidad de Sevilla, which has published several individual building EF calculations in the 2010s, both independently and in collaboration with researchers from other countries. The main results of these papers are summarised in Table 1. However, comparability is reduced by the fact that the Hungarian climate requires a higher degree of building insulation due to the heating demand in the colder winters.

Table 1. Literature on EF in new residential construction.

Location	Size of Building	Methodology	Specific EF	Source
Seville (Andalusia, Spain)	50 dwellings (5 detailed case studies)	holistic approach (EF and financial cost)	new construction: 0.260–0.291 gha/m^2 floor area renovation: 0.009–0.022 gha/m^2 floor area	[63]
n/a (Huelva, Spain)	107 dwellings, with parking spaces, storerooms, and shops in 2 purpose-built blocks (4 floors above ground level and 2 below ground each) 5444.91 + 4798.78 m^2 floor area	total annual EF (inclusive machinery, materials, manpower, and indirect costs) urbanization taken into consideration	0.385 gha/year/m^2 floor area	[61]
La Palma del Condado (Huelva, Spain)	107 multi-family dwellings, parking lots, storerooms, and commercial premises 8510.70 + 7504.22 m^2 floor area	total EF (inclusive machinery, materials, manpower, and indirect costs) urbanization is taken into consideration	0.228 gha/m^2 floor area	[65]
Seville (Andalusia, Spain)	single-family dwelling 143 m^2 total floor area	total EF (inclusive machinery, materials, manpower, and indirect costs)	0.17 gha/m^2 floor area	[66]
Temuco (Chilean Araucanía, Chile)	single-family dwelling 52 m^2 total floor area	total EF (inclusive machinery, materials, manpower, and indirect costs)	0.19 gha/m^2 floor area	[66]
Spain	92 projects with 1, 2, 3, 4, 5, and 10 floors above ground level	total EF (inclusive machinery, materials, manpower, and indirect costs)	1 floor—10.811 gha/person 2 floors—6.936 gha/person 3 floors—4.191 gha/person 4 floors—4.132 gha/person 5 floors—4.196 gha/person 10 floors—4.236 gha/person	[67]

3. Methodology

The aim of our former research (see [12,14]) was to develop an easy-to-use EF calculator for SMEs that could reliably measure corporate environmental impacts. Experiences of non-standardized calculations showed, however, that a standardized approach (see Table 2) could take only common elements of environmental impact into consideration. In other words, while the EF of meals, fossil fuels, electricity, etc. fitted to an easy-to-use, free, and online calculator, the EF of material usage would significantly reduce usability, thus the EF of material usage was excluded. This can be verified by the fact that the magnitude of material usage in total EF is relevant only in some sectors, for example in the case of agriculture or construction. To take into consideration the EF of material usage, we propose to use so-called satellite calculators [68], which could comprehend the developed core calculator. In this article, we propose an easy-to-use methodology for the calculation of the EF of material usage in the case of construction, which could be used for the development of an easy-to-use, free, and online satellite calculator.

Table 2. Element of ecological footprint (EF) calculated by the core calculator of Szennay et al. [12], their short description, and calculation method.

Element of EF	Description	Literature
EF_{meals}	Food consumption during work time, calculated on the basis of Hungarian national average values	Mózner [69]
$EF_{water\ consumption}$	Water consumed by employees during work time. Industrial water consumption is excluded	Chambers et al. [21]
$EF_{built\text{-}up\ area}$	Total area of non-water absorbent surfaces	Lin et al. [16]
$EF_{electricity\ consumption}$	Electricity consumption from electricity grid, including heating and boiling with electric devices	IEA [70] DEFRA 2018 [71]
$EF_{heating\ and\ boiling}$	Heating and boiling with fossil fuels, e.g., natural gas, coal, or wood.	DEFRA 2018 [71]
$EF_{transportation}$	All transportation related EFs, including commuting (both public transport and vehicles owned by employees or the enterprise); transportation of goods, use of corporate cars, flying, etc.; petrol, gasoline, and gas consumption of equipment (e.g., generators) are included	DEFRA 2018 [71]

The purpose of using the ecological footprint indicator in our research is not to obtain a result broken down into land use categories, but to provide a conservative estimate of how much building exceeds carrying capacity. Based on our previous research, the ecological footprint indicator can be used to distinguish between good and bad growth [64]. Ecological footprint (EF) calculations were based on the construction breakdown system (CBS) generally accepted in Hungarian practice. This means that the list—in principle—includes all materials and works planned to be incorporated into the building, including their volume expressed in natural units (e.g., m^2, m^3, pieces, etc.) in case of self-construction. In the case of the projects examined, the works carried out by the external contractor usually covered mechanical engineering, whereas, in the absence of a quantitative statement, the calculation of the ecological footprint was not carried out. Accordingly, calculations reported in this study refer only to buildings without mechanical works but already structurally complete, which is one of the limitations of the results.

The calculation was carried out (see Equation (1) in Table 3) in four steps. First, we performed a transformation of the CBS, i.e., identifying the material of the items indicated in it (see Appendix B) and converted them to the unit of measurement preferred in the calculation (e.g., m^2, m^3, pcs, etc.). The same unit of measurement allows us to aggregate the materials used in different packaging (e.g., 10, 15, or 30 cm thickness) in the calculation.

In the second step, the identified material types, converted to a common unit of measurement, were aggregated for the whole building. The reason for this is that the logic of the CBS reflects the workflow of the construction, which means that a material type may not only occur in several different presentations but also in several workflows or several batches.

For some materials, an additional unit conversion is required, as the EF database may contain a specific value expressed in a unit other than the preferred unit. It is important to underline that the preferred unit of measurement is used to aggregate the CBS items and thus primarily reflects the architectural perspective. While this corresponds to the unit of measurement in the EF database in most cases, some smaller items (e.g., PVC expansion profiles, etc.), and windows and doors require additional calculations.

The actual EF calculation, i.e., the evaluation of the identified and aggregated material species by their specific EF values, was performed in the fourth step. Specific values were determined using the ICE version 1.6a [72]. It is important to note that version 3.0 of ICE is also available [73] but using version 1.6a has two benefits: (1) it contains data on a more extensive scope of construction materials (e.g., plastics, insulation, windows, etc.), (2) the difference between specific values of 1.6a and 3.0 is rather small; in our two case studies it is approx. 3 and 11%, respectively. Although other databases, such as Simapro or

Ecoinvent, contain more accurate values, the sophistication of their methodology and the cost of the databases were not suitable for the development of a free, easy-to-use calculator that could be recommended to SMEs. This may reduce the reliability of the results, but the resulting calculations, which are correct in terms of magnitude, will be available to a much wider audience.

Table 3. Ecological Footprint calculation equations.

Equation	No.
$EF_{material}$ = ecological footprint of materials (gha) $EF_{material} = V_i \times CFi \times ACF_i \times E_i \times DF_i \times FIoC$ V_i: aggregated volume of the i-th material in the CBS expressed in its own preferred unit of measurement (e.g., m^2 of wall) CFi: conversion factor of the i-th material (e.g., 220.8 kg/m^2 in case of a wall built with 30 cm masonry blocks, assuming that 16 bricks are needed for each m2 of wall and each brick weighs 13.8 kg) ACFi: additional conversion factor of the i-th material (optional, only in cases of special items, e.g., PVC profiles) E_i: emission factor of i-th material (e.g., 0.21 $kgCO_2$/kg for 1 kg of brick) [73] DF_i: diversion factor, when E_i is expressed in an interval (default value = 1) FIoC: footprint intensity of carbon (0.338 global hectare/kg of CO_2 in Hungary) [17]	(1)
$EF_{windows}$ = ecological footprint of windows and glazed doors (gha) $EF_{windows} = N_i \times [(w_i \times h_i) \times (E_{glazing} + E_{loading}) + 2 \times (w_i \times h_i) \times E_{frame})] \times FIoC$ N_i: number of the i-th type of window(s) or glazed door(s) i: width of the frame of the i-th type of window or glazed door h_i: height of the frame of the i-th type of window or glazed door $E_{glazing}$: emission factor of double or triple glazing (e.g., 17.2 $kgCO_2$/kg for 1 m^2 of glass surface) [73] $E_{loading}$: emission factor of loading (e.g., in case of argon, 0 $kgCO_2$/kg for 1 m^2 of glass surface) [73] E_{frame}: emission factor of the frame (e.g., 1.625 $kgCO_2$/kg for 1 m of timber frame) [73] FIoC: footprint intensity of carbon (0.338 global hectare/kg of CO_2 in Hungary) [17]	(2)

The material types used and items in the inventory were not necessarily compatible, so several new items were added to the inventory (e.g., masonry elements). Similarly, in cases where the specific value of the inventory covers a relatively wide range for technical reasons, the inclusion of new elements has been applied. In such cases, we selected the value that best corresponds to the material type actually used by including data on real products. A good example of this is the case of crotch and facade insulation materials, where the specific densities, and hence the mass and CO_2 content of the two types, can differ significantly. Considering that most specific values were available in $kgCO_2$/kg, it is necessary to determine the mass of the material types under consideration. For this purpose, professional guides (e.g., [72,74]) and, where appropriate, product data sheets were used.

The calculation of the EF of the embodied carbon of windows and doors was made in a separate calculation (see Equation (2) in Table 3) based on the values given [72]. For the calculations, we took into account (1) the material of the window (wood, aluminum, PVC), (2) glazing (double or triple glazing), and (3) the filler between the glass layers (argon, krypton, xenon). As the CBSs obtained did not contain information on the latter, based on industry sources, we assumed the use of argon filler. Since this gas has the lowest EF, our results are either in agreement with or a lower estimate of the real facts. It is important to emphasize that while other solutions may give more accurate estimates of the materials incorporated, for the reasons explained earlier, these have also been calculated using ICE 1.6a. The calculator part is very user-friendly and can be used for other complex structures by modifying the structure used.

The sample included in the study includes 2 new condominium projects and the energy upgrade projects (i.e., insulation, replacement of windows and doors, and modernization of the heating system) of 5 existing condominiums. The main details of these projects are presented in Table 4, while detailed technical data are shown in the Appendix A. It is important to underline that for the new construction projects, we have taken the as-built condition as a basis, while mechanical (e.g., electricity, heating, water, heating, cooling, etc.), fencing, and all items not included in the CBS were excluded. Two factors combined explain the disregard for mechanical equipment. On the one hand, the CBS usually did not contain detailed information on it, so only very rough estimates would have been possible. On the other hand, the technology used (e.g., heating with gas, geothermal, heat pumps, etc.) or the use of specific items (e.g., centralized cooling) would have reduced the comparability of the results. The omission of the fencing was also necessary to ensure comparability since only one of the studied apartment buildings had a fence, and its exact technical specifications are not known.

Table 4. Key data from the projects examined.

Project	Main Attributes	Apartment Characteristics	Other Facts
new build condominium 1	three separate two-story buildings (ground floor, first floor)	28 apartments, average floor area 59.5 m^2 + covered terrace	28 storage rooms 31 units paved parking, fence
new build condominium 2	a five-story building (ground floor + 4 floors) with underground parking	123 apartments, average floor area 51.7 m^2 + terrace	41 storage rooms 56 above-ground + 73 underground parking spaces
energetic upgrade: prefabricated type A (large block)—1	five-story apartment building with a basement	40 apartments + a basement	N/A
energetic upgrade: prefabricated type A (large block)—2	five-story apartment building with a basement	40 apartments + basement	N/A
energetic upgrade: prefabricated type B (panel)—1	five-story apartment building (no information on basement)	40 apartments	N/A
energetic upgrade: prefabricated type B (panel)—2	five-story apartment building (no information on basement)	40 apartments	N/A
energetic upgrade: prefabricated type B (panel)—3	ten-story apartment building (no information on the basement)	60 apartments	N/A

The online calculator was available in a test phase, exclusively in Hungarian at the time of submission of the manuscript. The English version will be developed after preliminary industry testing.

4. Results

The EF of the embodied carbon of materials installed in the analyzed new condominiums is 398.24 and 1290.50 gha, which translates into an average of 14.22 and 10.49 gha per dwelling, respectively (see Table 5). This result suggests that larger projects, despite the additional material requirements of the underground parking, also have more favorable environmental impact characteristics, mainly due to the number of floors (1 and 4, respectively) and to a lesser extent to the smaller average floor area of the apartments (59.5 and 51.7 m^2, respectively). For the new-build condominium 1, a list of the apartments by the number of rooms was also available, which allowed us to estimate the expected number of occupants. The average number of occupants was assumed to be two-and-a-half for two-room flats, three for three-room flats, and three-and-a-half for four-room flats, giving an EF per occupant of 5.04 gha, which is 1.94 times higher than the per capita biocapacity of Hungary (2.6 gha/person) [75].

Two materials, structural concrete and reinforcing steel, account for the largest share of the environmental burden—71.6% and 75.3%, respectively, of the total EF considered. This is due to the combined effect of two factors, (1) the installed volume (2083 and 5851 m^3, respectively) and (2) the high specific weight of structural concrete (2500 tonnes/m^3). This result is consistent with the findings of other researchers [66,67].

Table 5. The ecological footprint of materials built-in for new construction projects.

Name	Unit of Measurement	New Build Condominium 1	New Build Condominium 2
GHG emission	tonnes of CO_2	1178.23	3818.03
ecological footprint	global hectares (gha)	398.24	1290.50
ecological footprint per dwelling	gha per apartment	14.22	10.49
footprint per square meter of useful floor area	gha per square meters	0.17	0.20
footprint per capita	gha per capita	5.04	N/A

The energetic upgrade projects only included changes to the building structures, so only the external thermal insulation works on the structures and effects of the possible replacement of windows and doors were quantified. Our results show that the environmental impact of these projects is significantly lower than for new buildings, ranging from 0.3 to 0.8 gha per dwelling, depending on the replacement of windows and doors (see Table 6). This is due to the fact that high mass and high environmental impact elements, in particular, the structure and masonry exist. Our results also show that in these cases, being relatively complex and heavy products, nearly half of the environmental impact is caused by the replacement of windows and doors.

Table 6. The ecological footprint of materials used in energy upgrade projects.

	Unit of Measurement	Prefabricated Type A (Large Block) 1	Prefabricated Type A (Large Block) 2	Prefabricated Type B (Panel) 1	Prefabricated Type B (Panel) 2	Prefabricated Type B (Panel) 3
built-in materials	m^2	1356.5	1468.9	1690.0	1690.0	2437.6
	m^3	332.9	352.2	401.7	401.7	500.3
windows and doors	Piece	0	0	142	142	228
number of apartments	Piece	40	40	40	40	60
total surface area (facade)	m^2	1152.9	1265.3	1484	1484	2064.9
total surface area (end slab)	m^2	345	345	560	560	462.5
CO_2	tonnes	36.0	38.6	80.2	78.7	138.8
per dwelling	tonnes/dwelling	0.9	1.0	2.0	2.0	2.3
ecological footprint	gha	12.2	13.0	27.1	26.6	46.9
per dwelling	gha/dwelling	0.3	0.3	0.7	0.7	0.8

5. Conclusions and Discussion

The most important practical implication of our results is that the environmental impact of the materials used in new condominium buildings in Hungary is determined by a small number of items, mainly concrete, which are typically heavy and often have a high environmental impact. For both projects studied, concrete and associated reinforcing steel together accounted for at least 70% of the EF, while the items with the 10 highest environmental impacts together are responsible for more than 90% of the EF of the total residential building (see Supplementary Materials). The generalisability of the results is enhanced by the fact that in our previous research, we found similar values for new single-family houses [68].

A further implication is that the process can be standardized quickly and cheaply, as hundreds of items are needed to be individually assessed to obtain results with sufficient accuracy since it is sufficient to assess the critical elements, concrete, and associated reinforcing steel, and larger mass items (e.g., masonry, plaster, windows, etc.), while remaining elements can be added at a flat rate determined by expert estimation.

Policy implication: since the EF is mainly determined by the structural elements and masonry, it is environmentally highly efficient to upgrade existing buildings that are in a structurally sound condition. The latter has a significantly lower environmental impact per dwelling compared with new construction (0.7–0.8 vs. 10.49–14.22). When considering the associated labor, energy used, and transportation, the difference is expected to increase further. Given many prefabricated housing units in the housing stock of the former socialist states of Central and Eastern Europe, and the limited number of housing types, our results can also contribute to the basis for the renewal of such urban areas. Moreover, as the energy savings of these buildings are also predictable, the extent of energy savings at the national level can be identified as a further research direction. The analysis is currently based on data from Hungary but could be adapted to other countries depending on the building technology, so the research could be extended in this direction, as well.

6. Limitations of Our Research

A limitation of our results is the size of the sample, i.e., the fact that we analyzed only two new-build condominiums and three, plus two, projects of former residential construction technologies. Although our experience shows that the projects analyzed, particularly energy upgrade projects, are a good representation of the improvements made, a larger sample would presumably increase the robustness of the results. A further limitation is that for the new construction projects, items not included in the CBS and not detailed, in particular, doors, mechanical engineering, and fencing, were not included in the analysis. However, these items are significantly smaller in volume and mass than the structure and masonry, and their environmental impact is therefore considered to be low. The main limitation of our research is that it does not answer the question of whether new construction or energy upgrade has a smaller ecological footprint since we must take into account the energy demand (and its source) and projected lifetime of the building, as well. At the same time, the calculation clearly shows the difference between the EFs of new construction and renovation and makes it clear that, if the new building is not significantly more energy efficient than the renovated one, the new construction is unlikely to be environmentally viable, which can help investors, clients and policymakers to make a case for a specific building or urban development direction.

Our current research does not cover other types of footprints (e.g., water footprints). Future extension of the analysis in this direction may refine the findings of our research.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/resources12010015/s1, Table S1: Project 1 (largest 10 items, 90%+ of embodied carbon); Project 2 (largest 10 items, 90%+ of embodied carbon).

Author Contributions: Conceptualisation and methodology C.S., Á.S. and Z.M.; Data collection. Á.S.; Validation and formal analysis, Á.S. and Z.M.; Writing—original draft preparation C.S., Á.S. and D.R.S.; Writing—review and editing, supervision and project administration C.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Ministry of Innovation and Technology of Hungary from the National Research, Development and Innovation Fund, financed under the *Tématerületi Kiválósági Program 2021 (TKP2021-NKTA)* funding scheme (Project no. TKP2021-NKTA-44).

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Main Technical Parameters of Construction Methods of Analysed Buildings

Appendix A.1. New Condominium 1

The buildings include 28 apartments, 28 storage rooms, corridors, and extra spaces. The apartments were arranged in three separate buildings, divided into two-, three- and four-room flats. Building A consists of 12 apartments, Building B has 10 apartments and Building C has 6 apartments. The foundations of the three buildings are strip foundations.

The buildings are masonry structures with a monolithic reinforced concrete slab, with attic walls and flat roof insulation on the upstairs slab. The main walls are made of 30 cm handmade masonry; the partition walls between the apartments are made of two layers of 20 cm handmade masonry with additional sound insulation in between, and the partition walls inside the apartments are made of 10 cm partition slabs. Roof structure: flat roof with a load-bearing layer of gravel, with a straight pitch, rainwater insulation, protective separation layers, and vapor proofing. Rainwater drainage is collected at points on the flat roof through concealed PVC pipes. The façade opening structures are made of white plastic Internorm windows with three layers of glazing and roller blinds (K = 0.7 m^2/K). The floor structure, façade behind the plaster, and roof structure are insulated with thermal insulation in the thicknesses indicated on the sectional drawings.

Appendix A.2. New Condominium 2

During the development, they built 120 apartments in three phases. Most of the materials for the project were supplied from the prefabrication plant of Leier Hungária Kft. in Győr, located three kilometers away from the construction site. The investment period for the building was 16 months. Bark walls, bark slabs, and bricks were also used in the construction. Leier products were used extensively in the basement of the house and also above ground. The use of prefabricated elements requires that the building structure and fittings to be incorporated into it are designed following the technology by the designers responsible for each branch (architects, structural engineers, mechanical engineers, and electricians). In this way, the construction phase can be shortened considerably, and the need for labor can be significantly reduced. The number of workers onsite can be significantly reduced by using Leier prefabricated wall, slab, and stair elements.

Appendix A.3. Prefabricated Type A (Large Block)

Block construction allowed for much more economical and faster construction than the small (brick) masonry units used previously. Block construction was used mainly for multi-family housing, which could be up to five stories high. The block walls were constructed using a 30 cm extended modular system. The average height of a story is 2.80 m. Consequently, the nominal height of the complete blocks is 2.80 m, the nominal height of the middle blocks is 1.40 m and the nominal height of the small blocks is 0.93 m. The nominal width of the blocks is 0.60 m, 0.90 m, and 1.20 m, respectively. Their nominal thickness is 30 cm (actual thickness: 29 cm).

Appendix A.4. Prefabricated Type B (Panel)

The panel construction method is characterized by the fact that the vertical and horizontal load-bearing and space-confining structures of the building are made of large prefabricated panel-like prefabricated elements. The technological processes can be well-mechanized, both in the prefabrication and assembly phases. The high degree of mechanization makes it possible to produce serial production. As a result, entire districts have been built up of buildings with identical structures and facades. Due to the prefabricated nature of the construction method, the proportion of monolithic structures onsite has been reduced, thus minimizing on-site formwork, concreting, and scaffolding. Some of the panels typical of the construction method could be delivered to the site in an almost fully finished state.

Appendix B. Items Included in the Calculator

Windows: material, filling, number of layers, size
Surface preparation: dolomite, slag, gravel
Onsite and precast concrete: concrete, lightweight concrete, reinforcing steel
Masonry: masonry units 10–12–20–25–30 cm
Plastering and rendering: plaster, glass fibre
Drywall: plasterboard 10.0–12.5 mm, fibre insulation, OSB board
Cladding: tiles, glue

Tiling: tin, PVC, aluminum

Finishing: plaster, paint (one/double coat)

Insulation: bitumen, PVC, vapor barrier board, gravel, perimeter insulation foam, polyethylene, PIR foam, EPS (step-resistant/non-step-resistant), XPS (step-resistant/non-step-resistant)

References

1. Elhacham, E.; Ben-Uri, L.; Grozovski, J.; Bar-On, Y.M.; Milo, R. Global Human-Made Mass Exceeds All Living Biomass. *Nature* **2020**, *588*, 442–444. [CrossRef] [PubMed]
2. Crutzen, P.J.; Stoemer, E.F. The "Anthropocene". *IGBP Glob. Chang. Newsl.* **2000**, *41*, 17–18.
3. Lewis, S.L.; Maslin, M.A. Defining the Anthropocene. *Nature* **2015**, *519*, 171–180. [CrossRef] [PubMed]
4. IPCC Summary for Policymakers. *Global Warming of 1.5 °C. An IPCC Special Report on the Impacts of Global Warming of 1.5 °C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*, 1st ed.; Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., et al., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2018; ISBN 978-1-00-915794-0.
5. Warszawski, L.; Kriegler, E.; Lenton, T.M.; Gaffney, O.; Jacob, D.; Klingenfeld, D.; Koide, R.; Costa, M.M.; Messner, D.; Nakicenovic, N.; et al. All Options, Not Silver Bullets, Needed to Limit Global Warming to 1.5 °C: A Scenario Appraisal. *Environ. Res. Lett.* **2021**, *16*, 064037. [CrossRef]
6. National Ready Mixed Concrete Association Concrete CO2 Fact Sheet 2012. Available online: http://docshare02.docshare.tips/files/27104/271046448.pdf (accessed on 13 July 2021).
7. psci.princeton.edu. Cement and Concrete: The Environmental Impact. Available online: https://psci.princeton.edu/tips/2020/11/3/cement-and-concrete-the-environmental-impact (accessed on 12 July 2021).
8. The Guardian. Concrete: The Most Destructive Material on Earth. Available online: http://www.theguardian.com/cities/2019/feb/25/concrete-the-most-destructive-material-on-earth (accessed on 14 July 2021).
9. Eurostat. Statistics on Small and Medium-Sized Enterprises-Statistics Explained. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php/Statistics_on_small_and_medium-sized_enterprises#General_overview (accessed on 26 November 2020).
10. European Commission. Number of Small and Medium-Sized Enterprises (SMEs) in the Non-Financial Business Economy of the European Union (EU27) in 2022, by Sector. Statista. Available online: https://www.statista.com/statistics/1252884/smes-in-europe-by-sector/ (accessed on 20 October 2022).
11. Szigeti, C.; Szennay, Á.; Lisányi Endréné Beke, J.; Polák-Weldon, R.; Radácsi, L. Vállalati ökológiailábnyom-számítás kihívásai a kkv-szektorban. *Veztud. Bp. Manag. Rev.* **2019**, *50*, 63–69. [CrossRef]
12. Szennay, Á.; Szigeti, C.; Beke, J.; Radácsi, L. Ecological Footprint as an Indicator of Corporate Environmental Performance—Empirical Evidence from Hungarian SMEs. *Sustainability* **2021**, *13*, 1000. [CrossRef]
13. Szennay, Á. Calculating Events' Travel-Related Ecological Footprint. In Proceedings of the 12th IEEE International Conference on Cognitive Infocommunications (CogInfoCom 2021), Online, 23–25 September 2021; pp. 673–676. Available online: https://www.researchgate.net/publication/365841938_Calculating_events\T1\textquoteright_travel-related_ecological_footprint (accessed on 3 January 2023).
14. Szigeti, C.; Szennay, Á.; Lisányi Endréné Beke, J.; Polák-Weldon, J.; Radácsi, L. Challenges of Corporate Ecological Footprint Calculations in the SME Sector in Hungary: Case Study Evidence from Six Hungarian Small Enterprises. In *Agroecological Footprints Management for Sustainable Food System*; Banerjee, A., Meena, R.S., Jhariya, M.K., Yadav, D.K., Eds.; Springer: Singapore, 2021; pp. 345–363. ISBN 9789811594960.
15. Wackernagel, M.; Lin, D.; Evans, M.; Hanscom, L.; Raven, P. Defying the Footprint Oracle: Implications of Country Resource Trends. *Sustainability* **2019**, *11*, 2164. [CrossRef]
16. Lin, D.; Hanscom, L.; Murthy, A.; Galli, A.; Evans, M.; Neill, E.; Mancini, M.S.; Martindill, J.; Medouar, F.-Z.; Huang, S.; et al. Ecological Footprint Accounting for Countries: Updates and Results of the National Footprint Accounts, 2012–2018. *Resources* **2018**, *7*, 58. [CrossRef]
17. Lin, D.; Hanscom, L.; Martindill, J.; Borucke, M.; Cohen, L.; Galli, A.; Lazarus, E.; Zokai, G.; Iha, K.; Wackernagel, M. *Working Guidebook to the National Footprint Accounts*; Global Footprint Network: Oakland, CA, USA, 2018.
18. Kovács, Z.; Farkas, J.Z.; Szigeti, C.; Harangozó, G. Assessing the Sustainability of Urbanization at the Sub-National Level: The Ecological Footprint and Biocapacity Accounts of the Budapest Metropolitan Region, Hungary. *Sustain. Cities Soc.* **2022**, *84*, 104022. [CrossRef]
19. Borucke, M.; Moore, D.; Cranston, G.; Gracey, K.; Iha, K.; Larson, J.; Lazarus, E.; Morales, J.C.; Wackernagel, M.; Galli, A. Accounting for Demand and Supply of the Biosphere's Regenerative Capacity: The National Footprint Accounts' Underlying Methodology and Framework. *Ecol. Indic.* **2013**, *24*, 518–533. [CrossRef]
20. Kovács, Z.; Harangozó, G.; Szigeti, C.; Koppány, K.; Kondor, A.C.; Szabó, B. Measuring the Impacts of Suburbanization with Ecological Footprint Calculations. *Cities* **2020**, *101*, 102715. [CrossRef]

21. Chambers, N.; Simmons, C.; Wackernagel, M. *Sharing Nature's Interest: Ecological Footprints as an Indicator of Sustainability*; Routledge: London, UK, 2000; ISBN 978-1-315-87026-7.
22. Wackernagel, M.; Beyers, B. *Ecological Footprint-Managing Our Biocapacity Budget*; New Society Publishers: Gabriola Island, BC, Canada, 2019; ISBN 978-0-86571-911-8.
23. Tóth, G.; Szigeti, C.; Harangozó, G.; Szabó, D.R. Ecological Footprint at the Micro-Scale—How It Can Save Costs: The Case of ENPRO. *Resources* **2018**, *7*, 45. [CrossRef]
24. Lazarus, E.; Lin, D.; Martindill, J.; Hardiman, J.; Pitney, L.; Galli, A. Biodiversity Loss and the Ecological Footprint of Trade. *Diversity* **2015**, *7*, 170–191. [CrossRef]
25. Butnariu, A.; Avasilcai, S. Research on the Possibility to Apply Ecological Footprint as Environmental Performance Indicator for the Textile Industry. *Procedia Soc. Behav. Sci.* **2014**, *124*, 344–350. [CrossRef]
26. McBain, B.; Lenzen, M.; Albrecht, G.; Wackernagel, M. Building Robust Housing Sector Policy Using the Ecological Footprint. *Resources* **2018**, *7*, 24. [CrossRef]
27. Balogh, E.; Simor, É.; Vörös, C. (Eds.) *Mikrocenzus 2016-7. Lakáskörülmények*; Központi Statisztikai Hivatal: Budapest, Hungary, 2018; ISBN 978-963-235-494-1.
28. KSH. Mikrocenzus 2016-7. Lakáskörülmények-2.1 Lakóegységek, Lakások. Available online: https://www.ksh.hu/mikrocenzus2016/kotet_7_lakaskorulmenyek (accessed on 5 October 2022).
29. Egedy, T. A magyar lakótelepek helyzetének értékelése. *Földrajzi Ért.* **2000**, *XLIX*, 265–283.
30. Sýkora, L. Post-Socialist Cities. In *International Encyclopedia of Human Geography*; Kitchin, R., Thrift, N., Eds.; Elsevier: Oxford, UK, 2009; pp. 387–395. ISBN 978-0-08-044910-4.
31. Paládi-Kovács, Á. A Telepszerű Lakásépítés Elterjedése a XX. Század Második Felében Magyarországon DLA Értekezés Mestermunkájának Bemutatása. Ph.D. Thesis, Pécsi Tudományegyetem, Pécs, Hungary, 2020.
32. Csoknyai, T. Iparosított Technológiával Létesített Lakóépületek Energiatudatos Felújítása. Ph.D. Thesis, Budapesti Műszaki és Gazdaságtudományi Egyetem, Budapest, Hungary, 2004.
33. Karlócainé Bakay, E. Lakótelepek szabadtérépítészete 1945-1990 között Budapest példáján. Ph.D. Thesis, Budapesti Corvinus Egyetem Tájépítészeti és Tájökológiai Doktori Iskola, Budapest, Hungary, 2012.
34. Bojer, A.; Eszenyi, O.; Hluchány, H.; Nagyné Forgács, E.; Simon, É.; Szabó-Jankovics, N. *Mikrocenzus 2016-2. A Népesség és a Lakások Jellemzői*; Központi Statisztiaki Hivatal: Budapest, Hungary, 2017; ISBN 978-963-235-499-6.
35. Szabó, B.; Bene, M. Budapesti lakótelepek a panelprogram előtt és után. *Ter. Stat.* **2019**, *59*, 526–554. [CrossRef]
36. Nedučin, D.; Krklješ, M.; Perović, S.K. Demolition-Based Urban Regeneration from a Post-Socialist Perspective: Case Study of a Neighborhood in Novi Sad, Serbia. *Sustainability* **2021**, *13*, 10430. [CrossRef]
37. Kovács, Z.; Egedy, T.; Szabó, B. Persistence or Change: Divergent Trajectories of Large Housing Estates in Budapest, Hungary. In *Housing Estates in Europe*; The Urban Book Series; Hess, D.B., Tammaru, T., van Ham, M., Eds.; Springer: Berlin/Heidelberg, Germany, 2018.
38. Lasselsberger Knauf Panel Épületek Felújítása. Available online: https://www.cemix.hu/upload/catalogdocs/Lb-K_PANEL_2009.pdf (accessed on 17 October 2022).
39. Osztroluczky, M.; Csoknyai, T. Solanova Projekt-Környezetbarát Energiatudatos Panelépület-Felújítási Mintaprojekt Dunaújvárosban. 2005. Available online: http://energotrade.hu/pdf/energotrade_solanova_leiras.pdf (accessed on 17 October 2022).
40. Kumar, A.; Singh, P.; Kapoor, N.R.; Meena, C.S.; Jain, K.; Kulkarni, K.S.; Cozzolino, R. Ecological Footprint of Residential Buildings in Composite Climate of India—A Case Study. *Sustainability* **2021**, *13*, 11949. [CrossRef]
41. Labaran, Y.H.; Mathur, V.S.; Muhammad, S.U.; Musa, A.A. Carbon Footprint Management: A Review of Construction Industry. *Clean. Eng. Technol.* **2022**, *9*, 100531. [CrossRef]
42. Ramesh, T.; Prakash, R.; Shukla, K.K. Life Cycle Energy Analysis of Buildings: An Overview. *Energy Build.* **2010**, *42*, 1592–1600. [CrossRef]
43. Jackson, D.J. Addressing the Challenges of Reducing Greenhouse Gas Emissions in the Construction Industry: A Multi-Perspective Approach. Ph.D. Thesis, The University of Edinburgh, Edinburgh, UK, 2020.
44. Holthaus, E. *Thee Future Earth a Radical Vision for Whats's Possible in the Age of Warming*; HarperCollins: New York, NY, USA, 2020.
45. Mostert, C.; Bock, J.; Sameer, H.; Bringezu, S. Environmental Assessment of Carbon Concrete Based on Life-Cycle Wide Climate, Material, Energy and Water Footprints. *Materials* **2022**, *15*, 4855. [CrossRef] [PubMed]
46. Farina, I.; Moccia, I.; Salzano, C.; Singh, N.; Sadrolodabaee, P.; Colangelo, F. Compressive and Thermal Properties of Non-Structural Lightweight Concrete Containing Industrial Byproduct Aggregates. *Materials* **2022**, *15*, 4029. [CrossRef] [PubMed]
47. Horváth, Á. *BIM 5D Web Alkalmazás (Költség és Idő Optimalizálás a Kivitelezésben)*; ELTE: Budapest, Hungary, 2020.
48. Somogyi, Á.; Lovas, T. Supporting BIM by terrestrial laser scanning. *Geod. Es Kartogr.* **2017**, *69*, 10–14.
49. Somogyi, Á.; Fehér, K.; Lovas, T.; Halmos, B.; Barsi, Á. Analysis of Gothic Architectural Details by Spatial Object Reconstruction Techniques. *Period. Polytech. Civ. Eng.* **2017**, *61*, 640–651. [CrossRef]
50. Liu, Z.; Li, P.; Wang, F.; Osmani, M.; Demian, P. Building Information Modeling (BIM) Driven Carbon Emission Reduction Research: A 14-Year Bibliometric Analysis. *Int. J. Environ. Res. Public Health* **2022**, *19*, 12820. [CrossRef] [PubMed]
51. Zhao, L.; Zhang, W.; Wang, W. BIM-Based Multi-Objective Optimization of Low-Carbon and Energy-Saving Buildings. *Sustainability* **2022**, *14*, 13064. [CrossRef]

52. de Paula, N.; Jyo, L.K.; Melhado, S.B. Sources of Challenges for Sustainability in the Building Design—The Relationship between Designers and Clients. *Buildings* **2022**, *12*, 1725. [CrossRef]
53. Onososen, A.; Musonda, I.; Tjebane, M.M. Drivers of BIM-Based Life Cycle Sustainability Assessment of Buildings: An Interpretive Structural Modelling Approach. *Sustainability* **2022**, *14*, 11052. [CrossRef]
54. Hammond, G.P.; Jones, C.I. Embodied Energy and Carbon in Construction Materials. *Proc. Inst. Civ. Eng. Energy* **2008**, *161*, 87–98. [CrossRef]
55. Yan, J.; Lu, Q.; Tang, J.; Chen, L.; Hong, J.; Broyd, T. Digital Tools for Revealing and Reducing Carbon Footprint in Infrastructure, Building, and City Scopes. *Buildings* **2022**, *12*, 1097. [CrossRef]
56. Leon, F.; Ramos, A.; Vaswani, J.; Mendieta, C.; Brito, S. Climate Change Mitigation Strategy through Membranes Replacement and Determination Methodology of Carbon Footprint in Reverse Osmosis RO Desalination Plants for Islands and Isolated Territories. *Water* **2021**, *13*, 293. [CrossRef]
57. Leon, F.A.; Ramos Martín, A.; Falcón Alvarado, Y.; Brito, S. Proposal to Determine the Carbon and Ecological Footprint of Seawater Reverse Osmosis Desalination in the Canary Islands Plants Considering the Energy Mix. *Desalin. Water Treat.* **2021**, *230*, 9–16. [CrossRef]
58. Leão, A.S.; Araujo, M.C.; de Jesus, T.B.; Almeida, E.d.S. Is the Soil-Cement Brick an Ecological Brick? An Analysis of the Life Cycle Environmental and Energy Performance of Masonry Walls. *Sustainability* **2022**, *14*, 12735. [CrossRef]
59. Pulselli, R.M.; Simoncini, E.; Ridolfi, R.; Bastianoni, S. Specific Emergy of Cement and Concrete: An Energy-Based Appraisal of Building Materials and Their Transport. *Ecol. Indic.* **2008**, *8*, 647–656. [CrossRef]
60. Li, D.; Joshi, V.; Lavender, C.; Khaleel, M.; Ahzi, S. Yield Asymmetry Design of Magnesium Alloys by Integrated Computational Materials Engineering. *Comput. Mater. Sci.* **2013**, *79*, 448–455. [CrossRef]
61. Solís-Guzmán, J.; Marrero, M.; Ramírez-de-Arellano, A. Methodology for Determining the Ecological Footprint of the Construction of Residential Buildings in Andalusia (Spain). *Ecol. Indic.* **2013**, *25*, 239–249. [CrossRef]
62. Bastianoni, S.; Galli, A.; Niccolucci, V.; Pulselli, R.M. The Ecological Footprint of Building Construction. In *The Sustainable City IV: Urban Regeneration and Sustainability*; WIT Press: Tallin, Estonia, 2006; Volume 1, pp. 345–356.
63. Ruiz-Pérez, M.R.; Alba-Rodríguez, M.D.; Castaño-Rosa, R.; Solís-Guzmán, J.; Marrero, M. HEREVEA Tool for Economic and Environmental Impact Evaluation for Sustainable Planning Policy in Housing Renovation. *Sustainability* **2019**, *11*, 2852. [CrossRef]
64. Tóth, G.; Szigeti, C. The Historical Ecological Footprint: From over-Population to over-Consumption. *Ecol. Indic.* **2016**, *60*, 283–291. [CrossRef]
65. Freire-Guerrero, A.; Alba-Rodríguez, M.D.; Marrero, M. A Budget for the Ecological Footprint of Buildings Is Possible: A Case Study Using the Dwelling Construction Cost Database of Andalusia. *Sustain. Cities Soc.* **2019**, *51*, 101737. [CrossRef]
66. González-Vallejo, P.; Muñoz-Sanguinetti, C.; Marrero, M. Environmental and Economic Assessment of Dwelling Construction in Spain and Chile. A Comparative Analysis of Two Representative Case Studies. *J. Clean. Prod.* **2019**, *208*, 621–635. [CrossRef]
67. González-Vallejo, P.; Marrero, M.; Solís-Guzmán, J. The Ecological Footprint of Dwelling Construction in Spain. *Ecol. Indic.* **2015**, *52*, 75–84. [CrossRef]
68. Szennay, Á.; Major, Z.; Beke, J. Ecological Footprint Satellite Calculators to Determine the Environmental Impact of Material Usage of SMEs. In Proceedings of the 12th IEEE International Conference on Cognitive Infocommunications (CogInfoCom 2021), Online, 23–25 September 2021; pp. 677–680. Available online: https://www.researchgate.net/publication/365841797_Ecological_footprint_satellite_calculators_to_determine_the_environmental_impact_of_material_usage_of_SMEs (accessed on 3 January 2023).
69. Mózner, Z.V. Sustainability and Consumption Structure: Environmental Impacts of Food Consumption Clusters. A Case Study for Hungary. *Int. J. Consum. Stud.* **2014**, *38*, 529–539. [CrossRef]
70. International Energy Agency. *Energy Policies of IEA Countries-Hungary 2017 Review*; International Energy Agency: Paris, France, 2017; Volume 176.
71. DEFRA. Greenhouse Gas Reporting: Conversion Factors 2018. Available online: https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2018 (accessed on 15 July 2020).
72. Hammond, G.; Jones, C. *Inventory of Carbon and Energy*; University of Bath: Bath, UK, 2008.
73. Embodied Carbon Footprint Database. *Circular Ecology*.
74. Dr Palotás, L. (Ed.) *Mérnöki Kézikönyv–I. Kötet*; Műszaki Könyvkiadó: Budapest, Hungary, 1981.
75. Global Footprint Network. Open Data Platform. Available online: http://data.footprintnetwork.org/#/analyzeTrends?type=EFCtot&cn=5001 (accessed on 20 October 2020).