applied system innovation

MDPI

Article

Measuring Carbon in Cities and Their Buildings through Reverse Engineering of Life Cycle Assessment

Luís Bragança [1,2,*] and María Concepción Verde Muniesa [2,3,*]

1 Institute for Sustainability and Innovation in Structural Engineering (ISISE), Advanced Production and Intelligent Systems (ARISE), University of Minho, 4800-058 Guimarães, Portugal
2 Civil Engineering Department, School of Engineering, University of Minho, 4800-058 Guimarães, Portugal
3 International Doctoral Programme (Ph.D.) in Sustainable Built Environment (iDiSBE), 4800-058 Guimarães, Portugal
* Correspondence: braganca@civil.uminho.pt (L.B.); id9627@alunos.uminho.pt (M.C.V.M.); Tel.: +34-606-555715 (M.C.V.M.)

Abstract: According to the European Green Deal, excessive carbon emissions are the origin of global warming and must be drastically reduced. Given that the building sector is one of the major sources of carbon emissions, results imperative to limit these emissions, especially in a city context where the density of buildings is commonly higher and rapidly increasing. All stages of the life cycle of a building, including raw material harvesting, manufacturing of products, use phase of the building, end of life, all generate or reduce carbon. The manufacture of construction materials accounts for 11% of all energy and process-related emissions annually. Additionally, recent estimates indicate that over 80% of all product-related environmental impacts of a building are determined during the design phase of the building. These indicators reflect the urgent need to explore a low-carbon measure method for building design. This is here done using a linear regression Reverse Engineering model and percentage calculation. One of the hypotheses formulated relates Global Warming Potential (GWP) of -30.000 CO_2eq or lower (around -165 CO_2eq/m^2) in the 25% of a block of houses, to carbon further reductions by 11%. This paper has identified barriers in terms of the databases needed to achieve this task.

Keywords: reverse engineering; life cycle assessment (LCA); carbon metrics; Sustainable Bio-Urbanism; machine learning; Artificial Intelligence

check for updates

Citation: Bragança, L.; Verde Muniesa, M.C. Measuring Carbon in Cities and Their Buildings through Reverse Engineering of Life Cycle Assessment. *Appl. Syst. Innov.* **2023**, *6*, 76. https://doi.org/10.3390/asi6050076

Academic Editors: Christos Douligeris and Evangelos Bellos

Received: 3 April 2023
Revised: 25 May 2023
Accepted: 26 May 2023
Published: 28 August 2023

1. Introduction

In 2014, the European Council agreed on the 2030 climate and energy framework [1], followed by the approval of the related European Union (EU) climate and energy policies by the European Council and the European Parliament. The EU's ambition to reduce greenhouse gas emissions (GHG) to at least 40% by 2030 is consistent with the guidelines of the European Commission for nearly zero-energy buildings [2–7], under EU reports for monitoring the countries' progress in the field.

This is also coherent with the European Green Deal´s longer-term objective [8,9] to transform the EU into a competitive low-carbon economy by 2050, in the scenario of the recommended reductions of carbon emissions to be made by EU countries. This objective aligns with the Intergovernmental Panel on Climate Change (IPCC) goal of reducing its carbon emissions by 80–95% by 2050 (compared to 1990 levels), with milestones of 40% by 2030 and 60% by 2040 [1]. Setting out a plan to "increase the EU (European Union) 2030 climate target to at least 50% and towards 55% in a responsible way" [9]. According to the European Commission 2019 Global Status Report [3], the built environment accounts for around 40% of annual global CO_2 emissions. Reducing building sector carbon emissions is essential for achieving the carbon neutrality European Commission target by 2050. In buildings, therefore, in cities [10,11].

EU climate action initiatives include three types of measures [1]: (1) cut GHG emissions; (2) expand the use of renewable energy and (3) meet energy efficiency targets.

This research focuses on the first type of measure, the cut in GHG emissions. In particular, it focuses on low-carbon nature-based solutions [12–14] (bio-based materials for walls and roofs in buildings) for building design, since low-carbon construction materials [15–18] have become critical in sustainable building design for the chosen climate action measure (1) above.

For that purpose, it is vital to have a thorough understanding of the building´s life cycle´s carbon emission process [19,20]. Life Cycle Assessment (LCA) is a modeling tool to evaluate environmental impacts related to a product, including carbon emissions, termed Whole Life Carbon (WLC), for the case of buildings [21,22]. The Communication from the Commission to the Council and the European Parliament of Integrated Product Policy concluded that Life Cycle Assessment provides the best framework for embodied carbon [23]. Carbon emissions occur during the entire life cycle of a building. The European standard EN 15978 [24] sets the system boundaries of whole-building WBLCAs (Whole Building Life Cycle Assessment) and the Calculation method of the environmental performance of buildings, including carbon emissions. In this paper, the Reverse Engineering method application and the percentage reduction analysis enable minimizing the concerns about uncertainty and variability of WBLCA [25]. The system boundary specified by the standard consists of the following 16 sub-stages grouped into four life cycle stages: the Product stage, Construction Stage, Use Stage, and End of Life [24].

- Product Stage:
  - A1. Raw material extraction
  - A2. Transport to manufacturing site
  - A3. Manufacturing
- Construction Process Stage:
  - A4. Transport to construction site
  - A5. Construction Process
- Use Stage:
  - B1. Use
  - B2. Maintenance
  - B3. Repair
  - B4. Replacement
  - B5. Refurbishment
  - B6. Operational energy use
  - B7. Operational water use
- End of Life Stage:
  - C1. De-Construction demolition
  - C2. Transport
  - C3. Waste processing
  - C4. Disposal
- (Supplementary Information Beyond Building Life Cycle:
  - D. Benefits and loads beyond system boundary: Reuse-Recovery-Recycling Potential).

The carbon emissions released during each stage of the building life-cycle vary [26,27]. Embodied carbon is the sum of GHG emissions during the stages: raw material extraction, transportation, manufacturing, construction, maintenance, renovation, and end-of-life for a product or a system. In the case of buildings, it comprises the construction phases, while operational carbon links to the use phases [24,28]. Embodied carbon is reported as Global Warming Potential (GWP). The Environmental Protection Agency (EPA) states [29,30]: "The Global Warming Potential (GWP) was developed to allow comparisons of the global warming impacts of different gases. Specifically, it is a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time, relative to the emissions of 1 ton of carbon dioxide (CO_2)".

The standard for the calculation methods of carbon emissions generated in the life cycle of a building [19,23,24,31] establishes that for the embedded carbon emission, life cycle assessment (LCA) is a widely accepted approach. LCA is defined by the International Standard ISO 14040 [31] as "the compilation and evaluation of the inputs, outputs, and the potential environmental impacts of a product system throughout its life cycle". In its "Integrated Product Policy" document, the European Commission underlined the need for consensus in LCA methodologies and more consistent data. As a result, initiatives were launched to this point [23,32,33]. For the study case of this document, the LCA tool LCAByg [34] was used for the GWP values calculation.

The LCA calculation process behind LCAByg and other LCA tools [35] shows high interoperability with other design, calculation, modeling, reverse engineering, machine learning, and coding tools [36,37]; thus, the method chosen in this paper [34,38,39], using LCAByg (2023), MatLab (https://www.mathworks.com/products/matlab.html) and Excel (2023) tools, is coherent with that objective. Most importantly, a future application of this method approach to other sustainability indicators, design variables, sustainability assessments, and reverse engineering tools—for instance, the economic factor, as other recent research documents study, is possible. In them, monetary values and their corresponding environmental inputs/outputs are analyzed with methods such as (EIO)-based methods of LCA evince [40].

Building LCA studies have often concentrated on a specific variables of the building [40] or on each stage of the life cycle of the building separately [41]; few have addressed the entire building over its whole life cycle due to the difficulties of acquiring accurate input data (building material quantities, building performance indicators) [42]. Design tools such as Building Information Modelling (BIM) and LCA Carbon calculation tools [41] allow for the avoidance of this barrier [42], offering add-ons/plugins to this end. Likewise, this paper's method can be helpful as a prediction/target seek/optimization/design (P/T/O/D) function add-on/plugin to design tools. The effect of building design on carbon emissions is currently well understood by academics around the globe, who have also conducted extensive research in this area using machine learning or similar tools, although limited to specific aspects such as:

(1) Studies for prediction, scope, also for carbon footprint [43], and optimization [44–46], or modeling/digital twins for design and energy [47–51]. Those are studies mainly focused on energy performance, design comparison for a building, parametric design, or optimization of a building for specific parameters.
(2) Studies for cost-sustainability analysis: Carbon-cost related, Sustainable assessment cost prediction through neural network, Artificial Intelligence (AI) Cost-Carbon tools [52,53].
(3) Studies based on a comparison between a design solution and a reference solution named conventional solution, usually defined in construction catalogs [54].
(4) Studies for the measurement of carbon in cities, for instance, through surveys and multi-country life cycle assessment techniques or other accounting principles [55,56].

This paper's approach is holistic, based on Reverse Engineering (RE) inductively [57–60]. Some definitions such as "Intermediate layer of Façade" that appears this paper´s Supplementary Material is defined in the LCAByg [34] website.

Some research documents on carbon emissions of buildings explore different construction solutions for a building by calculating and comparing the performance of different designs for the same building. Other research documents on carbon emissions of products explore the embodied carbon of different materials. Instead, this research document explores the impact that a percentage of new or refurbished houses in a block in a city could cause, measured in reduction percentage of relative values due to their low carbon and materials circular/resources efficiency design. This approach allows for standardization, and cross-cutting globalization.

The carbon emission measurements in this paper consider the life cycle process with basic inventory information of the design of a building and high model readability [61], since this research tries to support designers as a guide for rough reference values in the early stages of design (see model description in the Supplementary Material).

This research's percentage calculations are elaborated with the GWP values obtained from the LCA calculation [34] of different houses, considering different groups of materials for each. The hypothesis is that the group of 15 houses conforms to a city block. Therefore, as stated in the first paragraph of Section 1 in this document, energy performance is not a subject of this paper. Furthermore, house Type 2 [62] is formed from an example with LCAByg 3.0 and Okböaudat 2013–2016 of the LCAByg website, and the modelization (linear regression and others) was carried out in 2021 and then updated, resulting in the same model. As stated above, the premise of this paper is to elaborate on a standardized method and coherently its cross-cutting/global approach. For this purpose, for the case study of this paper, a Danish LCA tool is chosen, the LCAByg tool; a biogenic building design solution from an example of a house is selected as a global solution. Thus the investigation of different scenarios and regulations is considered.

Due to the complexity of the building environment, low-carbon building design to achieve EU goals faces numerous difficulties in the actual practice. This paper suggests that the lack of specific tools for designers to measure carbon emissions reduction on a city scale could be one of the reasons. Tools that would determine the percentage of improvement in carbon emissions reduction (for the whole city, a street, a block of houses) the house design would represent. This method will include prediction or/and optimization or/and seek target processes for building design (See Tables S1–S9 and Figure S2 in the Supplementary Material).

This document provides measurements with predicted values from a RE machine learning model elaborated in 2021–2022 that captures the relation between LCA (Life Cycle Assessment) GWP values (Tables S1–S5 in Supplementary Material). It considers the percentage of reduction of GWP and correlated GHG (Greenhouse Gas) in different hypothetical situations. Through a quadratic regression model case, this essay tries to outline the relationship between building design and carbon emissions in a city scenario and to investigate its obstacles and potential future advances.

The research's methodology is covered in Section 2. The Results in Section 3 are discussed in Section 4, and support material is provided, due to the elaboration in 2021 and some previous results in 2021 and 2022 of models used in this paper. The key conclusion is found in Section 5. This essay seeks to help designers as a guide to low-carbon building design in a positive way.

2. Materials and Methodology

In the present study case, the reduction of Global Warming Potential for different groups of houses in a block in a hypothetical city is calculated and shown in different tables presented here and at the support material document. In this Section, several results for the case of twelve hypothetical houses is shown in two tables. In Table 1, predicted, estimated and calculated values are shown, and in Table 2 several data are presented for three carbon emissions classes of houses: A, B, and C, depending on the amount of each house´s carbon emissions reduction classification. Similarly, other hypotheses are calculated (see Supplementary Material). Those tables can serve as a guide for designers, stakeholders of buildings or construction, and real state decision. Furthermore, this approach for measurement of Carbon emissions intends to function as a reference for circular solutions and the evaluation of other sustainability indicators.

This method for this first case hypothesis seeks the carbon reduction a low-carbon design would cause in a particular group of houses with the same typology. Table 1 shows the values of the GWP Total of the first nine houses; which are existing houses. Then, the other three houses (new or refurbished) GWP Total. The hypothesis establishes a value of -30.000 CO_2eq of GWP^T for each of these three last houses.

From there, we predict GWP^W and GWP^F (see nomenclature in Table 3) through linear regression. The linear regression model serves for the prediction of GWP values. Then the percentage of reduction of GWP, correlated GHG (Greenhouse Gas) is calculated for each case in Excel tool. Codes for the same calculation in MatLab and Python are developed likewise [38,39]. Finally, Environmental Product Declaration (EPD) values and carbon emissions equivalent per square meter values corresponding to those GWP values aforementioned, are showcased. Method for percentages calculations:

New Construction/Refurbished House: Types 10, 11 and 12
Percentage of new construction/refurbished houses in a block: $(100 \times n)/m)\%$

$\%GWP^T$ Red: It is explained further in Section 3.

- Absolute % Reduction. (Table 2 Column 8 First Value, intervals):

$$[100 \times (GWP^T{}_{Re} - GWP^T{}_{Ra\,(I,\,II,\,III\text{ or }IV)})]/GWP^T{}_{Re}$$

where: $GWP^T{}_{Re}$ Reference Value (in the linear regression model (quadratic) equal to 83,120 CO_2eq); $GWP^T{}_{Ra}$ Range Values (Table 2 Column 2, intervals): $GWP^T{}_{Ra\,I}$ = 83,120; $GWP^T{}_{Ra\,II}$ = 65,440; $GWP^T{}_{Ra\,III}$ = 37,230; and $GWP^T{}_{Ra\,IV}$ = −32,670 CO_2eq);

- Relative %. Percentage from Sum of pre-existing houses carbon emissions (In this case 9 houses are the existing houses) that the 25% of new/refurbished houses with the average carbon emissions GWP^T per range A, B and C, would represent (Table 2 Column 8 Second Value):

Considering that the Average Values per Class ($GWP^T{}_{Av}$), Average Values, $GWP^T{}_{Av}$, for Class C: $[(GWP^T{}_{Ra\,I} + GWP^T{}_{Ra\,II})/2$; multiplied per number of new/refurbished houses (n) is respectively:

Class C: $n \times [(GWP^T{}_{Ra\,I} + GWP^T{}_{Ra\,II})/2]$; Class B: $n \times [(GWP^T{}_{Ra\,II} + GWP^T{}_{Ra\,III})/2]$; Class A: $n \times [(GWP^T{}_{Ra\,III} + GWP^T{}_{Ra\,IV})/2]$, or $GWP^T{}_{Mx} - GWP^T{}_{Mn}$ of each range then, the Relative % Reduction (Table 2 Column 8 Second Value), per each range:

$$\left[100 \times \left(n \times GWP^T{}_{Av}\right)\right] / \sum_{i=p}^{i=1} GWP^T{}_i$$

where: n is the number of new construction/refurbished houses in a block of houses in a city; m is the number of (pre-existing + new/refurbished) total houses in a block of houses in a city; p is the number of pre-existing houses in a block of houses in a city; m = p + n and likewise:

$$\sum_{i=m}^{i=1} GWP^T{}_i - \sum_{i=p}^{i=1} GWP^T{}_i = \sum_{i=n}^{i=1} GWP^T{}_i$$

In another hypothesis, instead of Average, per n number of houses, we consider the Sum of carbon emissions of new/refurbished houses, in this case, houses Type 10, 11 and 12, to calculate the percent:

$$\left(100 \times \sum_{i=n}^{i=1} GWP^T\right) / \sum_{i=p}^{i=1} GWP^T{}_i$$

or, in another hypothesis: Percentage from maximum value of carbon emissions of the houses types, that the difference between maximum value of carbon emissions and average value per range represents (in this case $GWP^T{}_{Mx}$ and $GWP^T{}_{Re}$ values are coincident):

$$[100 \times (GWP^T{}_{Mx} - GWP^T{}_{Av(A,\,B\text{ or }C)})]/GWP^T{}_{Mx}$$

The Results and Discussion of this paper, suggest that an exhaustive fitting through the application of complex algorithms or statistical extensive methods are not reviewed at this research stage. The measurement values are calculated in the next Section 3.

3. Results

This section provides measurement results in percentages of GWP reduction for a block of twelve family-one floor-detached-houses in a hypothetical city. Its aims is to identify the design choices which would involve a reduction of carbon emissions that aligns with the reduction targets recommended by the European Commission for Carbon emissions reduction. The support material further data will consider other different hypotheses apart from the one shown below.

PRACTICAL APPLICATION OF THE MODEL AND THE CALCULATION METHOD:

Design of a Type for new or refurbished Home in a block, estimation of GWP Partial for Target, and Prediction of GWP Partial for Target, reduction percentages calculation.

The maximum occupation in that block in that area: 12 Houses.

Houses Types 1 to 9 (existing): Different values of GWP^T, obtained through LCA calculation. Considered conventional construction.

Houses Type 10, 11 and 12 (new/refurbished houses): Considered nonstandard or unconventional construction, GWP^T of each one −30.000 CO_2eq. Results are shown in Table 1 (see Table 3 for nomenclature):

Table 1. GWP^T Results; GWP^W, GWP^F Prediction Graph2 Figure S2 Functions; Normalized values.

TypeH	GWP^T	GWP^W Estimated	GWP^F Estimated	GWP^T n	$\lvert GWP^W \rvert$ n	GWP^F n	GWP^W Pred	GWP^F Pred	CO_2eq/m^2 [5]	A [6]
1	91,205	7630	6430	0.011	0.09 [2]	0.05	6463	6111	493	185
2	73,100	7630	6430	0.15	0.048 [2]	0.12	7007	5664	430	170
3	82,080	7630	6430	0.08	0.07 [2]	0.08	6722	5919	456	180
4	92,530	7630	6430	0	-- [3]	0.05	--	6111	487	190
5	86,580	7630	6430	0.05	0.08 [2]	0.066	6593	6009	468	185
6	91,205	7630	6430	0.011	0.09 [2]	0.05	6463	6111	493	185
7	82,260	7630	6430	0.084	0.07 [2]	0.08	6722	5919	457	180
8	72,480	7630	6430	0.163	0.04 [2]	0.12	7007	5664	453	160
9	90,095	7630	6430	0.020	0.09 [2]	0.05	6463	6111	487	185
10	−30,000	−5330	50	1	0.43	-- [1](1)	2057	52.9 [4]	−166	180
11	−30,000	−5330	50	1	0.43	-- [1](1)	2057	-- [1]	−162	185
12	−30,000	−5330	50	1	0.43	-- [1](1)	2057	-- [1]	−162	185

[1] Values cannot be found, should be normalized to 1, because it is the lowest GWP^T value; [2] It should be assimilated to value 0, because it is the highest GWP value of the Set. $\lvert GWP^W{}_n \rvert$, is the number in absolute terms; [3] Value cannot be found, because it is −0.1029 for a value of GWP^T n closed to 0 equal to: 5.426×10^{-6}; [4] The value of 52.9 is extracted from GWP^F of table of LCA GWP Results Supplementary Material Type 14; [5] GHG_e or CO_2eq/m^2 is Embodied GHG emissions per m^2 of a house, in CO_2eq/m^2; stated that CO_2eq = GWP × GHG emissions; GWP for Carbon = 1. See values [10], for Emission intensity on a building level, in $kgCO_2eq/m^2$; [6] A: Area of the house (m^2); TypeH: House Types for this hypothesis.

This hypothesis is a city scenario of 25% of new/refurbished homes (in a block of 12 houses) composed of biogenic solutions, intending a Target of a 10–11% reduction in GHG emissions as an example of materials impact indicator used.

The sum of the GWP^T of the 9 first types of houses, which are existing houses, is Sum (Types 1 to 9) = 761,535. If considering a reduction Target of 10 to 11% for that block of a city, the Total should be reduced to at least 685,381. So, the GWP^T of Type 10 or 11, or 12 = −25,384, rounded to −30,000 for an abstract Target. The Sum is 671,535 < 685,381 to 677,766 Target, so the values considered for the hypothesis calculation are correct. After the normalization (Figure S1 in Supplementary Material) of GWP^T ($GWP^T{}_n$ is in column number 5 of Table 1), two Linear Regression Functions are applied. To obtain the values of column number 10 of Table 1, the GWP^T of each house type is divided by its respective square meters of surface, the values are in $CO_2eq/m^{2,}$ and the respective values of GHGe/Kg is considered. For the cases of low GWP^T, or negative (Types 10 to 12), the function utility finds some barriers: Excel Data Goal Seek Tool or MatLab Tool or Python (3.11.4) code are not able to find a result, for the functions used, for the values of GWP^T normalized. The model used in this paper was carried out in 2021–2022 together with another model for the same issued problem with better performance.

The comparisons between the results for each house Type in columns 3 and 8 in Table 1, and between columns 4 and 9 of the same table respectively, conclude, that the model performs well in terms of abstract targets, to find references and ranges of values for housing design facilitation; with some limitations in seeking GWP^W accurate values. In the model, $GWP^T{}_{Re}$ or $GWP^T{}_{Mx}$ value is 83,120; while in Table 1, is 92,530.

The ranges found through this paper hypothesis, are presented in the following Table 2, or CHEC (Classification of House Embodied Carbon) Table, considering a 185 m^2 prototype house, and a% of new homes/refurbished homes. GWP^TRed% is the measure obtained in this paper, the percentage reduction of GWP Total achieved with each Class (A, B or C), considering that 25% of the number of the houses under measurement are houses refurbished/new homes Class A, B, or C. Depending on the Class, the percentage reduction achieved will be different, see Table 2. In this table, the A class range, GWP^T from 65,440 to 37,230 range of values, is a range wider than its equivalent classification range in the other models. For normalization Table 1 values, the maximum value considered here is 92,530 CO_2eq. In both two linear regression models that were carried out, their equivalent range of low-carbon unconventional solutions cover values between 16,410 GWP^T and −32,670 instead.

Table 2. Table of Classification of House Embodied Carbon (A, B or C) or CHEC Table.

Class	GWP^T	GWP^W	GWP^F	GWP^T n	GWP^W n	GWP^F n	%GWP^TRed [1]	Layer Wall [2]	EPD [3]	CO_2eq/m^2
C	83,120 to 65,440	7630	6430	0 to 0.14	0 to 0.76	0 to 0.35	0 to 21%/−29.2%	Standard d. [4]	158 min	449 to 353
B	65,440 to 37,230	−2270	4190	0.14 to 0.38	0.76	0.35	21% to 55%/−20%	Straw [5]	7.63	353 to 201
A	37,230 to −32,670	−5330	52.9	0.38 to 1	0.76 to 1	0.35 to 1	55% to 139%/-0.9%	Straw new [5]	7.63	201 to −177

[1] %GWP^T Red: The first value is the difference between $GWP^T{}_{Mx}$ and $GWP^T{}_{Ra}$ of each range (intervals values of ranges A, B or C), from $GWP^T{}_{Mx}$ or $_{Re}$, in percent of Reduction (in percentage), GWP^T maximum or reference value is 83,120 CO_2eq. The second value is: Percentage from the Sum of the nine houses pre-existing carbon emissions, of Sum of GWP^T 25% of new/refurbished houses (three houses of each Average value per range) represents. Sum of GWP Total existing = 761,535; Average Values of GWP Total in each range: 74,280/51,335/2,280 CO_2eq for Classes C, B, and A, respectively. These values are convenient for target seek and analysis; Similarly, they are appropriate in order to know the difference between GWP Total of the 9 existing houses and those 9 houses plus the 3 new houses. In this case, in Classes A,B,C respectively, (the same as average of each class 3 houses Sum): 761,535 − 984,375 = −222,840; 761,535 − 915,540 = −154,005; 761,535 − 754,695 = 6,840; respectively, meaning Carbon Reduction in CO_2eq. [2] Main component for that range of GWP, for external layer of Façade Wall [3] GWP in EPD data, of main component for each Type 16 and 17, Supplementary Material, in Kg CO_2eq, 158 min means minimum value; [4] Standard d.: Standard different solutions; [5] Straw new: Straw new house, Biogenic solution.

Other information: Sum of GWP^T of preexisting 9 houses in Table 1, equal to 761,535: Percentage reduction that the difference between GWP^T maximum Value, ($GWP^T{}_{Mx}$ or $GWP^T{}_{Re}$) and $GWP^T{}_{Av}$, presnets from $GWP^T{}_{Mx\ or\ Re}$ per range: 10.63%/38.23%/97.25% Classes C, B or A respectively, from $GWP^T{}_{Mx}$ or $GWP^T{}_{Re}$; If the GWP^T of a Class A house is −30,000 CO_2eq, then, the percentage of reduction in carbon emissions, %GWP^T Red, or difference between the existing houses sum of carbon emissions of those nine houses and the hypothesis sum of carbon emissions of twelve houses (nine existing and three new/refurbished additional houses with CO_2eq −30,000 each), from the existing houses sum of carbon emissions, is 11.81%. The CO^2eq/m^2 statistical data values from Table 1 Column 10 and Table 2 Column 11 are comparable to previous GHG studies [10], in this last case for a prototyped house of 185 m^2.

The reason for choosing those ranges is that the value of the Class B 65,440 is close to certain European recommendations for large buildings carbon emissions (GWP^T recommended Target value 74,000 CO_2eq; and upper limit value from 1 January 2023 equal to 111,000 CO_2eq), and that the value of 37,230 CO_2eq limits with the 55% of Reduction from the $GWP^T{}_{Re}$ or $GWP^T{}_{Mx}$, which is more suitable for reference rough values, and meaning that the CHEC is customizable for each particular city housing conditions, Targets or reference values.

When 25% of the houses of the Block of 12 houses hypothesis are Class C or Class B new/refurbished houses, the Target reduction of 10–11% of Carbon emissions cannot be achieved in a city context. The Carbon Reduction starts from around a Value of Class A lower than 0 CO_2eq. For instance, the Average Class A value of 2280 CO_2eq of GWP Total per new/refurbished house, for 3 houses in a Block of 12 houses, corresponds to a difference in carbon emissions of 0.9% increase or negative reduction (Table 2 row three, column eight, %GWP^TRed second value).

Three new/refurbished houses with a GWP Total at least as low as −30,000 CO_2eq per house, will be needed for around a percentage reduction of 10–11% (11.8% of Sum GWP^T reduction), for a group of 12 houses of a Block of a city, being 9 of them existing houses of Class C as reference, with average GWP Total of 84,615 CO_2eq.

4. Discussion

Several main questions related to (1) Carbon emissions Measurements (CEM), (2) Reverse Engineering (RE), and (3) Life Cycle Assessment (LCA), in this order, are discussed:

1. Carbon emissions Measurements:
    - 1.1. Real (in-situ, in real-time) carbon emissions measurement seems to be more accurate, and coherent to the approach of this paper, if derived from direct measurements, for target reductions, than the measures of KgCO_2eq per m^2 that are used in this paper for reference. However, it is proven, through the previous studies aforementioned and this paper´s results, the potential of the method to relate the GWP of the building and GHG, and the utility for building design choice, as the study is based on comparisons and abstract targets. This paper also provides measured raw data real Values of GWP and GHG, according to the data processing and modeling methods of this paper. With a different Data Base, raw data of GWP and GHG, a data set could be similarly related and modeled. The European reports that provide raw data on carbon emissions [2,63], highlight in one of its sections the importance of the reduction of Carbon removal from the LULUCF sector, due to wood fires and wood extraction for construction and energy. Verbatim reproduction from the document, in order to show the sort of data (Raw Data literal exact transcription for Spain, full content in Supplementary Material, Figure S4) is as follows: "Spain, 2021, ESP, 47486932, 8.609, 0.181, 233.650, 20.310, 9.520, 208.148, 19.870, 10.554, 4.383, 0.134, 4.920, 0.150, 18.575, 0.391, 705.016, 15100.203, 17219.338, 4858.969, 83.655, 1654.140, 2121.383, 7685.895, 112.529, 32708. . ."
    - 1.2. Likewise the variant Type 14 in the seven houses street hypothesis of this paper´s Supplementary Material leads to reduction in carbon emissions, other system construction variants of the design of the house, could most probably, lead to greater reductions of Carbon emission. According to the results, a reduction of 19.64%, occurs when one of the seven houses of a block include biogenic solutions instead of conventional solutions, in the hypothetical case of a group of seven houses in a street.
    - 1.3. In the fifteen houses hypothesis, if at least 53% of the houses of a block of 15 houses would choose a biogenic solution for the external layer of the façade walls (Types 8 to 15), the GHG of the emissions of the block (extendible to the city emissions) would be reduced greatly by design. Percentage to add to the 27.3% carbon emissions reduction from 1990 to 2021, or 21.7% change in total GHG emissions 1990–2017 in Europe and United Kingdom (EU-28), 29.5% for Denmark, values in Table 7.3 in [1]. Red%$GWPS^T$ presents similar values.

2. Reverse Engineering and Models: According to previous studies related to the subject compiled in this paper´s review, some researchers had concluded that the prediction model under multi-criteria evaluation shows better accuracy. However, for this study case, the third model, achieves high accuracy, probably because the model is structure-related [64] instead of energy related (contrary to the totality of the studies presented before in the References and Section 1 in this paper for multi-criteria modelization).
3. LCA
    3.1. Design Process The shape of the building envelope, material selection, and other aspects of the design of a building, directly affect its carbon emissions: a house design of more than 78% wood biogenic solutions would reduce those Carbon emissions to 184 $KgCO_2eq/m^2$ [65], therefore the cities, housing typology, low-carbon, approach seems adequate. LCA is typically studied separately, (once the design is defined), from the design process, rather than being integrated. The present study tries to show how to implement LCA within the design process as a fundamental issue that is necessary to be addressed to be able to promote a low impact built-environment. This approach has been taken to assess what the obstacles are that limit the use of LCA as an early-design tool. Moreover, allowing this LCA integration into the design process will assist in: helping designers to identify and avoid unnecessary impacts during the design process and knowing what the environmental impacts of buildings will be in an early stage.
    3.2. Carbon emissions and LCA Annually, the embodied carbon of building structures, substructures, and enclosures is responsible for 11% of global GHG emissions, as stated in 2019; in 2021, some reports state that 10% corresponds to the "Building construction industry", which is "the portion (estimated) of overall industry devoted to manufacturing building construction materials such as steel, cement, and glass" [1].
    3.3. Database possible inconsistencies Detailed information can be founded in Supplementary Material of this paper (Figure S3), related to the database used [66].

5. Conclusions

It has been demonstrated through this paper that percentage and average calculation methods for LCA target, predicted or optimized (through a linear regression model), indicators values can be useful in finding excellent benchmarking in carbon emissions reduction, for measurements and sustainable design in cities. Possible future work includes the simulation of different cases for percentage calculation for impact estimations of a design in a city context. Minor findings are the following: the difficulty in using the chosen materials database for LCA calculation, the consideration of the loss of forests in the most of low carbon design solutions, and consequently of its carbon reduction removal; unconventional instead of conventional sustainable design solutions as the best asset for reduction of carbon emissions; and the recommendation for coherence of the use of real in situ measurements of carbon emissions. The model used in this paper was carried out in 2021 and 2022. However, the GWP results, and the model are the same for the updated Database and LCA tool in 2022 and 2023.

Adding more data to the model for better accuracy in measurements, seemed the best option. This paper shows this is unnecessary; thus, as Erwin Data Modelers explained [67], the reasons for a RE application to a database are to comprehend the relation between the objects involved and to build upon it. Afterward, the method allows for redesigning the database structure, expanding the database with new database objects, and creating the system documentation. One of the hypotheses formulated relates to a Target in Carbon reduction of 11% when 25% of houses with a GWP^T of around -30.000 CO_2eq or lower (-165 CO_2eq/m^2). With reference to carbon emissions reduction recommendations and regulations in Denmark, this paper presents stricter target values than those.

Since conventional values are around 86,580 CO_2eq [65] in some recent studies; in regulations, limit values are around 110,000 CO_2eq and very ambitious target values are around 74,000 CO_2eq. In this paper, the reductions are considered from 92,530 CO_2eq or from 83,120 or from 84,615 CO_2eq average, which can be considered conventional housing in some studies, although can be considered low carbon housing in several actual regulations. The value 493 of GHG Emis. (Emission intensity on building level, CO_2eq/m^2), of the recent document these Table percentages is based on [10], and it was obtained using statistical data on construction cost per square meter. Further applications of the method should exploit its advantages which among others are its characteristics of a global method applicable in different countries and scenarios, the standardization of the method for different typologies and regulations, its interoperability with other sustainability assessment and design tools, its previous automation studies, flexibility and adaptability to be an easy guide for designers, normalization possibilities [68], and other methods compatibility [69].

To sum it up, this paper´s RE has been proven to help measurements to identify unconventional solutions in materials and circular systems for buildings design, useful for partial design estimation based on total design, also for further analysis for very crucial indicators related, design for itself can lead to reaching European Targets for resilience, health and biodiversity would be protected first, "clean energy" used in a building in the use stage of the building has not as much influence as circular-low impact-healthy construction solutions in fast pollution reduction in a city context. However, this method´s main merits are its capability for standardization, globalization, interoperability, automation, certification, economic benefits, and most importantly, for guiding designers.

Table 3. Nomenclature.

Abbreviation/Term	Definition/Description	Units
Type	The types corresponding to different houses construction compositions are numbered: 1, 2, 3,. . .	No
GWP^T	Global Warming Potential Total, of each house Type	CO_2eq
GWP^W estimated	Global Warming Potential Partial, external layer of Façade, of a house Type Estimated through analysis of LCA Calculation with Reverse Engineering	CO_2eq
GWP^F estimated	Global Warming Potential Partial, Foundation, of a house Type. Estimated through analysis of LCA Calculation with Reverse Engineering	CO_2eq
GWP^T n	Global Warming Potential Total of a house Type, normalized	No
GWP^W n	Global Warming Potential Partial, external layer of Façade, of a house Type normalized	No
GWP^F n	Global Warming Potential Partial, Foundation of a house Type normalized	No
GWP^W Pred	Global Warming Potential Partial, external layer of Façade, of a house Type. Predicted through quadratic regression function with Reverse Engineering and others	CO_2eq
GWP^F Pred	Global Warming Potential Partial, Foundation, of a house Type. Predicted through quadratic regression function with Reverse Engineering and others	CO_2eq
CO_2eq/m^2 or GHG_e/Kg	Carbon emissions per square meter of a house	CO_2eq/m^2
A	Area of each house	m^2
Class	The different classes of houses depending on their range reduction or intervals of GWP	No
GWP^W	Global Warming Potential Partial, external layer of Façade, of a house Type	CO_2eq
GWP^F	Global Warming Potential Partial, Foundation, of a house Type	CO_2eq
$\%GWP^T$Red	The first value is: Percentage reduction or the difference between maximum or reference GWP Total and the GWP Total of a house in each range intervals values (A, B, or C) from maximum or reference GWP^T The second value is: Percentage Reduction or the difference between Sum of existing houses and total houses GWP^T, from the GWPT Sum of exixting houses. In this case, 12 houses with 25% of new/refurbished houses Class A (−30.000 GWP^T), and Class A, Class B, and Class C (average values)	No
$GWP^T{}_{Re}$	Global Warming Potential Total, of house Type Reference Value	CO_2eq
$GWP^T{}_{Ra}$	Global Warming Potential Total of houses of the different ranges or intervals values	CO_2eq

Table 3. *Cont.*

Abbreviation/Term	Definition/Description	Units
$GWP^T{}_{Mx}$	Global Warming Potential Total, of the house Type with Maximum Value	CO_2eq
$GWP^T{}_{Mn}$	Global Warming Potential Total, of the house Type with Minimum Value	CO_2eq
Layer Wall	Main component for each range of GWP^T, for external layer of Façade Wall	No
EPD	GWP reference value for design in EPD of each main component of each Class	CO_2eq

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/asi6050076/s1, Figure S1: Normalization Formula [68]; Table S1: Composition of the Façade Wall Types 2 to 15 from model; Figure S2: Seeking of Values for a GWPT Target; Table S2: Basic Data: Materials and Construction Systems of the prototype House of model Type 1; Figure S3: LCAByg Database errors in Type 1: Expired Phase EPD; Table S3: Variants of the Exterior Wall of the 15 Types, main components from model.; Figure S4: Extract from raw Data [63]; Table S4: Thermal rough values of the Intermediate Layer of External Wall, Variants 1 to 7; Table S5: Normalization of the Total and Partial (Wall) GWP: Types 1, 2, and 3 of the Total 15; Table S6: Reduction in the GWP Emissions, hypothesis with 14.9% of new/refurbished houses; Table S7: Continuation of hypothesis Table S6 extendible to a city; Table S8: Normalization of Total and Partial GWP LCAByg results, Types 6, 15, 16, and 17; Table S9: Type 16 and Type 17 different Data in LCA calculation Input

Author Contributions: Conceptualization, M.C.V.M.; methodology, M.C.V.M.; software, M.C.V.M.; formal analysis, M.C.V.M.; investigation, M.C.V.M.; resources, M.C.V.M.; data curation, M.C.V.M.; writing—original draft preparation, M.C.V.M.; writing—review and editing, M.C.V.M.; visualization, M.C.V.M.; validation, L.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data is contained within the article or Supplementary Material.

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

References

1. European Environment Agency. The European Environment-State and Outlook 2020. In *Knowledge for Transition to a Sustainable Europe*; SOER 2020 edition; Publications Office of the European Union: Luxembourg, 2019; p. 327. Available online: https://www.eea.europa.eu/publications/soer-2020 (accessed on 3 February 2023).
2. Crippa, M.; Guizzardi, D.; Banja, M.; Solazzo, E.; Muntean, M.; Schaaf, E.; Pagani, F.; Monforti-Ferrario, F.; Olivier, J.; Quadrelli, R.; et al. *CO2 Emissions of All World Countries-JRC/IEA/PBL 2022 Report, EUR 31182 EN*; Publications Office of the European Union: Luxembourg, 2022; p. 16. [CrossRef]
3. Global Alliance for Buildings and Construction, International Energy Agency and the United Nations Environment Programme. *2019 Global Status Report for Buildings and Construction: Towards a Zero-Emission*; Efficient and Resilient Buildings and Construction Sector: Nairobi, Kenya, 2019; Available online: https://www.unep.org/resources/publication/2019-global-status-report-buildings-and-construction-sector (accessed on 3 February 2023).
4. Global Alliance for Building and Construction, International Energy Agency and the United Nations Environment Programme. 2021 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector. In *Nairobi, Kenya*; 2021; Available online: https://globalabc.org/resources/publications/2021-global-status-report-buildings-and-construction (accessed on 3 February 2023).
5. Official Journal of the European Union. *Commission Recommendation (EU) 2016/1318 of 29 July 2016: On Guidelines for the Promotion of Nearly Zero-Energy Buildings and Best Practices by 2020, All New Buildings are Nearly Zero-Energy Buildings*; Official Journal of the European Union, European Commission: Luxembourg, 2016; p. 1. Available online: https://eur-lex.europa.eu/eli/reco/2016/1318/oj (accessed on 3 February 2023).
6. European Commission. *Proposal for a Directive of the European Parliament and of the Council on the Energy Performance of Buildings (Recast), COM/2021/802 Final*; European Commission: Luxembourg, 2021; p. 19. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52021PC0802 (accessed on 3 February 2023).
7. European Commission. *Annexes: Proposal for a Directive of the European Parliament and of the Council on the Energy Performance of Buildings (Recast), COM/2021/802 Final*; European Commission: Luxembourg, 2021; p. 4. Available online: https://eur-lex.europa.eu/resource.html?uri=cellar:c51fe6d1-5da2-11ec-9c6c-01aa75ed71a1.0001.02/DOC_2&format=PDF (accessed on 3 February 2023).

8. European Commission. *Communication from the Commission. The European Green Deal, COM/2019/640 Final*; European Commission: Luxembourg, 2019; p. 4. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52019DC0640 (accessed on 3 February 2023).
9. European Commission. *Annex to the Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions: The European Green Deal, COM/2019/640 Final, Annex*; Link to document 2; European Commission: Luxembourg, 2019; p. 2. Available online: https://commission.europa.eu/publications/communication-european-green-deal_en (accessed on 3 February 2023).
10. Hoxha, E.; Röck, M.; Truger, B.; Steininger, K.; Passer, A. Austrian GHG emission targets for new buildings and major renovations: An exploratory study. In *IOP Conference Series: Earth and Environmental Science*; 2020; Volume 588, p. 6. Available online: https://iopscience.iop.org/article/10.1088/1755-1315/588/3/032052/meta (accessed on 3 February 2023).
11. Koutamanis, A. Sustainable Buildings in Sustainable Cities: A Reciprocal Relation. *Sustainability* **2021**, *13*, 3077. [CrossRef]
12. Hurmekoski, E. How can Wood Construction Reduce Environmental Degradation? European Forest Institute. 2017. Available online: https://www.researchgate.net/publication/316437436_How_can_wood_construction_reduce_environmental_degradation (accessed on 3 February 2023).
13. Koh, C.H.; Kraniotis, D. A review of material properties and performance of straw bale as building material. *Constr. Build. Mater.* **2020**, *259*, 120385. [CrossRef]
14. Polyisocyanurate Insulation Manufacturers Association. Comparing the GWP of Common Exterior Wall Insulation Materials. *PIMA Performance Bulletin*. 2020. Available online: https://www.polyiso.org/page/ComparingGWPWallInsulation (accessed on 3 February 2023).
15. Brojan, L.; Petric, A.; Clouston, P. A comparative study of brick and straw bale wall systems from environmental, economical and energy perspectives. *ARPN J. Eng. Appl. Sci.* **2013**, *8*, 920–926. Available online: https://www.semanticscholar.org/paper/A-COMPARATIVE-STUDY-OF-BRICK-AND-STRAW-BALE-WALL-Brojan-Petric/b4c4c095abc8aae8f3acf1351062d5f592698c9e (accessed on 3 February 2023).
16. EPD. Environmental Product Declaration for Straw as Insulation Material in UK, ESBA. 2022. Available online: https://strawbuilding.eu/epd-environmental-product-declaration-for-straw-as-insulation-material-in-uk/ (accessed on 3 February 2023).
17. EPD. Environmental Product Declaration for Brick Development Association. 2018. Available online: https://www.ibstockbrick.co.uk/wp-content/uploads/2018/06/BDA-EN-EPD-0002.3.pdf (accessed on 3 February 2023).
18. Chen, Z.; Gu, H.; Bergman, R.; Liang, S. Comparative Life-Cycle Assessment of a High-Rise Mass Timber Building with an Equivalent Reinforced Concrete Alternative Using the Athena Impact Estimator for Buildings. *Sustainability* **2020**, *12*, 4708. [CrossRef]
19. European Commission. European Platform on Life Cycle Assessment. Life Cycle Assessment (LCA). 2022. Available online: https://eplca.jrc.ec.europa.eu/lifecycleassessment.html (accessed on 3 February 2023).
20. Biogenic Carbon. One Click LCA. 2022. Available online: https://oneclicklca.zendesk.com/hc/en-us/articles/360015036640-Biogenic-Carbon (accessed on 3 February 2023).
21. Kurmayer, N.J. EU to Start Measuring 'Embodied' Carbon Emissions from Buildings. 2021. Available online: https://www.euractiv.com/section/energy-environment/news/eu-to-start-measuring-embodied-carbon-emissions-from-buildings/ (accessed on 3 February 2023).
22. Carabaño Rodríguez, R.; Bedoya, F.; Ruiz, D. La metodología del análisis de ciclo de vida para la evaluación del impacto ambiental en el sector de la construcción: Estado del arte. In Proceedings of the I Congreso Internacional sobre Investigación en Construcción y Tecnología Arquitectónica, Madrid, Spain, 11–13 June 2014; p. 3. Available online: https://oa.upm.es/32499/ (accessed on 3 February 2023).
23. Commission of the European Communities. Communication from the Commission to the Council and the European Parliament. Integrated Product Policy. Building on Environmental Life-Cycle Thinking. COM (2003)302 Final. 2003. Available online: https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2003:0302:FIN:en:PDF (accessed on 3 February 2023).
24. Sustainability of Construction Works-Assessment of Environmental Performance of Buildings-Calculation Method. UNE EN 15978 European EN 15978. 2012. Available online: https://www.en-standard.eu/search/?q=UNE+EN+15978&msclkid=e32bc7c6de6219554947a3fc0ecd8c44 (accessed on 3 February 2023).
25. KPMBLAB. Defining Whole Building Life Cycle Assessments by Methodology to Support Carbon Reduction in the Design Process-KPMB. 2022. Available online: https://www.kpmb.com/lab/defining-whole-building-life-cycle-assessments-by-methodology-to-support-carbon-reduction-in-the-design-process/ (accessed on 3 February 2023).
26. *EN 15804:2019+A1:2022*; Sustainability of Construction Works–Environmental Product Declarations–Core Rules for the Product Category of Construction Products. CEN: Brussels, Belgium, 2019.
27. *EN 15804:2012+A2:2020/AC: 2021*; Sustainability of Construction Works–Environmental Product Declarations–Core Rules for the Product Category of Construction Products. CEN: Brussels, Belgium, 2019.
28. Turnbull, G.; Graham, J.; Constable, D.; Dharmaraj, S.; KPMB Architects. Embodied Carbon Values in Common Insulation Materials. KPMB Lab, 2021. Available online: https://www.canadianarchitect.com/embodied-carbon-values-in-common-insulation-materials/ (accessed on 3 February 2023).

29. United States Environmental Protection Agency. Climate Change Indicators: Global Greenhouse Gas Emissions. EPA, Updated 2020. Available online: https://www.epa.gov/climate-indicators/climate-change-indicators-global-greenhouse-gas-emissions (accessed on 3 February 2023).
30. United States Environmental Protection Agency. Greenhouse Gas Emissions: Understanding Global Warming Potentials. EPA, Updated 2020. Available online: https://www.epa.gov/ghgemissions/understanding-global-warming-potentials (accessed on 3 February 2023).
31. *BS EN ISO 14040:2006+A1:2020*; Environmental Management. Life Cycle Assessment. Principles and Framework. CEN: Brussels, Belgium, 2020. Available online: https://www.en-standard.eu/bs-en-iso-14040-2006-a1-2020-environmental-management-life-cycle-assessment-principles-and-framework/?msclkid=d7cf4696a0911f1e4e1c22abb0c61a77 (accessed on 3 February 2023).
32. European Platform on LCA. EPLCA. Environmental Footprint. 2022. Available online: https://eplca.jrc.ec.europa.eu/EnvironmentalFootprint.html (accessed on 3 February 2023).
33. European Platform on LCA. EPLCA. ILCD International Life Cycle Data System. 2022. Available online: https://eplca.jrc.ec.europa.eu/ilcd.html (accessed on 3 February 2023).
34. LCAByg Tool. About: LCAbyg is a Tool that Calculates Life Cycle Assessments for Buildings. 2022. Available online: https://lcabyg.dk/en/ (accessed on 3 February 2023).
35. Ecochain. Life Cycle Assessment Software Tools-Overview. 2022. Available online: https://ecochain.com/knowledge/life-cycle-assessment-software-overview-comparison/ (accessed on 3 February 2023).
36. Autodesk. Building Information Modeling. BIM Revit. 2022. Available online: https://www.autodesk.es/collections/architecture-engineering-construction/overview?term=1-YEAR&tab=subscription (accessed on 3 February 2023).
37. Rhino. Rhinoceros 3D. 2022. Available online: https://www.rhino3d.com/ (accessed on 3 February 2023).
38. MatLab Online Tool. MatLab is a Programming and Numeric Computing Platform. 2022. Available online: https://matlab.mathworks.com/ (accessed on 3 February 2023).
39. Microsoft Corporation. Mirosoft 365. Excel. 2022. Available online: https://www.microsoft.com/es-es/microsoft-365/p/excel/CFQ7TTC0HR4R?ef_id=_k_8fd520e216581c6731a744df2a4f8a76_k_&OCID=AIDcmm409lj8ne_SEM__k_8fd520e216581c6731a744df2a4f8a76_k_&msclkid=8fd520e216581c6731a744df2a4f8a76&activetab=pivot:informaci%C3%B3ngeneraltab (accessed on 3 February 2023).
40. Azari, R. Economic Input-Output Life-Cycle Assessment. In Life Cycle Energy Consumption of Buildings; Embodied + Operational. Bioenergy (Second Edition). 2020. Available online: https://www.sciencedirect.com/topics/engineering/economic-input-output-life-cycle-assessment (accessed on 3 February 2023).
41. Peng, C. Calculation of a building's life cycle carbon emissions based on Ecotect and building information modeling. *J. Clean. Prod.* **2016**, *112*, 453–465. [CrossRef]
42. Carvalho, J.P.; Alecrim, I.; Bragança, L.; Mateus, R. Integrating BIM-Based LCA and Building Sustainability Assessment. *Sustainability.* **2020**, *12*, 7468. [CrossRef]
43. Kucukvar, M.O.; Tatari, O. Scope-based carbon footprint analysis of U.S. residential and commercial buildings: An input–output hybrid life cycle assessment approach. *Build. Environ.* **2014**, *72*, 53–62.
44. Polo-Mendoza, R.; Martinez-Arguelles, G.; Peñabaena-Niebles, R. A multi-objective optimization based on genetic algorithms for the sustainable design of Warm Mix Asphalt (WMA). *Int. J. Pavement Eng.* **2022**, 1–21. [CrossRef]
45. Sun, B.; Zhao, T.; Li, L.; Wang, Z.; Sun, P.; Peng, C. Optimization of regenerator operating parameters and thermal insulation construction for rotary regenerative thermal oxidizer (r-RTO) based on thermal-fluid coupling method and quadratic regression model. *Case Stud. Therm. Eng.* **2022**, *37*, 102314. [CrossRef]
46. Veza, I.; Karaoglan, A.D.; Ileri, E.; Kaulani, S.A.; Tamaldin, Z.A. Grasshopper optimization algorithm for diésel engine fuelled with etanol-biodiesel-diesel blends. *Cases Stud. Therm. Eng.* **2022**, *31*, 101817. [CrossRef]
47. Zhou, Y.; Zhang, J.; Hu, S. Regression analysis and driving force model building of CO_2 emissions in China. *Sci. Rep.* **2021**, *11*, 6715. [CrossRef] [PubMed]
48. Chen, C.; Zhao, Z.; Xiao, J.; Tiong, R. A Conceptual Framework for Estimating Building Embodied Carbon Based on Digital Twin Technology and Life Cycle Assessment. *Sustainability* **2021**, *13*, 13875. [CrossRef]
49. Appelbaum, A. For AIA Architect, Reverse Engineering: Modeling Future Scenarios in an Ongoing Energy Crisis. *J. Am. Inst. Archit.* **2012**. Available online: https://www.architectmagazine.com/aia-architect/aiafeature/reverse-engineering_o (accessed on 3 February 2023).
50. Gan, V.J.; Lo, I.M.; Ma, J.; Tse, K.T.; Cheng, J.C.; Chan, C.M. Simulation Optimisation Towards Energy Efficient Green Buildings: Current Status and Future Trends. *J. Clean. Prod.* **2020**, *254*, 120012. [CrossRef]
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. Massimo, D.E.; De Paola, P.; Musolino, M.; Malerba, A.; Del Giudice, F.P. Green and Gold Buildings? Detecting Real Estate Market Premium for Green Buildings through Evolutionary Polynomial Regression. *Buildings* **2022**, *12*, 621. [CrossRef]
53. Degot, C.; Duranton, S.; Frédeau, M.; Hutchinson, R. Reduce Carbon and Costs with the Power of AI. 2021. Available online: https://www.bcg.com/publications/2021/ai-to-reduce-carbon-emissions (accessed on 3 February 2023).

54. Ministerio de Transportes, Movilidad y Agenda Urbana. Catálogo de Elementos Constructivos (CEC). 2010, Updated 2011. Available online: https://www.codigotecnico.org/Programas/CatalogoElementosConstructivos.html (accessed on 3 February 2023).
55. Peng, Y.; Yang, L.E.; Sheffran, J. A life-cycle assessment framework for quantifying the carbon footprint of rural households based on survey data. *MethodsX* **2021**, *8*, 101411. [CrossRef] [PubMed]
56. Kwok, K.T. Challenge of Net-Zero Carbon Construction and Measurement of Energy Consumption and Carbon Emission Reduction to Climate Change, Economy and Job Growths in Hong Kong and Australia. In Proceedings of the ICASEEA 2021: International Conference on Architecture, Sustainable Environment and Engineering, Tokyo, Japan; 2022.
57. Gabriel, D. Inductive and Deductive Approaches to Research. 2013. Available online: https://deborahgabriel.com/2013/03/17/inductive-and-deductive-approaches-to-research/ (accessed on 3 February 2023).
58. Buyya, R.; Vecchiola, C.; Selvi, T. *Concurrent Computing, Mastering Cloud Computing: Foundations and Applications Programming*, 1st ed.; Morgan Kaufman, Elsevier: Amsterdam, The Netherlands, 2013.
59. Liu, Q.; Wu, Y. *Supervised Learning*; Springer: Berlin/Heidelberg, Germany, 2012.
60. Bhatti, A.; Nida, A.; Syed, N.A.; John, P. Chapter 5-Reverse Engineering and Its Applications. In *Omics Technologies and Bio-Engineering*; Barh, D., Azevedo, V., Eds.; Academic Press: Cambridge, MA, USA, 2018; pp. 95–110. Available online: https://app.dimensions.ai/details/publication/pub.1099655479 (accessed on 3 February 2023).
61. Allen, G.; Bajaj, A.; Khatri, V.; Ram, S.; Siau, K. Advances in Data Modeling Research. In Proceedings of the A Conference on a Human Scale, 11th Americas Conference on Information Systems, Omaha, NE, USA, 11–14 August 2005; p. 678.
62. Statens Byggeforskninginstitut Aalborg Universitet København. Available online: https://www.old.lcabyg.dk/index (accessed on 3 February 2023).
63. Ritchie, H.; Roser, M.; Rosado, P. Our World in Data: CO_2 and Greenhouse Gas Emissions. OWD, 2017, Last Revised in August 2020. Available online: https://ourworldindata.org/co2-and-greenhouse-gas-emissions (accessed on 3 February 2023).
64. Cang, Y.; Yang, L.; Luo, Z.; Zhang, N. Prediction of embodied carbon emissions from residential buildings with different structural forms. *Sustain. Cities Soc.* **2020**, *54*, 101946. [CrossRef]
65. Aalborg University. Anvendelse af træ i Byggeriet–Potentialer og Barrierer, AAU, 2020. Available online: https://vbn.aau.dk/da/publications/anvendelse-af-tr\T1\ae-i-byggerietpotentialer-og-barrierer-potentialer (accessed on 3 February 2023).
66. LCAByg, Help Manual, LCAByg Version 5.2. Brugervejledning til LCAByg_version 5.2. Available online: https://lcabyg.dk/en/download/49758 (accessed on 3 February 2023).
67. Erwin, the Data Governance Company, Erwin Data Modeler, Working with Data Models. 2019. Available online: https://bookshelf.erwin.com/bookshelf/public_html/2019R2/Content/User%20Guides/erwin%20Help/Reverse_Engineer.html (accessed on 3 February 2023).
68. Bragança, L.; Mateus, R. Building Sustainability Assessement and Certification Method Methodology MARS-H. Cost C25 5th MC Meeting. *Sustainability* **2008**, *2*, 10–20.
69. Morihata, A.; Sato, S. Reverse Engineering for Reduction Parallelization via Semiring Polynomials. In Proceedings of the 42nd ACM SIGPLAN International Conference on Programming Language Design and Implementation, PLDI, Virtual, 20–25 June 2021.