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

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Table S1. Composition of the Façade Wall Types 2 to 15 from model.

Layers	Composition of the Façade Wall
Internal	2 Layers Acrylic Finishing paint+Paint Primer+Cement Mortar
Intermediate	Light Concrete Block 100 mm+Cement Mortar+Mineral Wool Plates 300 mm x 45 mm
External	Variants (2-15)

Table S2. Basic Data: Materials and Construction Systems of the prototype House of model Type 1.

Construction System	Material/Components	Main Characteristic
Foundation	Reinforced Concrete+Insulation	C35/45
Exterior Wall	Variants (1 to 15)	--[1]
Interior Wall	Light Concrete[2] +Outdoor Paint	100 mm 2 Layers Paint+45 mm Insulation
Roof	Roof Tiles+Insulation+Impermeabilization or only Straw	
Floor/Slab	Reinforced Concrete+Insulation+Impermeabilization	C25/30
Water and Sanitary	Pipes/Drain regular	Diameter 22 mm
Climatization Installation	Geothermal	10kW
Ventilation System	Forced	150m^3/h
Windows/Doors	Frame Aluminium/Wood	Argon gas in Glass

[1] Different characteristics for 15 variants; [2] Type 1 Concrete, rest (2-7 included) Light Concrete. In Results Table Type 1 is number 2 for modelization.

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Table S3. Variants of the Exterior Wall of the 15 Types, main components from model.

Type	Composition of the outer Wall
1	108 mm Brick Wall+Cement Mortar [1]
2	108mm Brick Wall+Cement Mortar [2]
3	Natural Stone/Lime sandstone Brick+Metal substructure
4	Zinc Plates+Wooden Substructure for Ventilated Façade
5	Wood slats with wood substructure+Insulation
6-7	Exterior, gypsum, lime/cement-based
8-15	Straw Blocks+other biogenic solutions: Carbon negative or minimum

[1] Type 1, middle layer concrete; [2] Type 2, same for Types 2 to 7 included, middle layer light concrete.

Table S4. Thermal rough values of the Intermediate Layer of External Wall, Variants 1 to 7.

Intermediate Layer of External Wall Composition (EVE_Façade) [6]	l [2] (W/mK)	e [3] (m)	R (e/l) [4] (m^2K/W)
2 Layers Acrylic finishing paint+Paint Primer+	--[1]	--[1]	--[1]
Cement Mortar	1.8	0.025	0.0138
Light Concrete Block 100 mm	1.3	0.10	0.0769
Cement Mortar	1.8	0.025	0.0138
Mineral Wool Plates 300 mm x 45 mm	0.035	0.045	1.2857
Total (R_T)			1.3902
U (W/m^2K) = (1/ R_T) (Total Façade Wall: 0.359) [5]			0.7193

[1] Negligible values; [2] Thermal Conductivity; [3] Wall Thickness; [4] Thermal Resistance; [5] R_T×2 estimate; [6] EVE Façade [54].

$\overline{P_i} = \frac{P_i - P_{*i}}{P_i^* - P_{*i}}$: $\overline{P_i}$ Normalized Value; P_i Indicator Value; $P_i^* - P_{*i}$ Best minus Worst (or Reference) Performance Values.

Figure S1. Normalization Formula [68].

Table S5. Normalization of the Total and Partial (Wall) GWP: Types 1, 2, and 3 of the Total 15.

Type [2]	GWP^T	GWP^W	GWP^T Normalized	GWP^W Normalized
1	83,120	7,630	0	0
2	79,790	7,630	0.02773	0
3 [1]	76,810	4,640	0.05254	0.23070

[1] The list continues 4…to the 15 Total; 3 examples are shown in this Table. [2] Model Types.

Table S6. Reduction in the GWP Emissions, hypothesis with 14.9% of new/refurbished houses.

GWP^T Types of House Prototype Sums	GWP^T Sums [1]	CO^2 eq/m^2 [3]
Sum of GWP^T of 7 Types of Houses: TYPE 1, 2, 3, 4, 5, 6, 7	532,730	493[2]/449 to 389 [2]
Sum of ^{T} of 7 Types of Houses: TYPE 1, 2, 3, 4, 5, 6, 14	428,100	449 to -176 [2]
Reduction of GWP^T in %	19.64%	7% [3] to 30.4% [4]

[1] Sums, in CO^2eq; [2] CO^2 eq/m^2 or GHG Emissions; % calculated from the estimated Data in $KgCO_2eq/m^2$ [10] and considering Area per house of 185 m^2; [3] Reduction from Values of reference document [10]; [4] Reduction in percentage between maximum and average values of the 2 Groups.

Table S7. Continuation of hypothesis Table S6 extendible to a city.

GWP^T Types of House Prototype Sums	GWP^T Sums	Group number
Sum of GWP ^{T} of 7 Types of Houses: TYPE 1, 2, 3, 4, 5, 6, 7	532,730	1
Sum of ^{T} of other 7 Types of Houses: TYPE 1, 2, 3, 4, 5, 6, 14	428,100	2
Reduction of GWP ^{T} in % (Combinations 1 and 2)	19.64%	1-2 in perc. [3]
Sum of ^{T} of 15 Types of the same 6th Standard: TYPE 6 X 15 Houses	1,092,150[1]	3
Sum of ^{T} of 15 Types of Houses: TYPE 1, 2, 3, 4, 5, 6, 7, 8, 9, to 15	684,160[2]	4
Reduction of Sum of GWP ^{T} in % (Combinations 3 and 4)	37.36%	3-4 in perc.

[1] Type number 6th, 15 houses Type 6, GWP Total Sum. Reference Sum; [2] Percentage Reduction of GWP ^{T} considering 53 Percent of nonstandard solutions (Types 1 to 7 are standard solutions, and Types 8 to 15 are non-standard biogenic solutions) [3] perc., it means Percentage.

Table S8. Normalization of Total and Partial GWP LCAByg results, Types 6, 15, 16, and 17.

Type	GWP^T	GWP^W	GWP^F	GWP^T n	GWP^W n	GWP^F n	Red%GWP^T [1]	Red%GWP^T [2]	Red%GWPS^T [3]
6	72,810	789	6,430	0.085859427	0.52785493	0	12.40	0	0
15	-36,960	-5,330	6,430	1	1	0	144.46	150.76	37.36
16	23,800	-4,740	0	0.494003997	0.95447531	1.008295307	71.36	67.31	31.79
17	-30,280	-4,740	4,190	0.94437042	0.95447531	0.351256841	136.43	141.58	36.74

[1] Red% percentage reduction from the GWP Total (standard solution), maximum value, Type 1 of each Type GWP Total; [2] Red% percentage reduction from a GWP Total (standard solution) Type 6 of each Type GWP Total; [3] Red% percentage reduction between the GWP Total Sum of 15 houses of Type 6, and the Sum of houses Types 1,2,3,4,5,6,7,8,9,10,11,12,13,14 plus either 15, 16 or 17, from GWP Total Sum of 15 houses of Type 6.

Sum Type 6, 15 houses GWP Total is 1,092,150 CO^2eq; Sum Types 1 to 15 is 684,160; Types 1 to 14 added to Type 16 is 744,920; and Types 1 to 14 added to Type 17 is 690,840. In Table S8 Type 16, the GWP^F n, normalized value, is greater than 1, which proves that the polynomial regression function accuracy would most probably benefit from a larger Database, or else rely on other function. In this study this condition is recommended, it is not essential, since the objective is to find abstract objectives of indicators, relations between environmental impacts and the design of a building, it is not geared towards exact prediction at this point. Nevertheless a much more suitable for prediction/target seek/optimization/design (P/T/O/D) function was displayed in previous research documents. The main differences in the LCAByg tool inputs, system constructions, and materials, for comparison, between Type 15 and Types 16-17, is the addition of a Straw Roof, and, between Type 16 and Type 17 are the following:

Table S9. Type 16 and Type 17 different Data in LCA calculation Input.

Type	Description	Comp.	m^2	Kg/m^2
17	Construction System	Roof Straw	220	--
	Product	Roof Straw	^{2}--	220
16	Construction System	Roof Straw	280	--
	Product	Roof Straw	--	10
	Construction System	Wall Straw	124.47	--
	Product	Wall Straw	--	30

[1] Difference of Building components between Types [2] "---" means: Not applicable.

Two linear regression models were obtained: the functions and graph obtained with Types: 1,2,3,4,5,6,7,8,9,10,11,12,13,14,15 and the polynomial functions and graph obtained

with Types: 1,2 3,4,5,6,7,8,9,10,11,12,13,14,15,16,17. Lines (red, yellow, and green) separating the "zones" or reference values for the case of the function GWP Total and GWP Foundation, remain the same in both Graphs. Seek of Values for the second Graph:

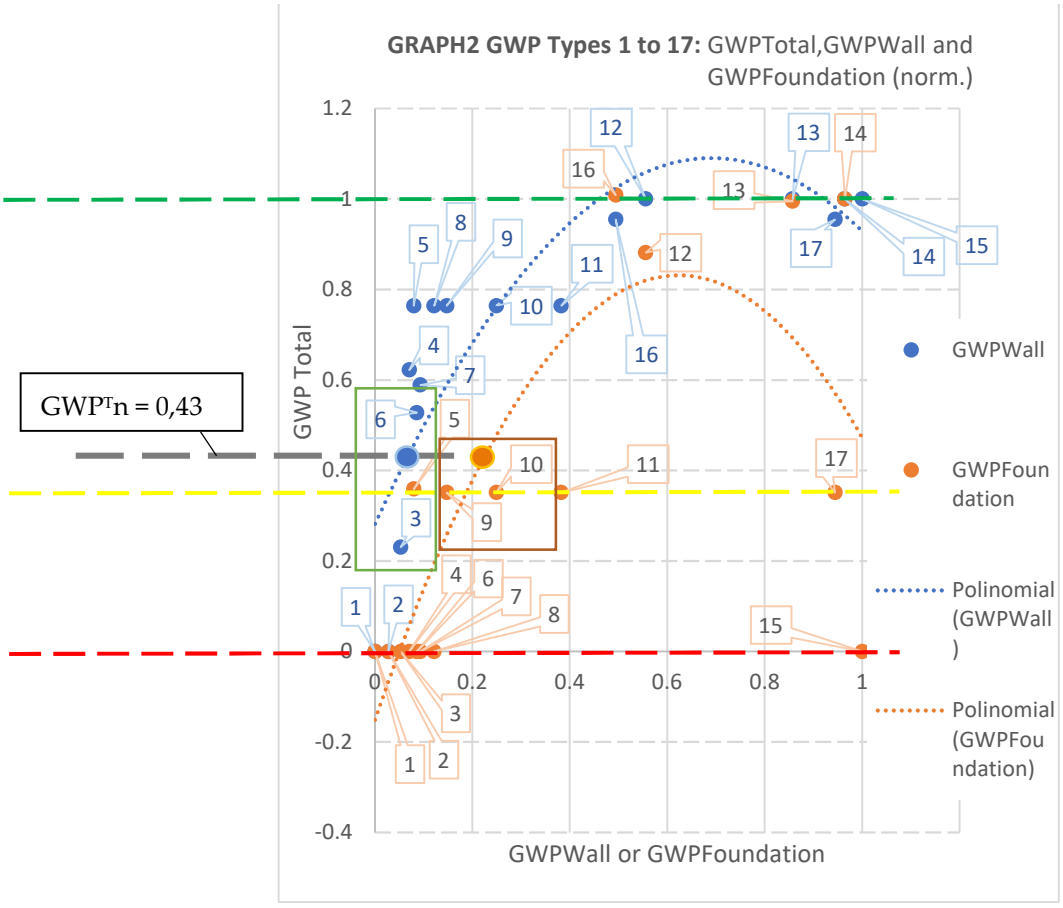

Figure S2. Seeking of Values for a GWPT Target.

For the elaboration of the model used in this case study, LCAByg [34] version 3 was used while version 5 permanence in the trial period at the end of 2020, then, the model was updated in 2021 and 2022 with LCAByg version 5.1 calculation results. Therefore the databases used were Ökobau 2013-14, 2016, and finally 2020 within LCAByg 5.1.013 version. LCAByg uses DGNB (2020) calculation, which considers three types of materials or system constructions data types: generic, industry, and specific. Biogenic carbon storage is reported as part of the GWP results. The negative emissions from storing the carbon are shown as part of the A1-A3 phases (storage is deducted from the GWP emissions in A1-A3) and in C3 where the same amount of carbon is added as it is released back to the atmosphere. In addition, each data type has an uncertainty factor that also always will refer back to the A1-A3 phase. That is if a construction product consists of a product specific A1-3 phase, but a generic C3 phase, the uncertainty factor will be 1.0. See the relationship between the data type and the uncertainty factor for DGNB certification in the manual document of the LCAByg v. 5.2 tool [66]. More free access information available is at the old LCAByg website page, for the construction systems composition of Prototype or Type 2 of this paper (eksempel LCA) [34, 62, 65 and 66]. Similarly, the machine learning models with LCA for building sustainable design were carried on well before the actual standard for sustainable construction products [27] was approved. The newer versions of LCAByg that include the 2021 DataBase show coherence with the model and method

used, since it calculates relative values and percentages. The Database errors that LCAByg encountered for the elaboration of this paper´s models in 2021, updated in July 2022, when the Types were calculated again by the Author for updating, were regarding the lack of data on one or more phases in only a few materials. The important thing is that the values of the resulting impacts relations in both versions of LCAByg remained the same. There were a few errors derived from the Database used when the Types LCA were calculated before, that according to the Manual of the tool [66], were not affecting the calculation process, however, the errors in the calculations of the Type 2 Database, for instance, were as follows (shown in the "Bygning of drift" section of LCAbyg tool [34]), "udløbet" means "withdrawn/expired".

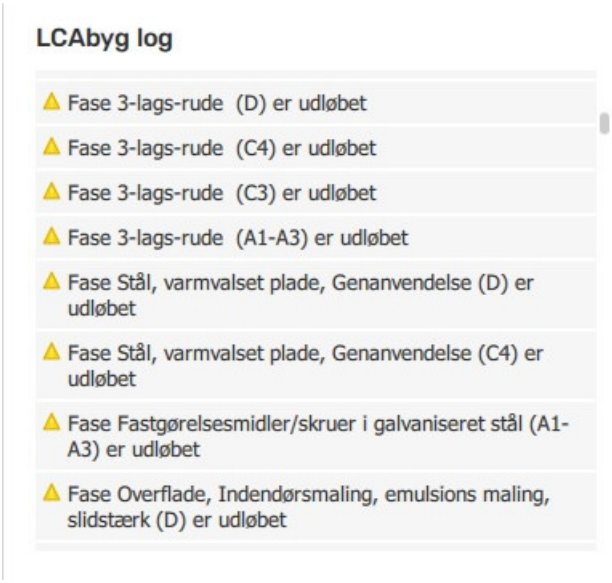

Figure S3. LCAByg Database errors in Type 1: Expired Phase EPD.

Reverse engineering is the process of creating a data model from a database or a script. The modeling tool creates a graphical representation of the selected database objects and the relationships between the objects. This graphical representation can be a logical or a physical model, in this case logical.

The main building component studied in the example is Façade Walls, and the variable/impact studied is Global Warming Potential. This indicator is related to Carbon and GHG emissions, which are frequently measured with sensors, and then, presented as the following Raw Data example. These values confirm the information in European report, which highlights in one of its sections the importance of the reduction of Carbon removal from the LULUCF sector, due to wood fires and other causes. "Calculations show that if we build 6310 homes in 2030 as wooden buildings instead of conventional heavy construction, we can save 800.000 tons of CO_2 compared to 2019" although it would come together with the reduction of forests´ Carbon removal [2]. It seems that, in further research about measuring Carbon emissions in cities, this factor should be added to the investigation, likewise, the contribution of new building constructions in general, and especially wood biogenic solutions constructions. Raw Data derived from direct measurements (for 2020-2021-2022, moment of this study model elaboration), is coherent to the method of this paper and it is shown here as an example, for Data processing since the Data collected are not formatted in Figure S4, for further studies.

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,,,,705.016,15100.203,17219.338,4858.969,83.6
55,1654.140,2121.383,7685.895,112.529,32708.590,,3.558,0.075,67.109,1.413,,,-
25.501,0.537,,,,,133.113,2.803,0.057,2.685,1553.231,0.515,0.629,0.507,0.124,1.564,0.
869,0.696,0.604,0.453,0.651,0.286,1.269,1.162,0.854,0.847,-0.647,1.125,0.907,,,,
country,year,iso_code,population,gdp,cement_co2,cement_co2_per_cap-
ita,co2,co2_growth_abs,co2_growth_prct,co2_including_luc,co2_includ-
ing_luc_growth_abs,co2_including_luc_growth_prct,co2_including_luc_per_cap-
ita,co2_including_luc_per_gdp,co2_including_luc_per_unit_energy,co2_per_cap-
ita,co2_per_gdp,co2_per_unit_energy,coal_co2,coal_co2_per_capita,consump-
tion_co2,consumption_co2_per_capita,consumption_co2_per_gdp,cumulative_ce-
ment_co2,cumulative_co2,cumulative_co2_including_luc,cumulative_coal_co2,cumula-
tive_flaring_co2,cumulative_gas_co2,cumulative_luc_co2,cumulative_oil_co2,cumula-
tive_other_co2,energy_per_capita,energy_per_gdp,flaring_co2,flaring_co2_per_cap-
ita,gas_co2,gas_co2_per_capita,ghg_excluding_lucf_per_capita,ghg_per_cap-
ita,land_use_change_co2,land_use_change_co2_per_capita,methane,methane_per_cap-
ita,nitrous_oxide,nitrous_oxide_per_capita,oil_co2,oil_co2_per_cap-
ita,other_co2_per_capita,other_industry_co2,primary_energy_consump-
tion,share_global_cement_co2,share_global_co2,share_global_co2_includ-
ing_luc,share_global_coal_co2,share_global_cumulative_cement_co2,share_global_cu-
mulative_co2,share_global_cumulative_co2_including_luc,share_global_cumula-
tive_coal_co2,share_global_cumulative_flaring_co2,share_global_cumula-
tive_gas_co2,share_global_cumulative_luc_co2,share_global_cumula-
tive_oil_co2,share_global_cumulative_other_co2,share_global_flar-
ing_co2,share_global_gas_co2,share_global_luc_co2,share_global_oil_co2,share_global_
other_co2,total_ghg,total_ghg_excluding_lucf,trade_co2,trade_co2_share

Figure S4. Extract from raw Data [63].