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Developing a New Data-Driven LCA Tool at the Urban Scale: The Case of the Embodied Environmental Profile of the Building Sector

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Abstract: Given the ambitious climate reduction targets of the European Commission for the building sector and the adoption of the life cycle assessment method for the environmental metrics, the authors of this research present a new tool that allows for an extensive evaluation of buildings (operational and embodied environmental profile). The tool developed is an engine written in Python that was applied to analyze the buildings of Milan, using several open databases available for the Lombardy region (Northern Italy). Approximately 240,000 building units were investigated and compared using ecoinvent 3.9.1 EN 15804 as a background library and characterization methods in compliance with EN 15978. The tool can establish reliable environmental benchmarks to implement building policies, such as climate footprint limits for new constructions as required by the recast Energy Performance of Buildings Directive (2023). This article shows the embodied impact of construction materials. The results for residential, commercial, and retail building units (old and new) are 15 kg CO_2 eq/(m^2 of net area × year) for the entire building stock (old and new building units) and 21 kg CO_2 eq/(m^2 of net area × year) for new buildings (nearly zero energy building units).

Keywords: LCA tool; construction technologies; urban planning; climate change; decarbonization

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1. Introduction

According to the demographic forecast, by 2050, 70% of the world's population will live in urban areas [1]. The environmental assessment of cities will be strategic because of (i) the expansion of building units to respond to growing populations and, (ii) consequentially, their significant environmental burdens [2]. It is estimated that they account for 60–80% of energy consumption [3]. The building sector is responsible for 50–60% of the utilization of natural resources at the European level, which corresponds to approx. 35–40% of energy consumption and CO_2 eq emissions. Thus, the improvement of their environmental profile is an indispensable driver for achieving sustainability targets of cities.

The recent attention of the building sector has shifted, as is well known, not only to the operational phase environmental burdens but also to the embodied impacts linked with the construction materials [4]. The analysis of energy consumption alone is no longer sufficient to support the design choices, considering that for nearly zero energy buildings (nZEBs), the embodied energy reaches around 50% or higher [5,6]. Accordingly, the evaluation of the embodied impacts is becoming significant to achieve a holistic analysis, driving building designers to improve the whole environmental performance of the sector. The nZEB concept was introduced in Europe within the legislative framework, including the Energy Performance of Buildings Directive 2010/31/EU [7] and the Energy Efficiency Directive 2012/27/EU [8]. Legislative Decree 63/2013 made nZEB mandatory for new buildings starting in 2018 for public and 2021 for private buildings (for Lombardy—Italy, nZEB has been mandatory since 2016 for both public and private sectors). In March 2023, the Energy Performance of Buildings Directive (EPBD) recast was proposed (to date, under discussion).

It sets ambitious objectives to achieve a zero-emission, fully decarbonized building stock by 2050; therefore, introducing the zero emission building (ZEB) [9] and imposing on member states a requirement to publish limit values of GHG emissions, calculated using the LCA method (operational and embodied) by 2027, and setting targets for new buildings by 2030 [10].

Among the life cycle approach methods (such as material flow analysis, environmental extended input–output table, etc.), the process-based environmental life cycle assessment (LCA) is widely accepted in Europe and at the international level for evaluating the environmental performance of buildings and is applied in research projects and policy development programs [11]. The LCA is an internationally standardized product-based valid scientific methodology [12,13] used in general to assess specific environmental profiles of goods and services. The European Commission (EC) chose the method as the reference for planning and monitoring the ambitious GHG reduction targets: emission reduction of 55% by 2030 compared with 1990 and the achievement of carbon neutrality by 2050—but also for avoiding significant harm to other environmental objectives. These include climate change adaptation, sustainable use and protection of water resources, transition to a circular economy, pollution prevention and control, and preservation and restoration of biodiversity and ecosystems, as stated in the European Taxonomy [14]. Several frameworks and programs have been launched by the European Commission in the present and previous decade—including the LCA as an environmental metric method (i.e., Level(s) framework, Environmental Footprint Program, EU Taxonomy, etc.).

Although the LCA is globally accepted, there is a shortage of tools to conduct large-scale assessments given the need for massive data collection and computational power to present these software to the market [15]. In this article, the authors describe an updated version of the tool presented by Famiglietti et al. (2022) [15], where the engine to evaluate the operational phase of buildings at the urban scale was described. Here, an extension of the analysis of the construction materials is shown. Thus, the novelty of this work is a new tool utilizing a data-driven approach that allows for a massive environmental evaluation of buildings (operational phase and embodied), expanding the application of the LCA method at the urban scale where existing software products are not specifically designed to be implemented and fail mainly due to the massive data processing required.

The outcome of the tool can be used to define preliminary limits and targets for buildings in the Lombardy region (Northern Italy), following the standard EN 15978 [16] indicated in the recast EPBD (2023). Namely, the words "data-driven approach" were used to describe the mode of operation of the engine. By requiring data at the city scale from open databases to calculate the environmental profile of building units, it differentiates the calculation approach from the other tools listed and is described in Section 1.1. The tool uses the values derived from the following databases as input data: (i) TABULA [17]; (ii) Geoportal of Lombardy region [18]; and (iii) Certificazione energetica degli edifici—CENED 2.0 [19], from now on, also referred to as "CENED"—an open-source database including the energy performance certificates (EPCs) of building units registered in the regional buildings energy registry. The EPCs contained in CENED comply with the European EPBD and decree DGR no. 3868/2015, thus providing a repository of data, which means that it can act as a starting point to follow the requirements of the new directive from the European Parliament (i.e., the model to calculate nominal energy needs that is under revision from being semi-static to dynamic, etc.).

The developed tool measures global warming potential (GWP) emissions and other 19 environmental impact categories using the Environmental Footprint 3.1 EN 15804 [20] and the Cumulative energy demand (CED), primary energy (nonrenewable) [21–24], characterization methods. The life cycle inventory (LCI) database used is ecoinvent 3.9.1 EN 15804 [25] for attributional modeling [26]. The results obtained are presented and discussed, providing a holistic view of the state-of-the-art of embodied impacts related to the building stock of Milan (240,000 building units were evaluated). It allows for assessing the strengths and weaknesses of the construction materials commonly used in buildings. But the tool can also be employed, potentially, to plan decarbonization strategies. With this in mind, the environmental profile is surveyed with 20 impact categories (GWP plus 19 others), permitting the assessment of the potential shifting burden to impact categories other than climate change during the decarbonization pathway, e.g., shifting problems from climate change to material resources, minerals/metals, etc.

1.1. Previous Work on the Topic

To the best of the author's knowledge, the following scientific research works have been produced so far; in many cases, such works helped to create the GWP limit values adopted by member states: Scholten and van Ewik [27] presented the legislative requirements for the Netherlands, introducing shadow prices for emissions of CO_2 eq. Lützkendorf [28] investigated the possibility of GWP limits, providing recommended actions for key stakeholders. Boverket [29], Kuittinen and Häkkinen [30], Lasvaux et al. [31], and Rasmussen et al. [32] described the LCA benchmark methodologies for Sweden, Finland, France, and Denmark, respectively. Gervasio and Dimova [33] and Lavagna et al. [6] provided a preliminary set of benchmarks for residential buildings, which may represent the existing residential building stock in Europe. Gervasio and Dimova analyzed 72 building models, while Lavagna et al. analyzed 24 statistically-based dwelling archetypes, both intending to quantify a baseline scenario for policy developments. Frischknecht et al. [34] described the methodology approach discussed during the International Energy Agency—Energy in Building and Communities, Annex 72—in which 20 countries were involved. Moschetti et al. [35] and Rasmussen et al. [4] analyzed residential buildings in Italy. Moschetti et al. defined reference values (in three different cities: Turin, Florence, and Bari), stating that residential buildings could spend around 140 kWh/($m^2 \times$ year), with emissions of 35 kg CO_2 eq/($m^2 \times$ year) based on net floor area. The outcomes were achieved using four archetypes: (i) single-family house, (ii) terraced house, (iii) multifamily building, and (iv) apartment block (12 in total), and with stratigraphies described in the TABULA database [17]. Rasmussen et al. provided life cycle assessment reference benchmarks for Northern Italy and Denmark residential buildings. The values were calculated based on national samples of residential buildings. For Italy, the data concerning 28 residential buildings were provided by the CasaClima Agency [36], for mainly wooden constructions. The outcomes showed a climate footprint 13.8 kg CO_2 eq/($m^2 \times$ year) based on gross heated floor area and considering a reference study period of 100 years. Concluding, the environmental benchmarks for buildings have been used for over a decade in voluntary certification schemes, i.e., German Sustainable Building Council (DGNB), BREEM, LEED, etc., as described in the review conducted by Trigaux et al. [37], where almost all of the scientific articles described above were also reviewed and discussed.

The outcomes of benchmark values analyzed by Trigaux et al. [37] are shown in Figure 1. The figure presents (on the left) the results of embodied and (on the right) full lifecycle impacts, highlighting (i) median, (ii) 25th and 50th percentiles, and (iii) standard deviation values as a boxplot. Moreover, the figure contains plotted target, reference, best practice, and limit values analyzed in the articles reviewed by Trigaux et al. [37].

Five European member states have already set limit values or are scheduled to introduce them for new building constructions, anticipating the requirement of the recast EPBD (2023), i.e., Netherlands, France, Denmark, Finland, and Sweden. Other member states like Italy shall produce reliable data by 2030.

Tools such as the environmental decision support system (EDSS) can significantly help with an initial definition and monitoring over time. Product-specific tools (also called "simplified") to assess the environmental lifecycle burdens of buildings, considering construction materials and heating, ventilation, and air conditioning (HVAC) systems, have been developed to reduce the evaluation time and streamline the assessment, to support designers and decision-makers compared with generic software. Various examples of software developed in compliance with EN 15978 are commercially available. AIA 2010 [38] classifies these tools according to the level of application and according to the skill required by users. For example, the application level can be generic if the software can be used for any product type, or it can be specific if constrained to only one product (e.g., analysis of buildings or building materials, such as One-Click LCA). Similarly, LCA tools can be classified according to the expertise users require. Users with no prior understanding of the LCA method might use the simplified, more user-friendly tools in which the user does not control most LCA settings. Hollberg and Ruth (2016) [39] introduced other types of software: (i) computer-aided drafting (CAD)-integrated LCA tools, (ii) component catalog tools (online catalogs for building components), and (iii) spreadsheet-based tools, where environmental profiles are calculated by multiplying the mass of materials with the respective environmental impact factors without providing information on the intervention matrix (described in Section 2).

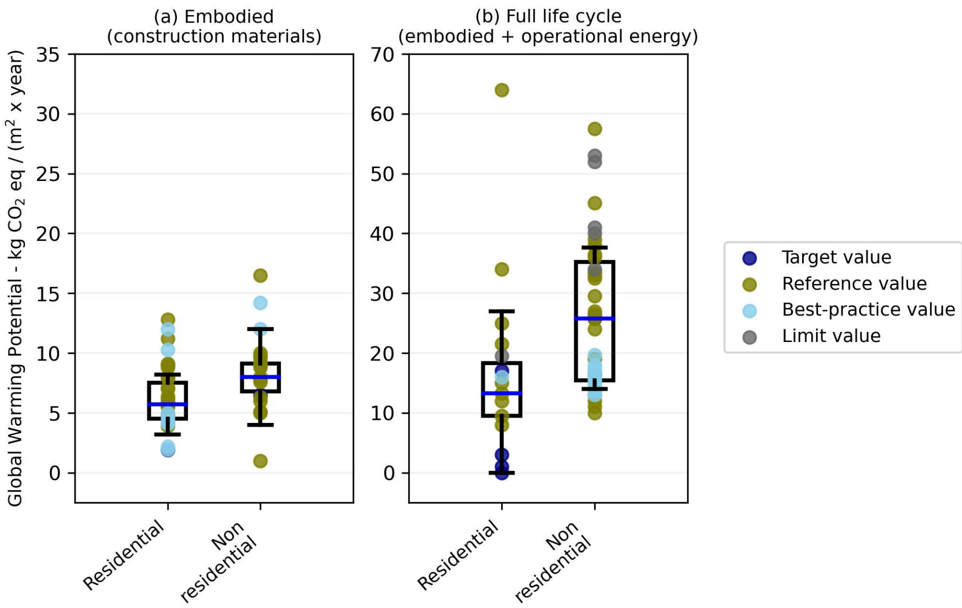

Figure 1. Benchmark values for the GWP subdivided into (**a**) embodied and (**b**) full lifecycle impacts from Trigaux et al. (2020) [37].

Among the indicated tools, particular interest in the recent scientific literature has been shown for CAD-integrated LCA tools [40]. Building information modeling (BIM) can facilitate the establishment of a bill of quantities (BoQ) and support project teams by providing immediate insight into how design decisions affect building performance. This approach can also be extended at the district level and integrated with urban building energy modeling (UBEM). However, this one does not find many examples in the market, given the huge amount of data to be managed to combine aspects of design and district-scale LCA. Ferrando et al. (2020) [41] reviewed the state-of-the-art UBEM tools that allow for the energy simulation of buildings at a large scale to evaluate energy scenarios, manage better, and design cities. City Energy Analyst [42], like others, i.e., CityBES, SimStadt, UMI, and CitySim [43–46], can run energy simulations and directly compare scenarios but without the LCA method integrated (it just provides the visualization of the equivalent CO_2 eq emissions). UrbanPrint, developed by the French research center Efficacity [47], seems the only one that aims at urban development projects—it is not possible to model more than 200 buildings [47]. It can run energy simulations and assess the potential impacts in compliance with EN 15978 (considering 26 impact category indicators). However, at present, no scientific publications have demonstrated its potential [48].

To summarize, tools have recently been developed that allow for (i) an LCA analysis at the individual building level (i.e., One-Click LCA, eLCA, LCAbyg, etc.) and (ii) tools that allow for an assessment of impacts at the district scale (see UBEM) working as EDSS.

Both tool types were scripted for use in the design phase (preliminary or executive) and as planning tools, predominantly used in the design phase.

This research provides an extension of the tool described by Famiglietti et al. (2022) [15]. The tool, written in Python [49], was created to map the environmental impacts of existing buildings (at the city scale) over time, an aspect not currently covered by tools on the market. The tool also permits analyzing the consequences of policies on environmental impacts, evaluating potential decarbonization scenarios, and assessing the potential shifting burden to impact categories. The results are provided using the lifecycle inventory database ecoinvent 3.9.1 EN 15804 as background. The lifecycle assessment model was built in compliance with EN 15978.

1.2. Focus and Aims of the Research

The motivation for this research lies in the necessity to equip cities with tools capable of providing environmental profile mapping of buildings (old or new) over time—permitting users to assess potential impacts generated during the operational stage (Famiglietti et al. 2022) [15] and during the lifecycle of building materials (this article), which, as is known, may represent the main contributor to new constructions. It also permits monitoring the potential for shifting the burden to impact categories other than climate change during the decarbonization pathway, i.e., shifting problems from climate change to acidification potential, etc.

The main goal of this research is to assess the environmental profile of buildings at an urban scale by applying the lifecycle assessment method (process-based, attributional) and following EN 15978. More specifically, the aims are as follows:

- To extend the tool implemented by Famiglietti et al. (2022) [15], including the embodied emissions of the construction materials;
- Evaluating potential GWP benchmarks (i.e., targets, reference, and limits) for the city of Milan with potential extension for the entire Lombardy region, never investigated before. Analyzing a much larger sample of buildings than so far reported by European member states the Netherlands, France, Finland, Denmark, and Sweden.

2. Materials and Methods

In this section, the authors provide detailed information concerning the engine developed for assessing the environmental profile of construction materials used in the building units, describing (i) the system boundaries and functional unit, (ii) the computational model, and (iii) the engine developed.

2.1. System Boundaries and Functional Unit

The model developed covers the following stages of EN 15978: Modules A1–5, C1–4, and D (Figure 2). The engine assesses Module B4 indirectly, i.e., having obtained information about the year of construction but no indications about replacements and refurbishment of individual building units from the CENED database, the environmental burden of the building technologies was normalized for their estimated useful life (e.g., 60 years for the load-bearing structural frames, 30 years for windows, etc.). The outcomes, therefore, are presented within Module A1–3. Modules B1, B2, B3, B5, and B7 were excluded from the analysis due to a lack of data in both databases and scientific publications.

The results were verified with SimaPro 9.5 [50] software and compared with previous scientific articles, as shown in Section 3.

The following elements were studied for each module of Figure 2:

- Load-bearing structural frames:
    - Basements (i.e., foundations, basement walls, and underground slabs);
    - Vertical structures (i.e., beams, columns, reinforced concrete baffles, and structural masonry walls).

- Non-load-bearing elements:
    - ○ Basement and internal slabs (floor tiles excluded);
    - ○ Internal partitions (partitions of building units);
    - ○ Ceiling slabs;
    - ○ Façades, opaque and transparent envelopes.
- Finishes:
    - ○ External finishes (i.e., plaster);
    - ○ Internal finishes (i.e., gypsum plasterboard with framework).

The m^2 of net area per year is defined as the functional unit (fU) of the analysis. The authors, in line with planning parameters of the Municipality of Milan (Italian legislation), consider the net area, i.e., the gross area excluding the surface occupied by external walls, uncovered parts (i.e., balconies, terraces, etc.), stairwells, common hallways, and internal walls.

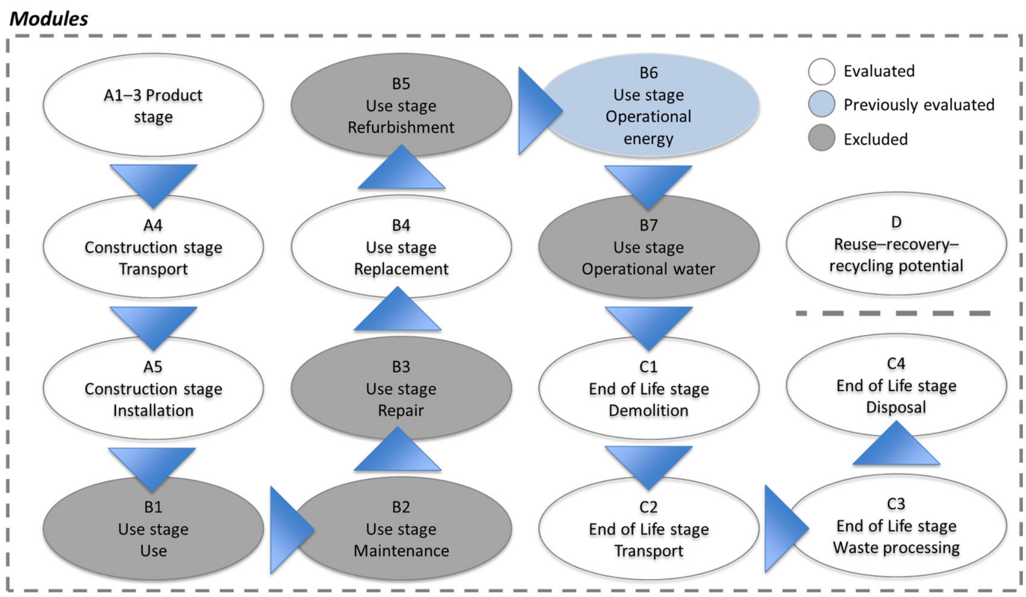

Figure 2. Modules of the EN 15978.

2.2. Computational Structure

The engine was programmed simplifying the equation provided by Heijungs and Suh [51]—Equation (1):

$$h = C \times B \times A^{-1} \times f \quad (1)$$

where

- h is a column vector with the impact category results (category indicators);
- C is the characterization matrix with the characterization factor;
- B is the intervention matrix which represents the environmental interventions of the unit processes (exchanges with nature—called the intervention matrix);
- A is the technology matrix, which represents the flows within the economic systems;
- f is the demand vector, representing the set of economic flows corresponding to the reference flow.

The reasons for the simplification are mainly due to the format of the ecoinvent database used and the characterization factors of the elementary flows. The ecoinvent database (EN 15804 with the Environmental Footprint 3.1 EN 15804 and Cumulative energy demand nonrenewable methods) was downloaded as a Microsoft Excel file, characterized by a matrix in which rows consisted of products (concerning a given process or activity) and columns were used for impact categories with specific emission factors linked with reference flows (e.g., kg CO_2 eq per kg of steel produced). Elementary flow characterization factors were obtained using the Brightway2 software package [52]. This simplification did not result in the B matrix, as described above (not having all the elementary flows by activity). Therefore, a characterization matrix Q′ was created, consisting of rows representing products (components) and the elementary flow and columns representing the impact category for each process and environmental intervention. The matrix was then multiplied by an A′ matrix to obtain the scores (per functional unit—fU) for each element of the building units analyzed (i.e., heat provided by generators, slabs, load-bearing structures, etc.). Matrix A′ comprises rows representing the building unit elements (per lifecycle stage) and columns representing products and environmental flows (e.g., kg of steel per fU, CO_2 emission for combustion of natural gas per fU, etc.). Figure 3 schematizes the two matrices, A′ and Q′, showing the matrix h′ with the scores, represented by building unit elements (per lifecycle stage) in rows and impact categories in columns.

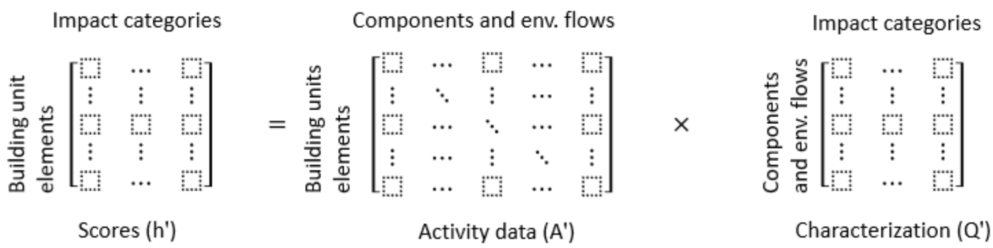

Figure 3. Computational structure of the engine developed.

2.3. Description of the Engine

As described for the operational phase engine in Famiglietti et al. (2022) [15], again, the engine is divided into three sections: (i) input model, (ii) computational model, and (iii) output model.

2.3.1. Input Model

The following information was imported from external databases: (i) the amount (mass or volume) of construction materials per building units (activity data), (ii) emission factors from ecoinvent 3.9.1 EN 15804, and (iii) characterization factors from the Environmental Footprint (EF) 3.1 EN 15804 and the Cumulative energy demand—primary energy, nonrenewable, based on low heating values—methods for the elementary flows. In particular, the activity data used by the tool are (i) the year of construction; (ii) the intended use (asset classes); (iii) the net floor area; (iv) average thermal transmittance of windows; (v) average thermal transmittance of opaque vertical envelopes; (vi) average thermal transmittance of the basement slabs; (vii) average thermal transmittance of the ceiling slabs; (viii) surface of windows; (ix) surface of dispersant walls.

Once the activity data have been imported, they are classified according to the year of construction into the following classes: (i) before 1930; from 1930 to 1945; (ii) from 1946 to 1975; (iii) from 1976 to 1990; (iv) 1991 to 2005; (v) from 2006 to 2009; and (vi) 2010 onward.

2.3.2. Computational Model

This section presents the lifecycle inventory (LCI) data created to evaluate the building units according to their asset class and year of construction.

As a first analysis to assess the environmental profile of buildings, the average height by asset class was evaluated. The research was conducted using data published by the Lombardy region through its geoportal, where all buildings are listed, providing the prevalent asset class and the surface area. Figure 4 shows the distribution stories for residential, commercial, and retail for Milan, considered in the same cluster in this research: the retail part on the ground floor and commercial or residential from the first onward. The outcomes of other asset classes are not presented because the sample of data is very limited (i.e., hospitals and clinics, recreational and leisure activities, sports clubs, industrial, artisan or similar activities, and schools). Figure 4a presents the probability density function

(PDF), represented by the area between the dotted red line and the axis x. Figure 4b reports the buildings of Milan classified into three clusters, defined using the k-means clustering method [53,54] and obtained by weighting the number of stories of each building according to their surfaces with respect to the total, thus assigning greater importance to taller buildings than to lower ones.

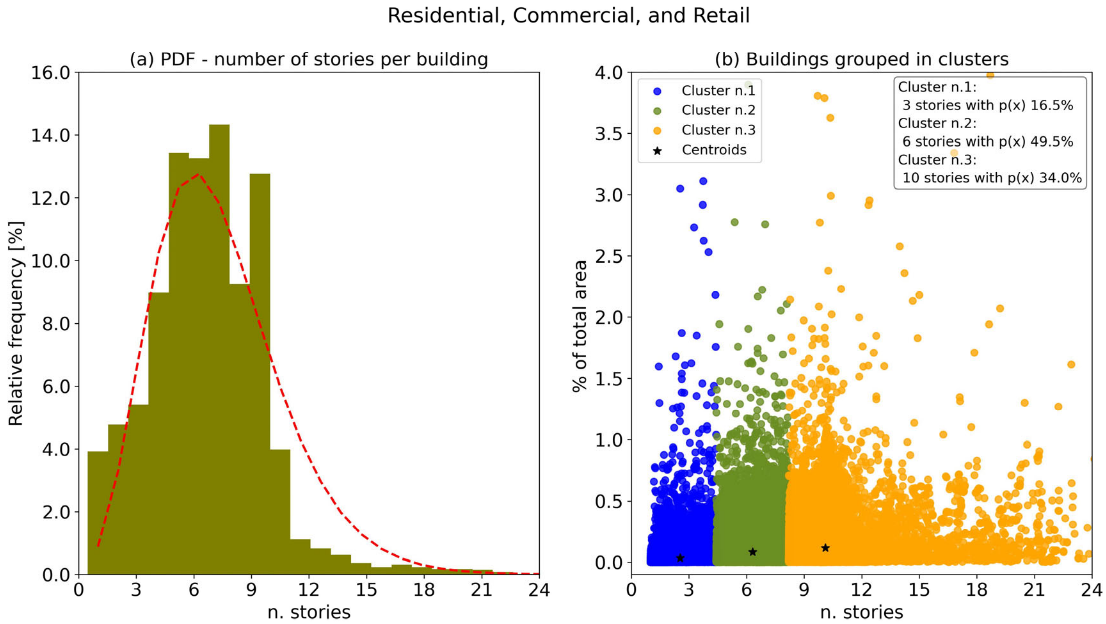

Figure 4. Number of stories per building: (**a**) probability density function and (**b**) buildings grouped in cluster.

The k-means clustering method follows an iterative procedure: initially, it creates k partitions and assigns the entry points to each partition randomly; then, it computes the centroid of each group; it later constructs a new partition by associating each entry point with the group that the centroid is closest to; finally, the centroids for the new groups are recomputed, and so on, until the algorithm converges. In mathematical form, the method calculates the minimum of Equation (2):

$$V(U, C) = \sum_{i=1}^{K} \sum_{X_j \in P_i} \| X_j - C_i \|^2 \quad (2)$$

where:

- *Xj* are the objects;
- *K* is the number of clusters defined;
- *Pi* are the object *Xj* grouped in partitions (from 1 to *K*);
- *Ci* are the centroids.

The outcomes obtained (for 3 clusters) show that (i) 16.5% of buildings have an average of 3 stories, (ii) 49.5% of buildings have an average of 6 stories, and (iii) 34.0% of buildings have an average of 10 stories—6.9 average stories as a total.

The information obtained using the k-means clustering method was used to estimate the amount of construction materials (i.e., stone masonry, solid brick masonry, and reinforced concrete) used for load-bearing structural frames, using as input parameters the number of stories (NS) in empirical relationships (number of stories—kg of construction material per m^2 of gross area). The empirical relationships are presented in Equations (3) and (4).

- Reinforced concrete (RC) amounts for foundations and vertical structures (i.e., beams, columns, and baffles) were obtained by collecting data from 33 buildings constructed in Milan covering a total gross area (GA) of 443,682 m^2, with an elevation per floor equal to 3 m. The equations range for buildings with stories from 1 to 14, with a number of underground floors from 1 to 2, considered in the Equation (2). The coefficient of determinations (R^2) of the two relationship formulas are equal to 0.56 and 0.53 for foundations and vertical structures, respectively.

$$kg\ of\ RC\ per\ m^2\ of\ GS = 1.55 \times N.stories^2 + 19.16 \times N.\ stories + 214.68 \quad (3)$$

$$kg\ of\ RC\ per\ m^2\ of\ GS = 1.16 \times N.stories^2 + 0.89 \times N.\ stories + 316.46 \quad (4)$$

The average percentages for reinforcing steel bars are 7% and 8% on mass, respectively. The intended uses of the buildings are residential, commercial (not open to the public), and retail, in some cases, on the ground floor; thus, with the same accidental load per legislation (equal to 2 kN/m^2 in compliance with the current legislation).
Figure 5 shows Equations (3) and (4). The authors highlight that the equations presented need future improvements to increase the tool's precision. This will be possible by increasing the sample of data in the coming years.

- Masonry structures were modeled according to the Decree no. 29 "Norme tecniche per le costruzioni in zone sismiche" (Ministero dei Lavori Pubblici, 1996). The decree provides the percentage of structural area compared to the total area per story (Table 1). The elevation per floor was assumed equal to 3.5 m.

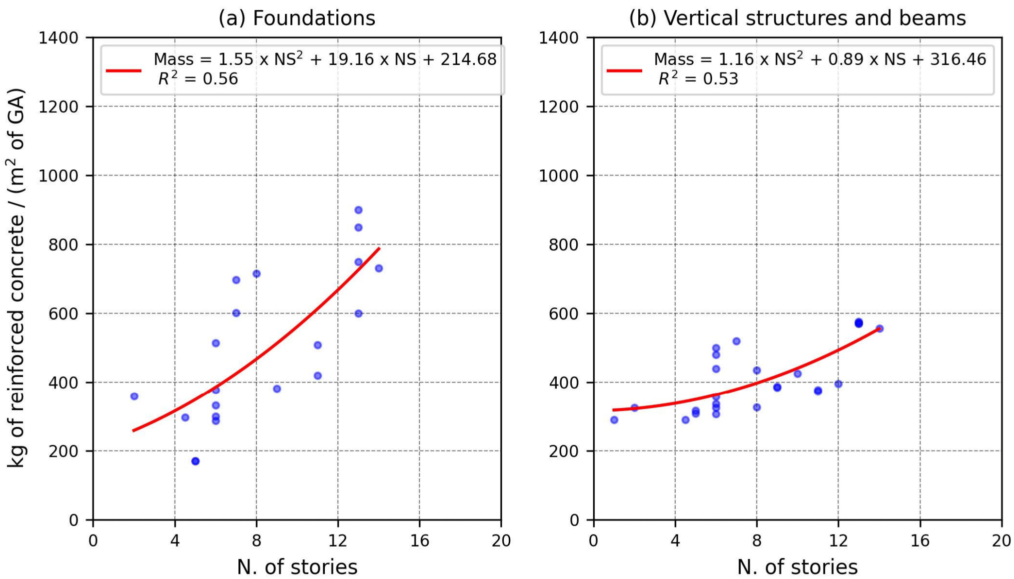

Figure 5. Relationships between number of stories and mass of reinforced concrete: (**a**) foundations and (**b**) vertical structure and beams.

Table 1. Percentage value of the structural area per story.

-	Story No. 1	Story No. 2	Story No. 3	Story No. 4	Story No. 5
One-story building	5%	-	-	-	-
Two-story building	5%	5%	-	-	-
Three-story building	6%	5%	5%	-	-
Four-story building	6%	6%	5%	5%	-
Five-story building	7%	7%	6%	6%	5%

In order to calculate the mass of solid bricks and stones for the two masonry structures, the following density values were used: 1800 kg/m^3 (UNI, 1986) and 2667 kg/m^3 (from the ecoinvent library), and the number of stories were fixed equal to 5 with a height of 3.5 m each, thus not considering the distribution shown in Figure 4. This is due to the information presented in Table 1. Additionally, 111 kg of concrete/m^2 of gross area was counted to hold together the masonry. Summarizing, 370 and 549, plus 111 kg/m^2 of gross area were considered for solid brick and stone masonry structures. Foundations were evaluated assuming 1 underground floor (3.5 m) with a concrete ground slab of 0.20 m. Therefore, the structure area of the ground floor was supposed to be buried for a depth of 3 m after the ground slab (precautionary approach).

The amount of construction material described above for reinforced concrete and masonry load-bearing structural frames referred to the gross area was converted to the net area using the following factors provided by the REDO firm [55]: (i) divide by 1.5 to obtain the available area and (ii) divide by 1.15 to obtain the net area.

The other building elements evaluated and first presented at the beginning of this section (Section 2—Materials and Methods) are defined according to the year of construction of the buildings as described in the TABULA database and integrated with the information listed in a recent publication by Carnieletto et al. [56]. Table A1 (Appendix A) shows an accurate definition of the technologies according to the period of construction. Thermal transmittances listed in the table were defined according to the databases used until 1975 (the last year in which the libraries did not report insulation materials for the external envelope in the stratigraphy). From 1976, the values are presented without the contribution of thermal insulation. The thickness of the insulation materials (and consequently the mass to calculate their environmental load) are automatically entered by the engine according to the transmittance given as an input parameter (explained in the input model section), the element transmittance values shown in Table A1, and Equation (5).

$$s_i = \rho \times \lambda \times \left(R_{input,\ i} - R_{base,\ i}\right) \quad (5)$$

where:

- s_i is the thickness of the thermal insulation for the element (i);
- ρ is the density of the thermal insulation in kg/m^3;
- λ is the conductivity of the thermal insulation in W/(m × K);
- $R_{input,\ i}$ is the thermal resistance of the element (i) provided as input information in (m^2 × K)/W;
- $R_{base,\ i}$ is the thermal resistance of element (i) listed in Table A1 in (m^2 × K)/W.

The typology of the thermal insulation materials considered are (i) polyurethane (PUR) foam with ρ equal to 30 kg/m^3 and λ equal to 0.025 W/(m × K) for building units until class from 1991 to 2005 and (ii) expanded polystyrene (EPS) with ρ equal to 20 kg/m^3 and λ equal to 0.033 W/(m × K) for building units belonging to the other class—from 2006 to 2009 and 2010 onward. The values for the thermal insulation properties were taken from the database of Aalborg University [57] and the critical review conducted by Grazieschi et al. [58].

The engine assesses the environmental burden of transparent envelopes, similar to the method used for the insulation materials. The thermal transmittance is given as an input parameter; consequently, 10 datasets describing window types having different transmittances were created within the tool. The datasets were built using the information provided by the ecoinvent database concerning three typologies of window frames: (i) wood, (ii) aluminum, and (iii) polyvinylchloride (PVC) and the production process for glass windows.

Table 2 briefly describes the dataset created for transparent envelopes. The second, third, and fourth columns describe the frames, the number of glass layers, and the thicknesses. The fifth column provides the thermal transmittance values. The last column reports in which range the dataset was used by the engine to calculate the environmental burden of the transparent envelopes. For example, if the input parameter for the building unit (i) is an average thermal transmittance equal to 3.5, the engine considers the window ID no. 2 (wood frame) as the technology installed. From thermal transmittance equal to 1.8 W/(m^2 × K), three technologies are provided: wood, aluminum, and PVC frames. Steel and wood–aluminum window frames [59] were excluded from the analysis for simplification. This is because TABULA does not provide information for values below 2.20 W/(m^2 × K); thus, the three technologies were considered, assigning to each a weight of 1/3 (having no information regarding the market). A comprehensive description of the datasets developed is provided in Supplementary Materials.

Table 2. Window layers and thermal properties.

ID	Materials	Layer	Glass Thickness (cm)	W/(m^2 × K)	Range of W/(m^2 × K)
1	Wood frame	Single glass	0.4	4.50	>4.0
2	Wood frame	Single glass	0.4	3.49	3.1 < U ≤ 4.0
3	Wood frame	Single glass	0.8	2.74	2.5 < U ≤ 3.1
4	Wood frame	Two glasses (air)	0.8	2.20	2.0 < U ≤ 2.5
5	Wood frame	Two glasses (argon)	0.8	1.80	1.6 < U ≤ 2.0
6	Aluminum frame	Two glasses (argon)	0.8	1.80	1.6 < U ≤ 2.0
7	PVC frame	Two glasses (argon)	0.8	1.80	1.6 < U ≤ 2.0
8	Wood frame	Three glasses (argon)	1.8	1.40	U ≤ 1.6
9	Aluminum frame	Three glasses (argon)	1.8	1.40	U ≤ 1.6
10	PVC frame	Three glasses (argon)	1.8	1.40	U ≤ 1.6

As explained at the beginning of this section, the engine covers Modules A1–5, C1–4, and D of EN 15978. Concerning Module B4, the engine assesses it indirectly, i.e., having obtained information about the year of construction but no indications about replacements and refurbishment of individual building units from the CENED database, the environmental burden of the building technologies indicated in the TABULA database and Carnieletto et al. (2021) [56] (explained in Tables 2 and A1) were normalized for their estimated useful life (e.g., 60 years for the load-bearing structural frames, 30 years for windows, etc.). Table 3 shows the estimated service life for each component according to the level(s) framework.

Table 3. Estimated service life.

Items	ESL (Years)
Load-bearing structural frames.	60
Slabs—bricks, stones, concrete, reinforcing steel.	60
Slabs—mortar, insulations (acoustic and thermal), gypsum plasterboard (with steel frame), and vapor and water barriers.	30
Façades—bricks.	60
Façades—cement plaster, thermal insulation, gypsum plasterboard (with steel frame), and windows.	30

Data from the literature were used for Modules A4 (transport to the construction site), A5 (installation), C1 (demolition and deconstruction), and C2 (transport to the end-of-life treatment plant). In particular, data provided by Rasmussen et al. (2019) [4], Asdrubali et al. (2013) [60], Weiler et al. (2017) [61], and Zabalza Bribián et al. (2011) [62] were selected as references for the following:

- Module A4: a distance of 50 km for inert materials and 300 km for additional materials—Rasmussen et al. (2019) [4];
- Module A5: a climate impact equal to 2% of Modules A1–3—Asdrubali et al. (2013) [60] and Rasmussen et al. (2019) [4];
- Module C1: energy consumption in kWh/m^2 of the net area for demolition of 14.45 (electricity) and 26.83 (diesel)—Weiler et al. (2017) [61];
- Module C2: a distance of 50 km for massive materials and 100 km for other materials—Asdrubali et al. (2013) [60] and Zabalza Bribián et al. (2011) [62].

Table A2 (Appendix B) summarizes the scenarios adopted to model "waste processing" (Modules C3), "disposal" (Module C4), and "benefits and loads beyond the system boundaries" (Module D). Recycling, incineration, and landfill shares are reported in the first column. The efficiencies of the recycling processes (selection and reprocessing) and the waste-to-energy plant in producing electricity and heat due to the combustion of solid wastes are presented in the second column. The quality of the outgoing material with respect to the substitute is in the third column (substitution ratios, in percentage). The substituted production (average suppliers) due to recycling and incineration with energy recovery activity is in the last column. The data indicated by Baldassarri et al. (2017) [63], Rigamonti et al. (2009) [64], and Ghose et al. (2017) [65] were assumed for disposal destination, recycling efficiency, substitution ratio, and avoided burdens. The mechanical compressive strength of concrete, bricks, and gravel (37, 11, and 150 MPa, respectively) were assumed to calculate the substitution ratios.

The efficiencies of Milan's waste-to-energy (WTE) plant were deducted from the report of the Italian Association of Urban Heating—AIRU (AIRU, 2018) [66]. Benefits and loads beyond the system boundaries were assessed by applying equations D.5 and D.8 described in EN 15804 +A2 [67]. The amount of input materials to the product systems that have been recovered (recycled or reused) from a previous system, determined at the system boundary (MMR_{in}) not listed in Table A2, were derived from the ecoinvent database.

The engine evaluates the environmental profile of each element used by building units according to the year of construction by providing the score in the 20 impact categories with respect to fU for each module of EN 15978 under consideration in this research.

2.3.3. Output Model

The outcomes from the computational model section (environmental profile of the construction materials) are associated with each energy performance certificate. The engine returns a Microsoft Excel file containing the outcomes of Modules A1–5, C1–4, and D.

2.4. Building Stock for Milan

In this section, the building stock of the city of Milan is presented, providing the number of building units according to the year of construction, the asset class, and the energy performance class. Also, the average thermal transmittances of each energy performance certificate (EPC) shared by Aria S.p.A. are presented in this section.

Table 4 shows the number of building units according to the year of construction. The asset classes are shown using the following reference code: (i) E1—residential; (ii) E2—commercial; (iii) E3—hospitals and clinics; (iv) E4—recreational and leisure activities; (v) E5—retail; (vi) E6—sports clubs; (vii) E7—schools; (viii) E8—industrial, artisan, or similar activities.

Table 4. Number of building units according to the year of construction.

Asset Class	Before 1930	1930–1945	1946–1975	1976–1990	1991–2005	2006–2009	2010 Onward
E1	5296	52,255	115,675	9755	7473	7534	12,812
E2	743	4863	7799	1567	910	596	583
E3	0	36	52	11	21	10	8
E4	89	597	689	77	53	33	95
E5	562	4822	6838	645	375	231	307
E6	4	34	146	20	25	17	50
E7	6	56	141	30	20	8	28
E8	149	1538	3914	622	420	316	152

Concerning the asset class E1, E2, and E5 subject of analysis in this research, building units are constructed for:

- 55% (115,675) from 1946 to 1975, 25% (52,255) from 1930 to 1945, 6% (12,812) from 2010 onward, and 14% the others for E1 asset class;
- 46% (7799) from 1946 to 1975, 29% (4863) from 1930 to 1945, 9% (1567) from 1976 to 1990, and 16% the others for E2 asset class;

- 50% (6838) from 1946 to 1975, 35% (4822) from 1930 to 1945, 5% (645) from 1976 to 1990, and 10% the others for E5 asset class.

The 1946–1975 class sees the largest number of building units, about 50% for all three classes, followed by the 1930–1945 class with about 30% and the 1976–1990 class with 9% for commercial and 5% for retail. Residential shows building units constructed since 2010 as the third most numerous class (6% of the total). The result confirms what other authors have already indicated, namely that the building stock consists mainly of old buildings built before 1990—Baldassarri et al. (2017) [63]. Similarly, Milan's building stock is confirmed to be active in terms of new construction, represented by 6% of residential building units built since 2010, as indicated by Centro Ricerche Economiche Sociologiche e di Mercato nell'Edilizia (CRESME)—the research center operating in Italy to describe and forecast economic and construction market trends at the territorial, national, and international levels [68].

Table 5 shows the number of building units according to the energy performance class (reported in CENED) and the year of construction. The breakdown is provided just for the three asset classes that are the subject of analysis. As expected, the higher number of buildings in the higher energy performance class (from A1 to A4) is for building units built since 2010 for all three asset classes.

In Figures 6, A1 and A2 graphically show the average thermal transmittances for residential, commercial, and retail, together with the ratio of the transparent envelope surface and the total envelope surface (opaque plus transparent). The average values for windows (transparent envelopes), opaque envelopes, ceilings, basements, and the ratio of surfaces are provided per energy class together with the standard deviation of the distributions (shaded filling area). It can be seen that the transmittance decreases from energy class G to energy class A4. On the contrary, the ratio of surfaces increases: along with the data shown in Table 5, the newer the building unit, the greater the transparent surface area.

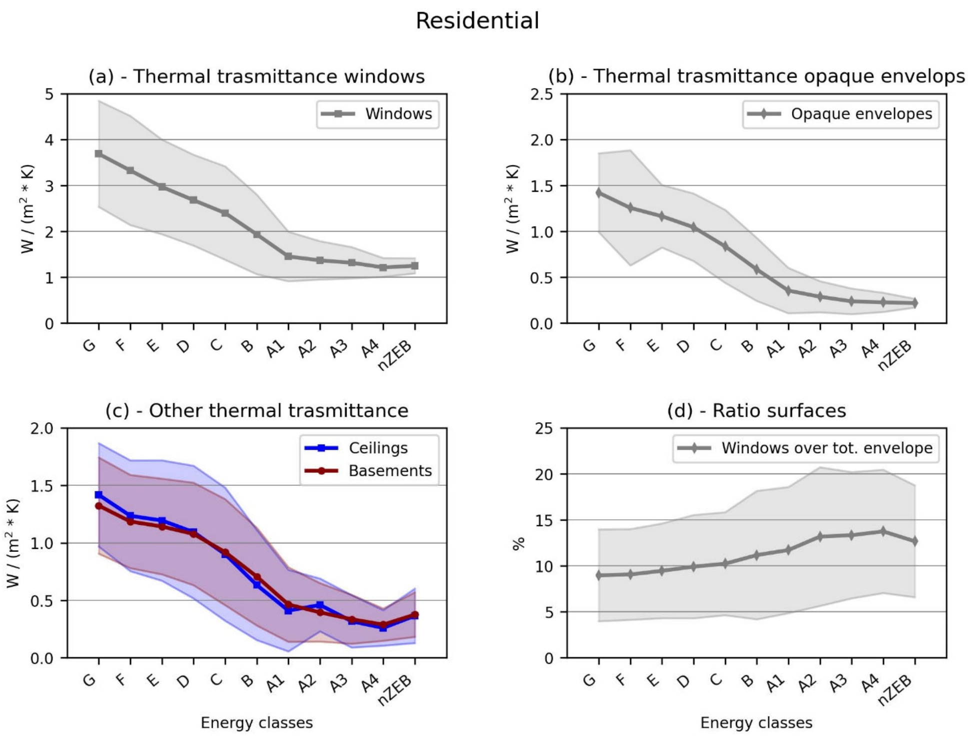

Figure 6. Residential building units' thermal transmittances and ratio surfaces.

Table 5. Building units energy class vs. year of construction.

Energy Class	Before 1930	1930–1945	1946–1975	1976–1990	1991–2005	2006–2009	2010 Onward
E1—Residential							
G	1948	16,770	36,990	2222	546	236	214
F	1530	16,213	36,432	2694	1347	572	259
E	991	10,839	22,964	2289	2079	897	345
D	521	5700	12,615	1433	2151	1417	348
C	119	1524	3752	553	949	1188	402
B	55	463	1275	220	250	1017	664
A1	66	289	948	173	64	738	1975
A2	43	250	484	96	63	552	2888
A3	9	142	129	23	17	462	3126
A4	14	65	86	52	7	455	2591
nZEB	6	84	198	5	0	171	3340
E2—Commercial							
G	48	288	545	76	18	1	8
F	86	507	1002	130	57	18	10
E	150	1039	1744	321	137	25	21
D	232	1712	2352	591	307	89	53
C	132	918	1368	288	220	90	72
B	63	226	415	105	127	174	68
A1	26	102	220	34	27	74	145
A2	2	51	125	16	7	52	132
A3	3	10	21	6	7	66	59
A4	1	10	7	0	3	7	15
nZEB	0	33	39	1	0	27	103
E5—Retail							
G	131	469	895	81	18	6	10
F	78	646	908	87	49	7	16
E	81	925	1561	108	63	16	21
D	129	1607	2116	234	124	33	37
C	65	785	967	100	66	48	36
B	54	253	265	23	44	58	36
A1	20	107	83	10	9	39	66
A2	2	27	28	0	2	16	46
A3	1	2	12	2	0	7	24
A4	1	1	3	0	0	1	15
nZEB	0	5	6	0	0	15	31

Maximum, minimum, and standard deviation values shown in the figures are also listed numerically below:

- Windows (i) from 3.69 ± 1.15 to 1.21 ± 1.20 W/(m^2 × K) for residential; (ii) from 4.01 ± 1.18 to 1.12 ± 0.22 W/(m^2 × K) for commercial; and (iii) from 4.74 ± 1.23 to 1.19 ± 0.13 W/(m^2 × K) for retail;
- Opaque envelopes (i) from 1.42 ± 0.43 to 0.22 ± 0.05 W/(m^2 × K) for residential; (ii) from 1.65 ± 0.60 to 0.32 ± 0.13 W/(m^2 × K) for commercial; and (iii) from 1.64 ± 0.67 to 0.36 ± 0.25 W/(m^2 × K) for retail;
- Basement slabs (i) from 1.32 ± 0.42 to 0.29 ± 0.14 W/(m^2 × K) for residential; (ii) from 1.48 ± 0.58 to 0.26 ± 0.17 W/(m^2 × K) for commercial; and (iii) from 1.55 ± 0.55 to 0.25 ± 0.08 W/(m^2 × K) for retail;
- Surfaces ratio (i) from 9 ± 5% to 14 ± 7% for residential; (ii) from 12 ± 8% to 32 ± 21% for commercial; and (iii) from 16 ± 12% to 33 ± 24% for retail.
- By comparing the above data, it is possible to verify, in part, the construction material technologies used by the engine (mainly according to the TABULA database) and described in Table A1. As stated, thermal transmittances listed in Table A1 were defined according to the databases used until 1975—the last year in which the libraries did not report insulation materials for the external envelope in the stratigraphy for which comparison is possible. From 1976, values in the table are presented without the contribution

of thermal insulation. The outcomes obtained are presented in Table 6, where the asset class values are calculated by adding the standard deviation to the average value.

Table 6. Comparison among thermal transmittances W/(m^2 × K).

Element	Table A1 Max	Residential	Commercial	Retail
Opaque envelopes	2.58	1.85	2.20	2.31
Ceilings	1.99	1.87	2.06	2.02
Basement slabs	1.64	1.74	2.06	2.10

If the ceiling transmittance values align with the values presented in Table A1, the opaque envelope appears to be lower, and the basement values higher. It can be justified in the following way—the values in Table A1 refer to the external walls. On the other hand, the transmittance values from CENED are averages of the whole vertical opaque envelope (external and internal). Regarding the basements, in Table A1, the transmittance values refer to unheated room slabs. CENED values are mixed on both unheated room and ground slabs. More detail of construction technologies per year of construction will be needed in future versions of the tool to increase the quality of the results.

3. Results

This section shows the results obtained for Milan by transforming the LCIs explained in Section 2 into potential environmental terms. A holistic environmental perspective of Milan is provided analyzing the environmental profile of the construction materials with respect to Modules (i) A1–3—product stage (A1—raw material supply, A2—transport, A3—manufacturing); (ii) A4–5—construction stage (A4—transport and A5—installation); (iii) C—end of life stage (C1—demolition/deconstruction, C2—transport, C3—waste processing, and C4—disposal); and (iv) D—reuse–recovery–recycling potential for construction materials. Concerning Module B4, the engine assesses it indirectly, i.e., having obtained information about the year of construction but no indications about replacements and refurbishment of individual building units from the CENED database, the environmental burden of the building technologies indicated in the TABULA database and Carnieletto et al. (2021) [56], as explained in Section 2, were normalized for their estimated useful life (see Table 3).

Tables 7 and 8 present the characterization results (for all three asset classes: residential, commercial, and retail), according to EN 15804. The outcomes are presented using m^2 of net area per year as fU.

Table 7 shows the outcomes, dividing the contribution according to the modules. As expected, the highest contributor is the production stage (Modules A1–3) for all the impact categories ranging from 96% (human toxicity, carcinogenic) to 79% (ecotoxicity, freshwater, eutrophication marine, and eutrophication terrestrial) of the total impact. The result can be justified by the fact that the materials used are predominantly inert, therefore characterized by nonrenewable primary energy demand, as decarbonization of the industry has not yet occurred with relief of associated environmental burdens. The other modules in the view cycle appear less relevant. The second most important stage is Module C2 (EoL—Transport), ranging from 9% (ecotoxicity, freshwater—inorganics) to 1% (human toxicity, carcinogenic). This stage is also associated with nonrenewable energy consumption linked to using fossil fuels for transportation. This module turns out to be more significant than Module A4 (construction stage—transport) because the lorry used in the model (specifically the engine) to assess the burdens is less efficient (lorry 3.5–7.5 metric tons vs. lorry 16–32 metric tons). The other modules are less relevant. In particular, (i) Module C1 (EoL—demolition) contributes a maximum of 5% (eutrophication marine and eutrophication terrestrial); (ii) Module A4 and A5 are negligible, contributing less than 3% for all impact categories. However, it is important to note that Module A5 was evaluated through scenarios. Careful evaluation would be necessary to make this conclusion more robust.

Table 7. Environmental profile of building units in Milan by module (per fU).

Potential Impacts	Units	A1-3	A4	A5	C1	C2	C3	C4	Module D
Ecotoxicity freshwater	CTUe	5.37×10^{1}	1.89×10^{0}	1.07×10^{0}	1.19×10^{0}	5.89×10^{0}	1.35×10^{0}	2.62×10^{0}	-2.31×10^{0}
Ozone depletion	kg CFC11 eq	2.01×10^{-7}	5.88×10^{-9}	4.03×10^{-9}	4.68×10^{-9}	1.72×10^{-8}	3.14×10^{-9}	4.61×10^{-9}	-2.31×10^{-8}
Acidification	mol H+ eq	5.01×10^{-2}	8.81×10^{-4}	1.00×10^{-3}	1.83×10^{-3}	2.42×10^{-3}	1.22×10^{-3}	1.50×10^{-3}	-4.13×10^{-3}
Eutrophication marine	kg N eq	1.25×10^{-2}	3.03×10^{-4}	2.50×10^{-4}	7.45×10^{-4}	7.81×10^{-4}	5.64×10^{-4}	7.66×10^{-4}	-7.70×10^{-4}
Eutrophication terrestrial	mol N eq	1.33×10^{-1}	3.20×10^{-3}	2.67×10^{-3}	8.13×10^{-3}	8.22×10^{-3}	6.03×10^{-3}	6.49×10^{-3}	-8.25×10^{-3}
Eutrophication freshwater	kg P eq	3.35×10^{-3}	1.89×10^{-5}	6.70×10^{-5}	2.01×10^{-5}	6.70×10^{-5}	9.00×10^{-6}	2.74×10^{-5}	-2.52×10^{-4}
Human toxicity, noncarcinogenic	CTUh	1.18×10^{-7}	2.72×10^{-9}	2.36×10^{-9}	8.63×10^{-10}	7.84×10^{-9}	1.46×10^{-9}	1.91×10^{-9}	-8.63×10^{-9}
Photochemical ozone formation	kg NMVOC eq	4.96×10^{-2}	1.32×10^{-3}	9.92×10^{-4}	2.50×10^{-3}	3.50×10^{-3}	1.87×10^{-3}	2.10×10^{-3}	-3.55×10^{-3}
Human toxicity, carcinogenic	CTUh	3.26×10^{-8}	1.23×10^{-10}	6.51×10^{-10}	7.53×10^{-11}	4.07×10^{-10}	1.17×10^{-10}	1.06×10^{-10}	-2.07×10^{-9}
Particulate matter formation	disease inc	1.90×10^{-6}	2.15×10^{-8}	3.79×10^{-8}	4.29×10^{-8}	4.61×10^{-8}	1.18×10^{-7}	1.21×10^{-7}	-4.60×10^{-8}
Ionizing radiation	kBq U-235 eq	6.32×10^{-1}	5.13×10^{-3}	1.26×10^{-2}	1.34×10^{-2}	2.22×10^{-2}	2.02×10^{-3}	9.44×10^{-3}	-3.84×10^{-2}
Material resources, metals/minerals	kg Sb eq	5.86×10^{-5}	8.87×10^{-7}	1.17×10^{-6}	2.31×10^{-7}	3.55×10^{-6}	1.54×10^{-7}	4.40×10^{-7}	-9.96×10^{-7}
Energy resources, nonrenewable	MJ	1.20×10^{2}	3.86×10^{0}	2.40×10^{0}	3.65×10^{0}	1.12×10^{1}	2.29×10^{0}	3.52×10^{0}	-1.21×10^{1}
Land use	Pt	1.55×10^{2}	2.28×10^{0}	3.11×10^{0}	3.71×10^{-1}	4.63×10^{0}	1.75×10^{0}	4.65×10^{0}	-1.57×10^{0}
Water use	m^3 depriv.	3.58×10^{0}	1.89×10^{-2}	7.17×10^{-2}	5.60×10^{-2}	6.39×10^{-2}	2.69×10^{-2}	5.05×10^{-2}	-2.40×10^{-1}
Climate change	kg CO_2 eq	1.21×10^{1}	2.71×10^{-1}	2.41×10^{-1}	2.64×10^{-1}	7.93×10^{-1}	7.77×10^{-1}	6.93×10^{-1}	-9.93×10^{-1}
Climate change—fossil	kg CO_2 eq	1.27×10^{1}	2.70×10^{-1}	2.55×10^{-1}	2.55×10^{-1}	7.92×10^{-1}	2.62×10^{-1}	3.56×10^{-1}	-9.75×10^{-1}
Climate change—biogenic	kg CO_2 eq	1.24×10^{-1}	2.32×10^{-4}	2.48×10^{-3}	8.61×10^{-3}	6.53×10^{-4}	3.81×10^{-2}	2.99×10^{-2}	-1.72×10^{-2}
Climate change—LU and LUC	kg CO_2 eq	4.84×10^{-2}	1.31×10^{-4}	9.67×10^{-4}	3.30×10^{-5}	4.64×10^{-4}	2.83×10^{-5}	1.29×10^{-4}	-1.04×10^{-3}
Cumulative energy demand—nonrenewable energy resources	MJ	1.20×10^{2}	3.86×10^{0}	2.40×10^{0}	3.65×10^{0}	1.12×10^{1}	2.29×10^{0}	3.52×10^{0}	-1.21×10^{1}

Table 8. Environmental profile of building units in Milan by element (per fU).

Potential Impacts	Units	Basements	Vertical Structure	Basement Slabs	Internal Slabs	Ceiling Slabs	Opaque Envelopes	Transparent Envelopes
Ecotoxicity freshwater	CTUe	1.00×10^{1}	1.47×10^{1}	2.82×10^{0}	1.38×10^{1}	3.75×10^{0}	8.01×10^{0}	1.47×10^{1}
Ozone depletion	kg CFC11 eq	3.88×10^{-8}	5.57×10^{-8}	7.58×10^{-9}	4.58×10^{-8}	1.09×10^{-8}	2.28×10^{-8}	6.00×10^{-8}
Acidification	mol H+ eq	9.98×10^{-3}	1.49×10^{-2}	2.14×10^{-3}	1.20×10^{-2}	3.77×10^{-3}	5.22×10^{-3}	1.10×10^{-2}
Eutrophication marine	kg N eq	2.71×10^{-3}	4.45×10^{-3}	5.92×10^{-4}	3.44×10^{-3}	9.32×10^{-4}	1.64×10^{-3}	2.16×10^{-3}
Eutrophication terrestrial	mol N eq	2.91×10^{-2}	4.79×10^{-2}	6.18×10^{-3}	3.55×10^{-2}	9.79×10^{-3}	1.75×10^{-2}	2.24×10^{-2}
Eutrophication freshwater	kg P eq	7.84×10^{-4}	9.12×10^{-4}	1.33×10^{-4}	8.10×10^{-4}	2.14×10^{-4}	1.61×10^{-4}	5.52×10^{-4}
Human toxicity, noncarcinogenic	CTUh	2.49×10^{-8}	3.14×10^{-8}	4.86×10^{-9}	2.82×10^{-8}	8.04×10^{-9}	1.02×10^{-8}	2.79×10^{-8}
Photochemical ozone formation	kg NMVOC eq	1.16×10^{-2}	1.80×10^{-2}	2.30×10^{-3}	1.33×10^{-2}	3.52×10^{-3}	6.36×10^{-3}	6.89×10^{-3}
Human toxicity, carcinogenic	CTUh	9.18×10^{-9}	1.02×10^{-8}	1.21×10^{-9}	7.71×10^{-9}	1.77×10^{-9}	1.77×10^{-9}	2.22×10^{-9}
Particulate matter formation	disease inc	4.90×10^{-7}	1.11×10^{-6}	1.03×10^{-7}	2.57×10^{-7}	6.83×10^{-8}	1.09×10^{-7}	1.50×10^{-7}
Ionizing radiation	kBq U-235 eq	1.21×10^{-1}	1.88×10^{-1}	3.48×10^{-2}	1.80×10^{-1}	3.47×10^{-2}	3.19×10^{-2}	1.08×10^{-1}
Material resources, metals/minerals	kg Sb eq	9.82×10^{-6}	1.27×10^{-5}	2.48×10^{-6}	1.38×10^{-5}	3.89×10^{-6}	5.45×10^{-6}	1.70×10^{-5}
Energy resources, nonrenewable	MJ	2.52×10^{1}	3.84×10^{1}	6.22×10^{0}	3.17×10^{1}	8.96×10^{0}	1.66×10^{1}	2.00×10^{1}
Land use	Pt	9.13×10^{0}	1.49×10^{1}	3.15×10^{0}	2.27×10^{1}	5.37×10^{0}	8.54×10^{0}	1.09×10^{2}
Water use	m^3 depriv.	8.25×10^{-1}	1.05×10^{0}	1.58×10^{-1}	7.61×10^{-1}	1.72×10^{-1}	1.79×10^{-1}	7.31×10^{-1}
Climate change	kg CO_2 eq	2.92×10^{0}	4.02×10^{0}	6.46×10^{-1}	3.37×10^{0}	9.24×10^{-1}	1.48×10^{0}	1.74×10^{0}
Climate change—fossil	kg CO_2 eq	2.88×10^{0}	3.98×10^{0}	6.27×10^{-1}	3.32×10^{0}	9.17×10^{-1}	1.53×10^{0}	1.70×10^{0}
Climate change—biogenic	kg CO_2 eq	4.62×10^{-2}	4.13×10^{-2}	1.80×10^{-2}	5.36×10^{-2}	5.75×10^{-3}	1.83×10^{-3}	3.78×10^{-2}
Climate change—LU and LUC	kg CO_2 eq	1.40×10^{-3}	2.05×10^{-3}	2.89×10^{-4}	1.79×10^{-3}	5.24×10^{-4}	1.13×10^{-3}	4.33×10^{-2}
Cumulative energy demand—nonrenewable energy resources	MJ	2.52×10^{1}	3.84×10^{1}	6.22×10^{0}	3.17×10^{1}	8.96×10^{0}	1.66×10^{1}	2.00×10^{1}

Unlike the other impact categories, climate change—biogenic has the lowest contribution in Module A1–3 due to carbon uptake from the wood-based material used for slabs and windows. Uptake emissions are then released in Module C3 (EoL—incineration) and C4 (Module C4—EoL disposal), closing the balance with more emissions released in the atmosphere than uptakes. EN 15804 adopts the $-1/+1$ method to evaluate biogenic CO_2, it consists of tracking all biogenic carbon flows over the building lifecycle. In this approach, biogenic CO_2 uptake (–1) and release (+1) are considered, as well as the transfers of biogenic carbon between the different systems. Numerically, the impact category contributes 61% for Module A1–3, 19% for Module C3, and 15% for Module C4. The other Modules range from 4% (Module C1) to 0.1% (Module C4). The higher benefits for reuse–recovery–recycling potential (Module D) are linked with primary energy saved thanks to the avoided production of components or energy recovery. “Energy resources, nonrenewable” and “Cumulative energy demand—nonrenewable energy resources” scored an 8% potential saving compared with the burden obtained with the sum of Modules A1–5 and C1–4.

Table 8 shows the results dividing the contribution according to the technical elements (UNI, 1981), from now on also referred to as “elements”. The authors consider (i) load-bearing structural frames (LBSF), basements (i.e., foundations, basement walls, and underground slabs), vertical structures (i.e., beams, columns, reinforced concrete baffles, and structural masonry walls); (ii) non-load-bearing structural elements (NLBSE), basement slabs, internal slabs, and ceilings; and (iii) façades, opaque and transparent external envelopes. The LBSF represents the highest contributor ranging from 70% (particulate matter) to 14% (land use). Compared with the 20 impact categories (climate change, fossil, biogenic, and LULUC included), it is only for “ozone depletion”, “land use”, and “climate change—land use and land use change” that the LBSF does not constitute the largest source of burden, equal to 25%, 14%, and 7%, respectively. The NLBSE represents the second largest contributor, ranging from 36% (ionizing radiation) to 18% (land use). Compared with façades, it has a more significant impact on 15 out of 20 categories. The five impact categories are “ecotoxicity, freshwater—inorganics”, “ozone depletion”, “resource use, minerals/metals”, “land use”, and “climate change—land use and land use change”. Finally, façades are the main contributor to “land use”, higher than LBSF and NLBSE due to the wood window material (88% compared with 14% and 18%, respectively). Similarly, they are the largest contributor to “climate change—biogenic” (88% compared with 7% and 5%, respectively). Analyzing the elements within the three classifications (LBSF, NLBSE, and façades), presented in Table 8:

- The vertical structure has a higher environmental score for all the impact categories analyzed than the foundations. It is strictly linked with the number of underground floors considered in the model. The engine developed considers buildings with not more than two underground floors. Potentially increasing the number of underground stories for the same number of aboveground floors, the conclusion could change;
- The internal slabs have a higher environmental score for all impact categories assessed, followed by ceilings and basement slabs. This is due to the larger surface area of the internal floors compared to other floors (buildings with an average height of 6.9 stories);
- Transparent envelopes have a higher environmental score for all impact categories analyzed, except for “ozone depletion”, due to the emissions released during the thermal insulation production process. Also, in this case, the conclusion is linked with the ratio of the transparent surface enveloped and the total surface enveloped. The building units analyzed have a ratio from 10% to 36% (see Figures 6, A1 and A2).

The asset class breakdown with (i) 210,800 residential, (ii) 17,061 commercial, and (iii) 13,780 retail building units highlights that the results obtained mainly reflect the residential sector.

Table 9 shows the impact categories results for residential building units. The table reports the mean and median values, the standard deviation (SD), the standard error of the mean (SEM), and the 25th and 75th percentiles. The authors point out the lower coefficient of variation (CV). The CV is calculated as the ratio of SD and mean, e.g., for “climate change”, the result is approx. 16%. The lower CV is because the analysis was carried out using fixed data in terms of material amounts for LBSF (higher contributor), as well as the

NLBSE, varying the construction technology only according to the year of construction (as described in Section 2.3.2 and Table A1). The amounts related to materials used per individual building unit are related only to the surface area of the envelope (opaque and transparent), the type of window bodies based on the average transmittance, as well as the amount of thermal insulation to achieve the transmittances declared in CENED. An open CENED-type database should also be structured for the building materials used, such as by computerizing the reports under the "ex-legge 10" [69] containing the necessary information, to have a wider coefficient of variation in the future.

The order of magnitude was in line with Asdrubali et al. (2013) [60], Causone et al. (2021) [70]—average of the two assessments given—Rasmussen et al. (2019) [4], and Famiglietti et al. (2023) [71]. These studies were selected because they analyzed Italian case studies and accounted for residential/hospitality (hostel) use of buildings. Summarizing the results presented by the scientific articles cited range from approximately 9 to 28 vs. 15 kg CO_2 eq/(m^2 of net area × year) obtained and shown as a sum of the modules' contribution in Table 7.

The authors of this research scaled up the climate profile reported in the scientific papers mentioned to the net area and divided the outcomes for the reference study period (RSP) indicated by the authors. The large differences among the building typologies, construction materials, elements, and modules analyzed can justify the high variability of the results. For instance:

- Building typologies and construction materials:
    - Asdrubali et al. (2013) [60] analyzed a single-family house (three stories), a multi-dwelling residential building (four stories), and a commercial building (five stories) without underground floors and in reinforced concrete;
    - Causone et al. (2021) [70] analyzed a building with eight stories without an underground floor. Structures in reinforced concrete and wooden load-bearing frame;
    - Famiglietti et al. (2023) [71] analyzed 14 buildings with 5 stories on average, without underground floors. Structures in reinforced concrete with blast furnace slag (40%) and recycled steel bars (95%);
    - Rasmussen et al. (2019) [4] assessed 3 single-family houses and 25 multifamily buildings provided by Casa Clima agency (the number of stories is not provided). The structures are in wooden load-bearing frames without an underground floor.
- Elements and Modules:
    - Asdrubali et al. (2013) [60] and Famiglietti et al. (2023) [71] considered technical element subsystems like staircases, ramps, and balconies (not included in this research) and all modules listed in EN 15978;
    - Rasmussen et al. (2019) [4] excluded the foundation and Module C1.

Figure 7 shows the climate profile of building units (residential, commercial, and retail) according to the (a) year of construction and modules, (b) year of construction and elements, and (c) energy class and modules. Figure 7a reports that newly constructed building units have the highest burdens in relation to the highest consumption of building materials, as they have to ensure the higher thermophysical performance of the envelope. The values range from approx. 12 to 21 kg CO_2 eq/fU for building units built "before 1930" and "2010 onwards", respectively. Likewise, "2010 onwards" provides greater benefits from reuse–recovery–recycling potential (Module D). Figure 7c presents similar outcomes to Figure 7a due to the energy class reflecting the year of construction significantly, as already shown in Table 5, where the energy performance certificates were classified according to the year of construction and energy performance classes.

Figure 7b presents the same trend, with building units built since 2010 (2010 onward) having the highest climate profile, especially in relation to the envelope (opaque and transparent), graphically confirming what has just been described and previously introduced in Section 1 (Introduction) of this research, i.e., the analysis of energy consumption alone is no longer sufficient to support the design choices, considering that for nearly zero energy buildings (nZEBs), the embodied energy reaches around 50% or higher.

Table 9. Statistical distribution of the results for residential (per fU).

Potential Impacts	Units	Mean	Median	SD	SEM	25th Perc.	75th Perc.
Ecotoxicity freshwater	CTUe	6.74×10^{1}	6.29×10^{1}	1.73×10^{1}	3.77×10^{-2}	5.73×10^{1}	7.15×10^{1}
Ozone depletion	kg CFC11 eq	2.41×10^{-7}	2.11×10^{-7}	9.15×10^{-8}	1.99×10^{-10}	1.89×10^{-7}	2.38×10^{-7}
Acidification	mol H+ eq	5.87×10^{-2}	5.57×10^{-2}	1.06×10^{-2}	2.31×10^{-5}	5.25×10^{-2}	6.17×10^{-2}
Eutrophication marine	kg N eq	1.58×10^{-2}	1.52×10^{-2}	2.70×10^{-3}	5.88×10^{-6}	1.42×10^{-2}	1.65×10^{-2}
Eutrophication terrestrial	mol N eq	1.67×10^{-1}	1.60×10^{-1}	2.85×10^{-2}	6.20×10^{-5}	1.50×10^{-1}	1.75×10^{-1}
Eutrophication freshwater	kg P eq	3.55×10^{-3}	3.45×10^{-3}	4.76×10^{-4}	1.04×10^{-6}	3.27×10^{-3}	3.68×10^{-3}
Human toxicity, noncarcinogenic	CTUh	1.35×10^{-7}	1.27×10^{-7}	2.59×10^{-8}	5.65×10^{11}	1.20×10^{-7}	1.41×10^{-7}
Photochemical ozone formation	kg NMVOC eq	6.17×10^{-2}	5.92×10^{-2}	9.06×10^{-3}	1.97×10^{-5}	5.64×10^{-2}	6.41×10^{-2}
Human toxicity, carcinogenic	CTUh	3.41×10^{-8}	3.44×10^{-8}	5.44×10^{-9}	1.18×10^{11}	3.11×10^{-8}	3.63×10^{-8}
Particulate matter formation	disease inc	2.19×10^{-6}	1.04×10^{-6}	6.72×10^{-6}	1.46×10^{-8}	9.87×10^{-7}	1.19×10^{-6}
Ionizing radiation	kBq U-235 eq	6.87×10^{-1}	5.96×10^{-1}	3.69×10^{-1}	8.04×10^{-4}	5.51×10^{-1}	7.30×10^{-1}
Material resources, metals/minerals	kg Sb eq	6.45×10^{-5}	6.24×10^{-5}	1.35×10^{-5}	2.94×10^{-8}	5.55×10^{-5}	7.00×10^{-5}
Energy resources, nonrenewable	MJ	1.46×10^{2}	1.44×10^{2}	2.67×10^{1}	5.82×10^{-2}	1.27×10^{2}	1.55×10^{2}
Land use	Pt	1.66×10^{2}	1.59×10^{2}	6.04×10^{1}	1.31×10^{-1}	1.29×10^{2}	1.88×10^{2}
Water use	m^3 depriv.	3.85×10^{0}	3.63×10^{0}	1.20×10^{0}	2.61×10^{-3}	3.35×10^{0}	3.98×10^{0}
Climate change	kg CO_2 eq	1.51×10^{1}	1.44×10^{1}	2.19×10^{0}	4.77×10^{-3}	1.38×10^{1}	1.57×10^{1}
Climate change—fossil	kg CO_2 eq	1.49×10^{1}	1.43×10^{1}	2.12×10^{0}	4.61×10^{-3}	1.37×10^{1}	1.55×10^{1}
Climate change—biogenic	kg CO_2 eq	2.13×10^{-1}	2.45×10^{-1}	1.85×10^{-1}	4.03×10^{-4}	1.83×10^{-1}	2.47×10^{-1}
Climate change—LU and LUC	kg CO_2 eq	4.79×10^{-2}	4.64×10^{-2}	2.02×10^{-2}	4.40×10^{-5}	3.52×10^{-2}	5.69×10^{-2}
Cumulative energy demand—nonrenewable energy resources	MJ	1.46×10^{2}	1.44×10^{2}	2.67×10^{1}	5.82×10^{-2}	1.27×10^{2}	1.55×10^{2}

The model implemented and the results achieved were also validated (Appendix D) by testing the reliability of the assumptions made using one-at-a-time sensitivity analysis (OAT-SA) [72].

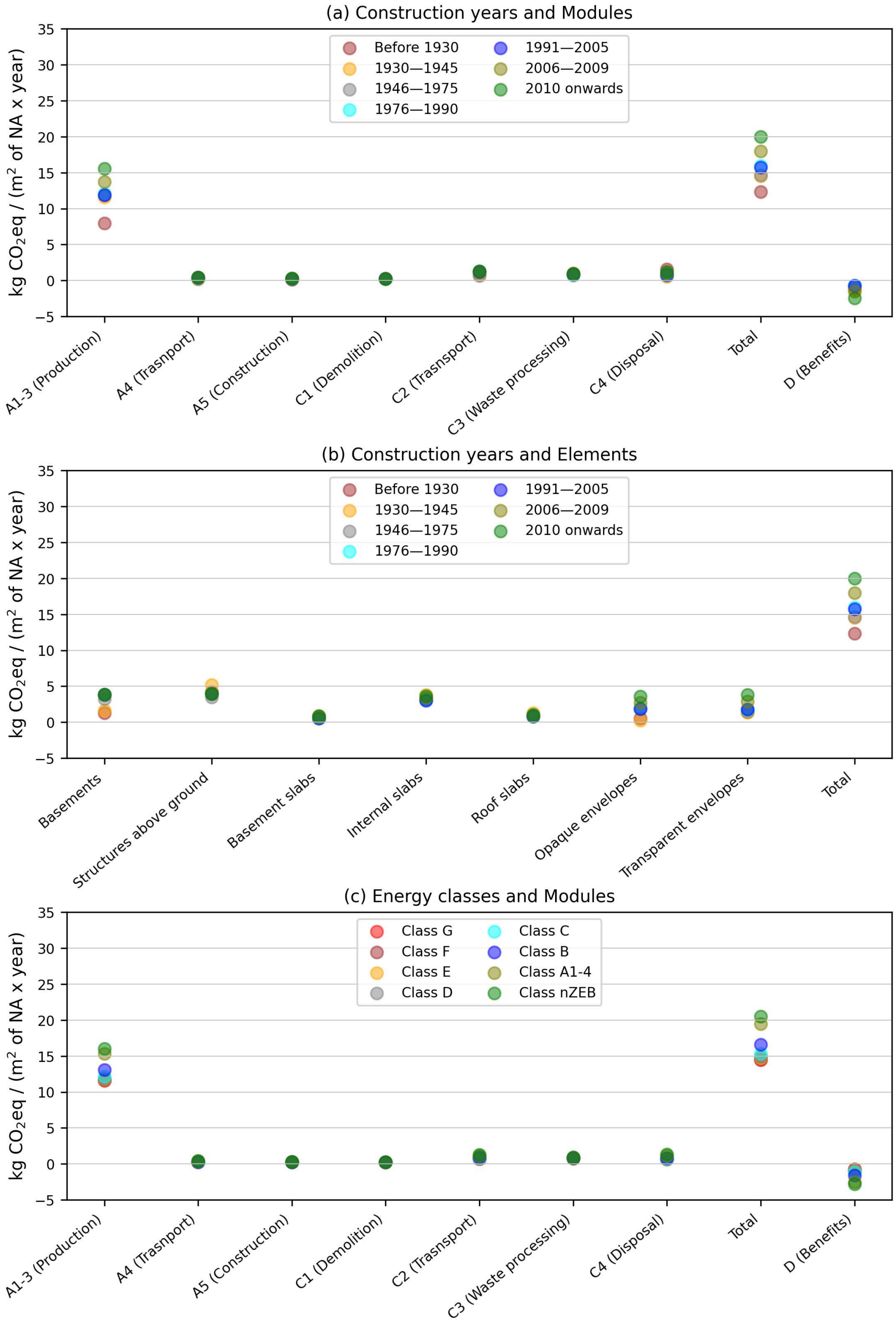

Figure 7. Contributions according to the (**a**) year of constructions and modules, (**b**) year of constructions and elements, and (**c**) energy class and modules.

4. Discussion

The average value equal to 15 kg CO_2 eq/(m^2 of net area × year) obtained in this research appears to be equal to the upper bound of the results obtained by Trigaux et al. (2020) [37]. In the figure, the outcomes range from below 5 to approx. 16 kg CO_2 eq/(m^2 of net area × year). Similarly, the results concerning the limits on GWP emissions imposed by EU Member States are low compared to what has been achieved. Values range from 12 to 26 kg CO_2 eq/(m^2 of net area × year) with Module B6 (use stage—operational energy) included. The database used for evaluations should be analyzed, as well as the building types, to make a robust comparison. The national limits reflect a different overall building stock to that of a city like Milan, which consists mainly of tall buildings (averaging 6.9 stories) and with at least 1 story underground. Such assumptions greatly affect the climate footprint of buildings, as we have seen in the results obtained and presented in this article. In addition, Milan's building stock was modeled predominantly by assuming the traditional reinforced concrete structures (from the TABULA database), using Portland cement, with a significant contribution to "climate change". Moreover, the emission factor of the Italian electricity mix (494 g CO_2 eq/kWh$_e$) appears to be much higher than those of the member states analyzed: about twice high as those of Denmark and Finland (approx. 290 and 270 g CO_2 eq/kWh$_e$), and more than twice with respect to France and Sweden (approx. 90 and 50 g CO_2 eq/kWh$_e$). Furthermore, the limits provided by France were calculated using a dynamic model regarding the characterization factor of CO_2 eq emissions over time. The French model greatly benefits mass timber structures because the emissions associated with Module C3, C4 are characterized by a lower characterization factor of 1. For instance, the emissions of CO_2 eq released at year 50 are reduced by multiplying them by a factor of 0.58 [73].

Potential reduction strategies for Milan's new buildings are presented by (i) increasing the rate of recycled steel in reinforced concrete to 95% (from 55% provided by ecoinvent) and (ii) using eco-cement (i.e., pozzolans, blast furnace slag, and fly ash), in this example, CEM II/B (Portland composite cement: clinker and blast furnace slag) provided by the ecoinvent library. By 2030, according to the Government Territory Plan of Milan, new buildings will cover 2,420,920 m^2 (net area). Thus, those two solutions were chosen because they are potentially applicable given the low cost of application at present compared to other building materials, i.e., mass timber [71], as evidenced by the urban redevelopment projects launched by the city of Milan through the "reinventing cities" call for proposals by C40 [74]. The solutions lead to a reduction of 2 kg CO_2 eq/fU, corresponding to 290.5 kt CO_2 eq, scaling the benefit to the entire area of new construction. Future insights will be needed should demand for these two materials increase, as the production depends on the demand for other goods (steel and primary cast iron), so the prices may fluctuate. Future insights should also cover other supplementary cementitious materials to substitute clinker, like bioderived resources and geopolymers [75,76], and design solutions, i.e., the shape and strength of load-bearing structural frames [77].

The authors underline that the engine is potentially already suitable for the other cities of the Lombardy region (where Milan is located), having almost all the necessary data available, i.e., from (i) CENED, the asset classes, surfaces, thermal transmittances, etc.; (ii) TABULA, the technologies according to the period of construction; and (iii) the geoportal of Lombardy region, the number of stories per buildings. The authors emphasize more limits in using the relationships described with Equations (3) and (4), shown in Figure 5, outside the city context. The correlations are valid for buildings with one- to two-story underground floors and above four stories outside the ground; thus, they are not suitable for not multistorey buildings. Additionally, the amount of concrete and steel is related according to the Italian classification of seismic zones for Milan (zone 3). The application of the engine in other Italian cities is possible if open databases containing available information such as those listed are available. Worldwide application is feasible with due revision of the lifecycle inventory.

Future improvement of the results obtained, e.g., increasing the coefficient of variation (CV) values for each impact category (shown in Table 9), can be obtained by computerizing the reports under the "ex-legge 10", thus creating an open CENED-type database containing specific information for non-load-bearing structural elements (NLBSE) of each building unit. The developed data-driven tool would assess various building technologies' burdens with greater granularity. Namely, the stratigraphies used in this article for NLBSE, defined according to the year of construction (shown in Table A1), would be superseded by the primary data presented in the database. Future engine improvement should also allow for the assessment of Module B1, B2, B3, B5, B7, which is now excluded. In particular, Module B7 (use stage—operational water) is of considerable scientific interest. However, this assessment will only be possible by monitoring the performance of water-using products installed in building units, e.g., integrated within the energy performance certificate.

5. Conclusions

In this research work, the authors explained the general structure of the process-based lifecycle assessment tool (attributional modeling) developed to evaluate buildings' embodied (construction materials) environmental profile at the urban scale. The motivation for this research lies in the necessity to equip cities with tools capable of providing environmental profile mapping over time, and it had the following aims:

- To extend the tool implemented by Famiglietti et al. (2022) [15], including the embodied emissions of the construction materials;
- Evaluating potential GWP benchmarks (i.e., targets, reference, and limits) for the city of Milan with potential extension for the entire Lombardy region, never investigated before, by analyzing a much larger sample of buildings than so far reported by European member states the Netherlands, France, Finland, Denmark, and Sweden.

The engine was written in Python and permits lifecycle assessment evaluations following the EN 15978 standard, analyzing 20 potential impact categories using ecoinvent 3.9.1 EN 15804 as a background database and the Environmental Footprint 3.1 and Cumulative energy demand (primary energy—nonrenewable) characterization methods.

The results show the environmental profile of the building units covering approx. 240,000 properties (35% of the total floor area of the city, equal to 81 km^2 for the Agenzia Mobilità Ambiente Territorio of the Municipality of Milan—AMAT). The validation of the results was implemented by (i) testing each lifecycle inventory (described in Section 2) using SimaPro 9.5 software (standard lifecycle assessment software), (ii) comparing the outcomes with what was found by previous scientific studies, and (iii) performing a one-at-a-time sensitivity analysis on the most significative assumptions.

A holistic view of the construction materials and the associated emissions at the neighborhood or city scale is allowed by the engine permitting the evaluation across a plurality of buildings and focusing on 20 impact categories (i.e., climate change, eutrophication, acidification, etc.). Therefore, the engine can be utilized as a planning tool for achieving Europe's 2050 targets.

The calculation derived the following conclusions for residential, commercial, and retail building units, respectively:

- Entire building stock (old and new building units), 15 kg CO_2 eq/(m^2 of net area × year);
- Nearly zero energy buildings (new building units), 21 kg CO_2 eq/(m^2 of net area × year);
- The outcomes achieved are higher if compared with what was presented by Trigaux et al. (2022) [37] and EU member states with the limit values for new constructions, from 1 to 17 and from 12 to 26 (operational energy included) kg CO_2 eq/m^2 of net area × year, respectively;
- Increasing the rate of recycled steel in reinforced concrete from 55% to 95% and using eco-cement (CEM II/B—Portland composite cement: clinker and blast furnace slag) leads to a reduction of 2 kg CO_2 eq/(m^2 of net area × year), corresponding to 290.5 kt CO_2 eq, scaling the benefit to the entire area of new construction.

The starting point for future engine improvements is to refine the lifecycle inventory of construction technologies and cover a higher percentage of the surface involving more building units. Other future research steps can be summarized as:

- Developing a large database for construction materials by computerizing the reports under the "ex-legge 10" containing the necessary information;
- Validating the model on a larger number of case studies;
- Developing maps of the city using geographical information systems (GIS) to set planning strategies;
- Assessing impacts concerning land use related to city sprawl [78];
- Associating cost and socioeconomic indicators with the environmental profile to identify priority areas for intervention and obtaining a lifecycle Sustainability assessment (LCSA).

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su151511518/s1, MS Excel file LCI construction technologies.xlxs.

Author Contributions: Conceptualization, J.F.; methodology, J.F.; software, J.F.; validation, J.F.; formal analysis, J.F.; investigation, J.F.; resources, J.F.; data curation, J.F. and H.M.; writing—original draft preparation, J.F.; writing—review and editing, J.F.; visualization, J.F.; supervision, M.M.; project administration, J.F. and M.M. All authors have read and agreed to the published version of the manuscript.

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Appendix A

Table A1. Description of the technologies according to the period of construction.

Year of Build	Construction Element	Description	Thermal Transmittance (W/(m^2 × K))
Before 1930	External wall	Stone masonry	2.58
	Internal slabs in unheated rooms	Vaults in solid bricks	1.64
	Internal slabs	Beams–wooden slabs	-
	Ceiling slabs	Beams–wooden slabs	1.22
	Load-bearing structural frames	Stone masonry	-
1930–1945	External wall	Solid bricks	1.48
	Internal slabs in unheated rooms	Steel beams and vaults in solid bricks	1.56
	Internal slabs	Steel beams and hollow bricks	-
	Ceiling slabs	Steel beams and hollow bricks	1.99
	Load-bearing structural frames	Solid bricks masonry	-
1946–1975	External wall	Hollow bricks (25 cm) with cavity (5 cm)	1.11
	Internal slabs in unheated rooms	Reinforced brick–concrete slabs, traditional screed	1.52
	Internal slabs	Reinforced brick–concrete slabs, traditional screed	-
	Ceiling slabs	Reinforced brick–concrete slabs, traditional screed	1.61
	Load-bearing structural frames	Reinforced concrete frames	-
1976–1990	External wall	Hollow bricks (30 cm) with cavity (10 cm)	0.70
	Internal slabs in unheated rooms	Reinforced brick–concrete slabs, traditional screed	1.52
	Internal slabs	Reinforced brick–concrete slabs, traditional screed	-
	Ceiling slabs	Reinforced brick–concrete slabs, traditional screed	1.61
	Load-bearing structural frames	Reinforced concrete frames	-
1991–2005	External wall	Hollow bricks (40 cm)	1.11
	Internal slabs in unheated rooms	Reinforced brick–concrete slabs, lightweight screed	1.54
	Internal slabs	Reinforced brick–concrete slabs, lightweight screed	-
	Ceiling slabs	Reinforced brick–concrete slabs, lightweight screed	1.63
	Load-bearing structural frames	Reinforced concrete frames	-
2006–2009	External wall	Hollow bricks (30 cm)	0.96
	Internal slabs in unheated rooms	Reinforced brick–concrete slabs, lightweight screed	1.54
	Internal slabs in unheated rooms	Full slab in reinforced concrete	1.67
	Internal slabs	Reinforced brick–concrete slabs, lightweight screed	-
	Ceiling slabs	Reinforced brick–concrete slabs, lightweight screed	1.63
	Load-bearing structural frames	Reinforced concrete frames	-
2010 onward	External wall	Hollow bricks (30 cm)	0.96
	Internal slabs to unheated rooms	Reinforced brick–concrete slabs, lightweight screed	1.54
	Internal slabs to unheated rooms	Full slab in reinforced concrete	1.67
	Internal slabs	Reinforced brick–concrete slabs, lightweight screed, and gypsum plasterboard	-
	Ceiling slabs	Reinforced brick–concrete slabs, lightweight screed, and gypsum plasterboard	0.91
	Load-bearing structural frames	Reinforced concrete frames	-

Appendix B

Table A2. EoL scenarios, benefits, and loads.

Material	EoL Scenario	Values (%)	Recycling and WTE Efficiency	Substitution Ratio	Avoided Burdens
Reinforced concrete	Recycling Incineration Landfill	61.2% 0.0% 38.8%	70% for steel	1:0.25 concrete 1:1 steel	Gravel extraction for road filling. Primary production from pig iron.
Steel	Recycling Incineration Landfill	97.0% 0.0% 3.0%	81.45%	1:1	Primary production from pig iron.
Wood and massive wood	Recycling Incineration Landfill	0.0% 49.0% 51.0%	20.70% for electricity 27.20% for heat	-	Electricity from the national grid and heat production from a natural gas boiler.
Light and solid bricks	Recycling Incineration Landfill	60.0% 0.0% 40.0%	100%	1:0.11	Gravel extraction for road filling.
Stones	Recycling Incineration Landfill	60.0% 0.0% 40.0%	100%	1:1	Gravel extraction for road filling.
Polystyrene	Recycling Incineration Landfill	0.0% 100.0% 0.0%	20.70% for electricity 27.20% for heat	-	Electricity from the national grid and heat production from a natural gas boiler.
Gypsum plasterboard	Recycling Incineration Landfill	15.0% 0.0% 85.0%	-	1:1	Primary gypsum production.
Bitumen	Recycling Incineration Landfill	0.0% 50.0% 50.0%	20.70% for electricity 27.20% for heat	-	Electricity from the national grid and heat production from a natural gas boiler.
Vapor barrier in PVC	Recycling Incineration Landfill	0.0% 100.0% 0.0%	20.70% for electricity 27.20% for heat	-	Electricity from the national grid and heat production from a natural gas boiler.
Window frames in PVC	Recycling Incineration Landfill	5.4% 15.0% 74.6%	55.71% for recycling 20.70% for electricity 27.20% for heat	1:1	Primary production of PVC granulate. Electricity from the national grid and heat production from a natural gas boiler.
Window frames in wood	Recycling Incineration Landfill	0.0% 49.0% 51.0%	20.70% for electricity 27.20% for heat	-	Electricity from the national grid and heat production from a natural gas boiler.

Appendix C

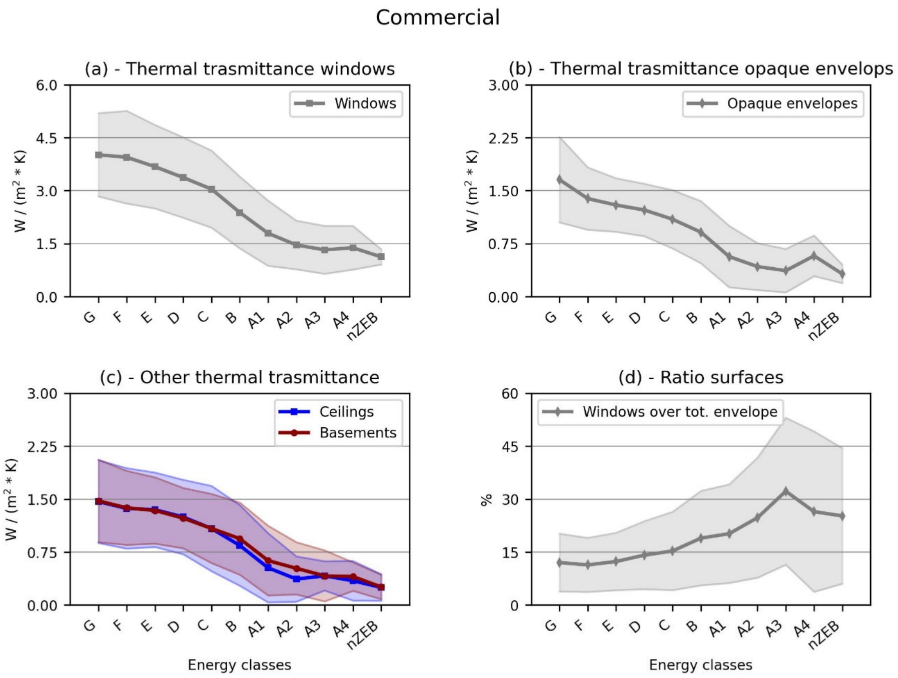

Figure A1. Commercial building units' thermal transmittances and ratio surfaces.

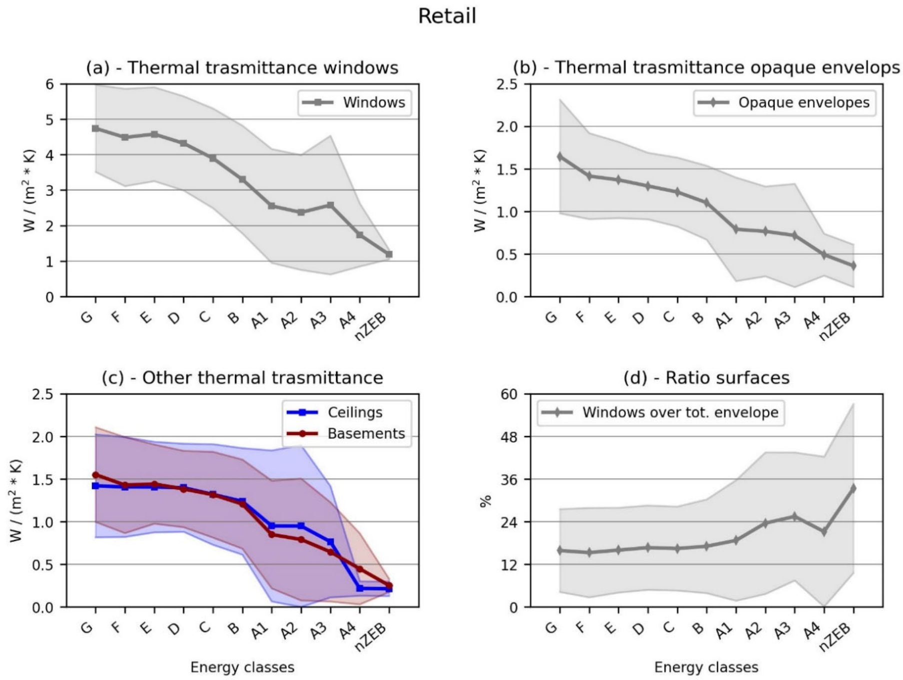

Figure A2. Retail building units' thermal transmittances and ratio surfaces.

Appendix D

The results obtained using one-at-a-time sensitivity analysis (OAT-SA), performed by changing the value of uncertain factors one-at-a-time while keeping the others constant, are shown in Figure A3. The figure shows the baselines (red color lines) and the results of the OAT-SA as bars. The analysis was carried out as follows: (i) varying the amount of reinforced concrete by moving the intercept of Equations (3) and (4) (214.68 $\pm$ 100 and 316.46 $\pm$ 100) to represent the extreme values shown in Figure 5; (ii) changing the thermal insulation from expanded polystyrene (EPS) to extruded polystyrene (XPS) (for basement and ceiling slabs and opaque envelopes) and rock wool (for opaque envelopes); and (iii) considering one window typology for values below 2.20 W/(m^2 x K), not covered by the TABULA database (Table 6). The results show that variability under 10% (in absolute terms) for Figure A3a, from 0% for rock wool thermal insulation to 8% for load-bearing structural frames (LBSF) increased. The results show greater variability for new constructions (Figure A3b), from 1% for rock wool thermal insulation to 17% for aluminum window frames (all the other values are below 10%).

The outcomes of the OAT-SA are considered consistent, being less than 10% (excluding the aluminum window frames). The authors consider high variability due to aluminum window frames to be unlikely, i.e., that aluminum window frames account for 100% of the Milan market.

Figure A3. One-at-a-time sensitivity analysis for (**a**) the entire building stock (old and new building units) and (**b**) new constructions (nearly zero energy buildings—nZEBs).

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