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Emergy analysis of building manufacturing, maintenance and use: Em-building indices to evaluate housing sustainability

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Abstract

In recent years, integrated building design practices based on the definition of "green building" criteria as common standards of measurement have been promoted. For example, Green Building Rating Systems such as LEED (US) and BREEAM (UK) provide national standards for developing high-performance sustainable buildings. However, integrated environmental accounting methods and global sustainability indicators are still required to evaluate the general environmental performances of buildings, because housing is greatly concerned with global environmental problems such as the use of non-renewable energy, the overexploitation of materials, the exhaustion of resources and the wasting of energy.

In this work, an emergy (spelled with an "m") analysis has been applied to a building to account for the main energy and material inflows to the processes of building manufacturing, maintenance and use. Building materials, technologies and structural elements have been measured and compared to each other in order to evaluate their impacts and to provide a basic calculation that may be used for evaluation and selection. A comprehensive appraisal of the building industry is then expected through a series of synthetic indices. Results represent a source of information that will also be useful for future studies on the urban and regional scale.

Keywords: Emergy analysis; Em-building indices; Housing sustainability

1. Introduction

About 30–40% of the total natural resources that are used in industrialized countries are exploited by the building industry. Almost 50% of this energy flow is used for weather conditioning (heating and cooling) in buildings. Almost 40% of the world's consumption of materials converts to the built environment, and about 30% of energy use is due to housing. For example, in the US, a rate of 35–60% of the national energy budget is used to maintain buildings (Roodman and Lenssen [1]; Stein [2]). Since 75% of the electrical supply in the US is thermoelectricity, a large amount of CO_2 emissions also depend on housing, in addition to the emissions due to building materials production. In the E.U., the energy consumption for housing and services was 371.4 Mtoe (million tons of oil equivalent) in 2000 (Eurostat [3]), which is higher than other sectors such as transport and industry.

An environmental policy for the building industry would aim to maintain a high quality of the built environment while optimizing the use of resources. Since energy consumption, energy wasting, emissions and environmental impacts due to housing are expected to increase in the next few years, an accurate monitoring and management of the building industry is urgently required.

Buildings could theoretically be conceived as thermodynamic engines that use energy to provide specific services, and that maintain their performances constant in time with respect to variable context conditions such as climate, temperature, humidity, sun irradiation, and air motion. Building management therefore refers to the energy exchanges between buildings and their living context made by human beings and the surrounding environment. In particular, material and energy inflows to the building can be calculated in order to evaluate building environmental performances, since a sustainable building is one that is able to maintain its performances constant in time, with low levels of energy and material inputs. A more detailed discussion on eco-buildings is available in the literature cited (Tzikopoulos et al. [4]; Godfaurd et al. [5]). In brief, eco-buildings have the following features:

- they make the most of energy and material inflows;
- they supply a part of their energetic need through natural processes;
- they use renewable and local materials;

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- they have minimal impact on natural cycles (i.e. water cycles);
- they belong to their environmental context (resources, landscape, society, history).

Eco-architecture represents an attempt to respond to global environmental problems and to reduce environmental impacts directly or even indirectly due to the building and housing industry, which include, for instance, the exhaustion of natural resources (for example, non-renewable resources such as oil, natural gas, and raw materials), the emission of CO_2 and other greenhouse gasses, and soil erosion.

In the last few years, new sustainable building technologies have been developed and applied to buildings in order to achieve higher energetic efficiency and to reduce energy consumption and waste. Building ecology calls for a clear and comprehensive vision of natural resource management based on the measurement of their real ‘‘environmental cost’’, which depends on their availability, regeneration rate and environmental impact (absorption of wastes), with respect to natural constraints. Some of the most recent studies on building environmental assessment are available in the literature cited (Olgyay and Herdt [6]; AboulNaga and Elsheshtawy [7]; Scheuer et al. [8]).

An ecological assessment of buildings is expected to evaluate building technologies and materials, and to define standards for making choices while taking into account the different steps of the building process ‘‘from the cradle to the grave’’, from the extraction of raw materials to their assemblage and use and even until their disposal or recycling. Integrating accounting methods and synthetic indicators are then expected to provide general information on the environmental sustainability of buildings.

2. Indicators applied to the building industry

An ‘‘indicator’’ is a tool able to give synthetic information regarding a more complex phenomenon within a wider sense; it works to make a trend or a process that is not immediately clear more visible. Indicators simplify information that is often relative to multiple factors, and enable investigators to communicate and compare results.

The calculation of indicators follows different targets according to which of the two classes is noted:

A. State-pressure environmental indicators account for specific parameters, through conventional physical units, in order to verify their compatibility with specific environmental variables; they often evaluate very localized factors based on data collected in a specific area. A first-level information is thus achieved, but this needs to be further processed in order to obtain truly synthetic information.
B. Sustainability indicators provide a general evaluation based on a comprehensive balance, integrating a multiplicity of phenomena that may even be non-homogeneous; they attempt to evaluate general behaviours from the viewpoint of global sustainability, with special reference to the problems of resource overexploitation and energy waste.

Methods for evaluating buildings are usually based on environmental state-pressure indicators. These techniques are known worldwide and developed at the national level. Some examples are the Building Research Environmental Assessment Method (BREEAM in UK) and the Leadership in Energy and Environmental Design (LEED, in the USA). These methods provide a list of indicators, based on objective values, that compare buildings’ performances and impacts to their environmental constraints, which are defined as their sustainability threshold.

Global sustainability indicators are obtained by processing data relative to different parameters (given in mass and energy units) through thermodynamics-based algorithms. Different measures can be involved in the creation of a unique synthetic balance. Some examples of these are the Emergy analysis, the Ecological footprint, and the Exergy assessment.

These methods enable the study of relationships between buildings and their environmental context, an ecosystem. A holistic approach is thus developed (the whole is more than its parts) by gathering information and providing general evaluations of buildings.

3. Introduction to the emergy analysis

Emergy analysis (spelled with an ‘‘m’’) is an environmental accounting method that develops an energy systems language for the thermodynamics of open systems (Odum and Odum [9]; Odum [10]). Emergy analysis is concerned with quantifying the relationships between human-made systems and the biosphere. When applied to a building, it quantifies all the natural resources used for building manufacturing, maintenance and use.

Emergy is the available solar energy previously used, directly and indirectly, in order to make a service or product (Odum [10–12]). The emergy evaluation assigns a value to products and services by converting them into equivalents of one form of energy, solar energy, that is used as the common denominator through which different types of resources, either energy or matter, can be measured and compared to each other. The unit for emergy is the *solar emergy joule* (sej).

The emergy of different products is assessed by multiplying mass quantities (kg) or energy quantities (J) by a transformation coefficient, namely transformity or specific emergy. Transformity is the solar emergy required, directly or indirectly, to make 1 J or kilogram of a product or service. Every time a process is evaluated, previously calculated transformities are used as a practical way of determining the emergy (sej) of commonly used products or services.

By definition, the solar emergy B_k of the flow k coming from a given process is:

$$B_k = \sum_i \mathrm{Tr}_i E_i \quad i = 1, \ldots, n \tag{1}$$

where E_i is the actual energy content of the ith independent input flow to the process and Tr_i is the solar transformity of the ith input flow.

4. Emergy analysis of buildings

In this section, a case study is presented with an emergy analysis applied to a building. A few other case studies are available in the literature cited; see for example: Brown and Buranakarn [13]; Meillaud et al. [14]; Buranakarn [15].

This case study is applied to a contemporary building with very common characteristics, in order to provide more general information that may be applied to a widespread architecture (even through a specific case study), such as that of many growing neighbourhoods and suburbs of contemporary cities in Italy and in most of southern Europe.

The building under study is a 10,000 m^3 block (2500 m^3 are underground) for residential and office use in central Italy. It is comprised of 2700 m^2 flats, distributed on a basement, a ground-floor, three upper floors and an under-roof floor. The structure consists of a reinforced concrete frame with pillars and beams. The external wrapping is formed by two side walls (adjoining blocks), two facades (brickworks with cavities), an insulated basement, and a tile roof.

Since this study on a single building with common features attempts to evaluate general impacts due to the building industry and the portion of resource exploitation relative to housing, three phases have been assessed separately: (1) building manufacturing process; (2) building maintenance; (3) building use.

In Fig. 1 an energy system diagram of a building is shown, that represents the processes and the energy and material inflows involved in a building life cycle. In this diagram the three phases above are represented with different options:

1. Building manufacturing: this is the process of gathering and assembling materials to generate a built stock (the building) that persist during an indefinite lifetime as a permanent reservoir or memory of energy once spent.
2. Building maintenance: energy and materials inflows are needed periodically in order to maintain the built stock (the building) constant in time; this means, in other words, the restoring of standard technical requirements for the building use resisting its physical entropic degradation. In terms of evolutionary physics this would be the maintaining of a steady state in open dynamic systems.
3. Building use: a rectangle in the diagram represents interactions with users that need constant energy inflows for lighting, cooking, cooling, and heating; the main inputs to this phase are given by the consumption of electricity, gas and water.

In the diagram, the interaction (the large arrow on the left) of different inputs in the building yard, such as soil, energy, machinery, human labour, materials, transport and other services, generates a built reservoir, the building (represented by the symbol of 'stock', a triangle on a semicircle) in which energy and materials have been stocked. Further energy and material inflows interact (the large arrow on the right) and converge directly on the built stock (once the building yard has been dismantled) for its maintenance during the entire building's lifetime. Maintenance resists the entropic degradation represented by the outgoing arrow down from the stock to the heat sink (down the diagram). The building use is represented in the diagram by a rectangle overlapping the built stock, and feeds on constant inflows of energy and matter such as electricity, water and gas. After use, water becomes grey and goes out of the building and into any water management system.

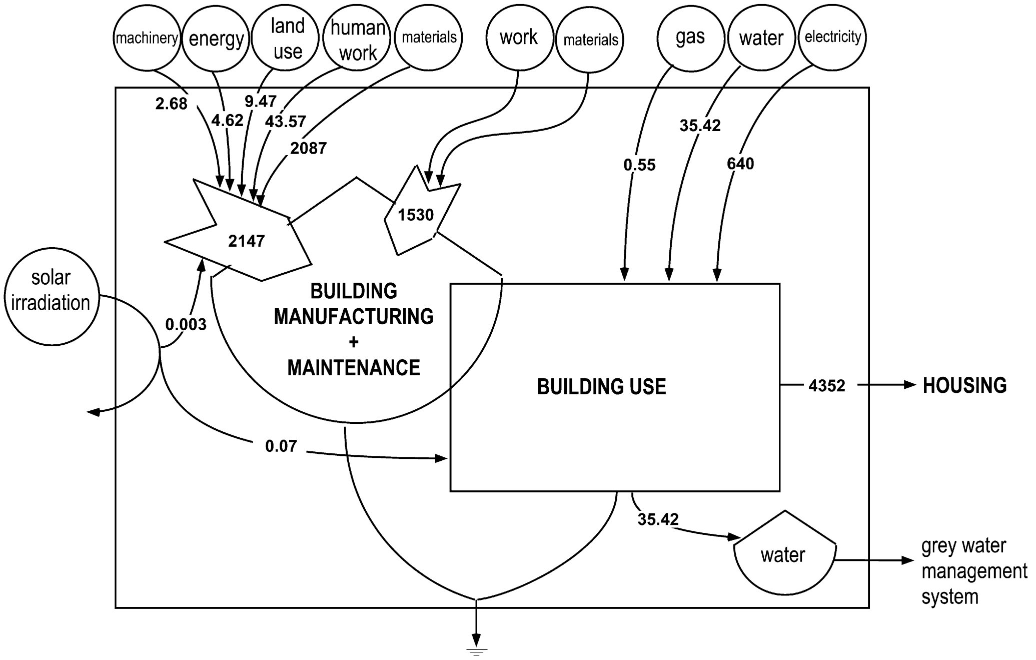

Fig. 1. The energy system diagram of a building: building manufacturing, maintenance and use (sej × 10^{14}).

Values related to each arrow are reported in the diagram in sej as a preview of the final results. A more detailed discussion investigating these values will be presented later in this paper.

All the inputs to the process are then assessed relative to the three phases above.

4.1. Emergy analysis of the building manufacturing process

An inventory of inputs to the process with relative raw data has been collected from an official document, namely the *building metric computation*, that is edited by the work director. In this document, the quantity of materials and hours of human labour (usually with their relative economic costs) are reported in a succession of steps that cover from the first to the last brick settled.

Raw data (mass quantities) in the *building metric computation* has been reported in Table 1, and has been aggregated into different structural parts; it has been processed through the relative transformities and expressed in terms of solar emergy joules. Emergy flows represent a measure of energy used in the process that could be conceived as the content of a reservoir, the building itself.

References for transformities used in the table are: a, Odum et al. (2000) [16]; b, Simoncini (2006) [17]; c, Brown and Buranakarn (2003) [13]; d, Meillaud et al. (2005) [14]; e, Odum et al. (1987) [18]; f, Odum (1996) [10]; g, Brown and Arding (1991) [19]; h, Bastianoni et al. (2005) [20]; i, Ulgiati et al. (1993) [21]. Values of specific emergy (transformities) are relative to the 15.83 baseline.

Emergy flows have been reported relative to the materials used to build each component and structural part. Other factors have also been assessed in order to achieve a comprehensive evaluation of the entire manufacturing process, such as solar irradiation (to the building yard during the complete process), soil erosion (the loss of organic matter content in the built area equivalent to an average 3% of 1 m depth ground volume), machinery, fuel and human work (*cal* of human metabolism per hour × Joules per *cal* × working hours).

In terms of emergy flows and emergy reservoir (materials), the results highlight the environmental cost relative to the different constitutive parts of the building, and assign a corresponding rate of 'energy memory':

- Groundwork and building frame cover about 41% of the whole emergy use for building manufacturing.
- External wrapping made of side walls, facades, ground-floor and roof cover 20% of the entire emergy investment.
- Floors, internal walls, pavements and other coverings cover about 35% of the total emergy use.
- Human labour covers 2% of the total emergy.
- Soil erosion is a portion of 0.44%, representing the loss of organic matter in the building ground.

Soil erosion has been assumed to be a parameter used in order to evaluate the permanent loss of biocapacity in the built-up area due to excavation and construction; an average of 3% of organic matter in the ground excavated has been considered. This portion of organic matter was calculated for 1 m deep excavation, assuming that there is not any organism under the first meter (total 6 m deep excavation). This has probably been undervalued, since the content of organic matter in the ground is variable; it can persist to a depth of more than 1 m, and can achieve 10–20% or even more in some cases. The calculation has been performed as follows:

$$\underset{\text{(ground volume)}}{(380\,\text{m}^3)} \cdot \underset{\text{(density)}}{(1,600,000\,\text{g/m}^3)} \cdot \underset{\text{(\%organic subsance)}}{(0.03)} \cdot \underset{\text{(energy content)}}{(5\,\text{kcal/g})} \cdot \underset{\text{(Joules per cal)}}{(4186\,\text{J/kcal})}$$

Human labour has been calculated as follows:

$$\underset{\text{(human metabolism)}}{(125\,\text{kcal/h})} \cdot \underset{\text{(Joules per cal)}}{(4186\,\text{J/cal})} \cdot \underset{\text{(working hours)}}{(33,584\,\text{h})}$$

Solar irradiation has been calculated as follows:

$$\underset{\text{(building area)}}{(1656\,\text{m}^2)} \cdot \underset{\text{(solar irradiation per year)}}{(5.16 \times 10^9\,\text{J/m}^2)} \cdot \underset{(1-\text{albedo})}{(1-0.2)} \cdot \underset{\text{(time for building manufacturing)}}{(2.5\,\text{years})}$$

The detailed description above based on the emergy analysis enables us to evaluate the emergy investment required for building manufacturing. Structural elements, technologies, and materials in buildings could be selected in order to decrease these values, and to therefore evaluate and direct choices in the executive project even before the actual manufacturing of the building.

4.2. Index: building emergy per volume (em-building volume)

Assuming that this case study is a likely example of a common approach to the manufacturing of contemporary buildings, emergy of building materials has been assessed for a 10,000 m^3 building and then allocated to a unit of volume. In Table 2 the emergy per m^3 and the percentage due to building materials used either in mass units and emergy units (sej) is shown. A small amount of the total emergy flow is due to human work, building yard installation and machinery, and solar irradiation.

The above results enable us to make a list of building materials based on their 'environmental cost' (in terms of sej) that depends on both their quantity and their transformity (quality). In fact, since transformity is an indicator of energy hierarchy (for a more detailed study see Brown et al., 2003 [22]) that accounts for all the inputs and transformations occurring in the production process (i.e. from raw material extraction to their final grade form), building materials have been evaluated through the emergy analysis by assessing both their environmental impact (quality) and their use in the building industry (quantity). The emergy per volume (m^3) of a building is 1.07×10^{15} sej.

Table 1
Emergy analysis of building manufacturing process

Item	Specification	Volume (m^3)	Density (kg/m^3)	Raw data	Unit	Transformity or Specific Emergy (sej/unit)	Ref.	Emergy (sej)	%
Solar irradiation	Irradiation on building yard			1.71×10^{13}	J	1.00	Def.	1.71×10^{13}	0.0002%
Land use (soil erosion)	Soil organic matter (3% of 1 m depth vol.)			3.82×10^{11}	J	1.24×10^{5}	a	4.73×10^{16}	0.44%
Groundwork								2.25×10^{18}	20.93%
Basement foundation	Concrete	68.50	2400	164400	kg	1.81×10^{12}	b	2.98×10^{17}	
Basement foundation	Steel		7850	28995	kg	6.97×10^{12}	c	2.02×10^{17}	
Lean concrete	Concrete	373.43	2400	896232	kg	1.81×10^{12}	b	1.62×10^{18}	
Lean concrete	Steel		7850	17761	kg	6.97×10^{12}	c	1.24×10^{17}	
Building frame								2.10×10^{18}	19.55%
Bearing wall	Concrete	43.82	2400	105168	kg	1.81×10^{12}	b	1.90×10^{17}	
Beams and pillars	Concrete	287.00	2400	688800	kg	1.81×10^{12}	b	1.25×10^{18}	
Armours (beams, pillars, stairs, balcony)	Steel		7850	26135	kg	6.97×10^{12}	c	1.82×10^{17}	
Overhangs	Concrete	25.58	2400	61392	kg	1.81×10^{12}	b	1.11×10^{17}	
Stairs	Concrete	30.80	2400	73920	kg	1.81×10^{12}	b	1.34×10^{17}	
Elevator box	Concrete	47.64	2400	114336	kg	1.81×10^{12}	b	2.07×10^{17}	
Elevator box	Steel		7850	3800	kg	6.97×10^{12}	c	2.65×10^{16}	
External wrapping (side walls + facades)								9.45×10^{17}	8.80%
Side wall (20 cm thick)	Lightened brick	18.38	1000	18380	kg	3.68×10^{12}	c	6.76×10^{16}	
Side wall (25 cm thick)	Lightened brick	2.00	1000	2000	kg	3.68×10^{12}	c	7.36×10^{15}	
Side walls thermal insulation	HDPE	76.56	30	2297	kg	8.85×10^{12}	c	2.03×10^{16}	
Binder (side wall 20 cm)	Mortar	0.71	1300	919	kg	3.31×10^{12}	c	3.04×10^{15}	
Binder (side wall 25 cm)	Mortar	0.06	1300	80	kg	3.31×10^{12}	c	2.65×10^{14}	
Facades (external skin)	Brick	153.12	1045	160010	kg	3.68×10^{12}	c	5.89×10^{17}	
Facades	Pierced brick	102.08	625	63800	kg	3.68×10^{12}	c	2.35×10^{17}	
Binder	Mortar	1.96	1300	2552	kg	3.31×10^{12}	c	8.45×10^{15}	
Plaster	Plaster	0.80	1	1	kg	3.29×10^{12}	d	3.82×10^{12}	
Thermal insulation	PVC	0.27	1380	374	kg	9.86×10^{12}	c	3.69×10^{15}	
Thermal insulation	HDPE	0.77	1600	1238	kg	8.85×10^{12}	c	1.10×10^{16}	
Floors								1.38×10^{18}	12.83%
Floor (24 cm thick)	Concrete	117.74	2400	282575	kg	1.81×10^{12}	b	5.12×10^{17}	
Floor (24 cm thick)	Brick			165144	kg	3.68×10^{12}	c	6.08×10^{17}	
Floor (20 cm thick)	Concrete	22.18	2400	53228	kg	1.81×10^{12}	b	9.64×10^{16}	
Floor (20 cm thick)	Brick			29501	kg	3.68×10^{12}	c	1.09×10^{17}	
Thermal insulation	HDPE	94.90	30	2847	kg	8.85×10^{12}	c	2.52×10^{16}	
Vapour barrier	PVC	2.08	1380	2873	kg	9.86×10^{12}	c	2.83×10^{16}	
Groundfloor								2.43×10^{17}	2.26%
Floor (35 cm thick)	Concrete	47.04	2400	112884	kg	1.81×10^{12}	b	2.04×10^{17}	
Thermal insulation	Exp. Polystyrene	84.66	30	2540	kg	8.85×10^{12}	c	2.25×10^{16}	
Thermal insulation	HDPE	0.83	1600	1331	kg	8.85×10^{12}	c	1.18×10^{16}	
Vapour barrier	PVC	0.29	1380	402	kg	9.86×10^{12}	c	3.96×10^{15}	
Roof								9.95×10^{17}	9.27%
Roof	Brick	240.24	1050	252252	kg	3.68×10^{12}	c	9.28×10^{17}	
Roof	Lightened brick	6.97	667	4645	kg	3.68×10^{12}	c	1.71×10^{16}	
Roof	Concrete	3.81	2400	9145	kg	1.81×10^{12}	b	1.66×10^{16}	
Electro welding net	Steel		7850	202	kg	6.97×10^{12}	c	1.41×10^{15}	
Binder	Mortar	1.54	1300	2002	kg	3.31×10^{12}	c	6.63×10^{15}	
Tile covering	Tile			6986	kg	3.68×10^{12}	c	2.57×10^{16}	
Internal walls								9.14×10^{17}	8.52%
Walls	Lightened brick	99.76	667	66507	kg	3.68×10^{12}	c	2.45×10^{17}	
Binder	Mortar	0.96	1300	1247	kg	3.31×10^{12}	c	4.13×10^{15}	
Plaster	Plaster	78.50	1450	113825	kg	3.29×10^{12}	d	3.75×10^{17}	
Paint	Paint	7.85	1450	11383	kg	2.55×10^{13}	c	2.91×10^{17}	
Pavements and coverings								1.42×10^{18}	13.24%
Thresholds	Tufa	35.60	2560	91136	kg	2.44×10^{12}	a	2.22×10^{17}	
Binder	Mortar	0.12	1500	178	kg	3.31×10^{12}	c	5.89×10^{14}	

Table 1 (*Continued*)

Item	Specification	Volume (m^3)	Density (kg/m^3)	Raw data	Unit	Transformity or Specific Emergy (sej/unit)	Ref.	Emergy (sej)	%
Cymatium	Tufa	1.44	2560	3687	kg	2.44×10^{12}	a	9.00×10^{15}	
Binder	Mortar	0.02	1500	34	kg	3.31×10^{12}	c	1.13×10^{14}	
Basement pavement	Gres	5.11	2200	11246	kg	4.80×10^{12}	c	5.40×10^{16}	
Flats	Gres	17.86	2200	39283	kg	4.80×10^{12}	c	1.89×10^{17}	
Binder	Mortar	1.92	1500	2886	kg	3.31×10^{12}	c	9.55×10^{15}	
External pavement	Fired brick	2.36	1200	2827	kg	4.80×10^{12}	c	1.36×10^{16}	
Binder	Mortar	0.17	1500	262	kg	3.31×10^{12}	c	8.66×10^{14}	
Floor rough	Concrete	69.75	800	55800	kg	1.81×10^{12}	b	1.01×10^{17}	
Binder	Mortar	96.17	2100	201959	kg	3.31×10^{12}	c	6.68×10^{17}	
Stairs	Tufa	5.43	2560	13888	kg	2.44×10^{12}	a	3.39×10^{16}	
Binder	Mortar	0.10	1500	154	kg	3.31×10^{12}	c	5.11×10^{14}	
Kitchens and bathrooms	Gres	9.46	2200	20803	kg	4.80×10^{12}	c	1.00×10^{17}	
Skirting board	Gres	1.76	2200	3876	kg	4.80×10^{12}	c	1.86×10^{16}	
Binder	Mortar	0.08	1500	117	kg	3.31×10^{12}	c	3.87×10^{14}	
Windows								4.48×10^{16}	0.42%
Flat glass	Glass	0.08	2500	201	kg	1.41×10^{12}	e	2.84×10^{14}	
Internal casing frame	Wood (fir)	1.54	600	925	kg	2.40×10^{12}	f	2.22×10^{15}	
Basement casing frame	Iron			160	kg	6.97×10^{12}	c	1.12×10^{15}	
External casing frame	Aluminium	0.24	2700	635	kg	2.13×10^{13}	c	1.35×10^{16}	
Internal casings	Wood (fir)	6.55	600	3931	kg	2.40×10^{12}	f	9.44×10^{15}	
External casings	Aluminium			851	kg	2.13×10^{13}	c	1.82×10^{16}	
Sheet-metal works								9.20×10^{16}	0.86%
Tube	Copper	0.08	8900	705	kg	1.04×10^{14}	g	7.32×10^{16}	
Sheet-metal half-tube	Copper	0.02	8900	181	kg	1.04×10^{14}	g	1.88×10^{16}	
Drainage system								5.51×10^{16}	0.51%
Biological box	Concrete	4.16	2400	9989	kg	1.81×10^{12}	b	1.81×10^{16}	
Sink	Concrete	0.46	2400	1106	kg	1.81×10^{12}	b	2.00×10^{15}	
Tube	PVC	1.55	1380	2143	kg	9.86×10^{12}	c	2.11×10^{16}	
Covering	Concrete	3.20	2400	7680	kg	1.81×10^{12}	b	1.39×10^{16}	
Building yard installation								3.65×10^{16}	0.34%
Crane (tare weight)	Steel			1922	kg	6.97×10^{12}	c	1.34×10^{16}	
Excavators (tare weight)	Set of materials							2.83×10^{13}	
	Steel (67.50%)			2070	g	6.97×10^{9}	c	1.44×10^{13}	
	Aluminium (5.80%)			178	g	2.13×10^{10}	c	3.79×10^{12}	
	Rubber (4.20%)			129	g	7.22×10^{9}	f	9.30×10^{11}	
	Plastics (7.70%)			236	g	9.86×10^{9}	c	2.33×10^{12}	
	Glass (2.90%)			89	g	1.41×10^{9}	f	1.26×10^{11}	
	Copper (1.40%)			43	g	1.04×10^{11}	g	4.46×10^{12}	
	Zinc (0.50%)			15	g	1.04×10^{11}	g	1.59×10^{12}	
	Other metals (0.90%)			28	g	6.97×10^{9}	c	1.92×10^{11}	
	Other materials (9.10%)			279	g	1.68×10^{9}	f	4.69×10^{11}	
Fuel for electricity generator	Fuel oil			2.46×10^{11}	J	9.30×10^{4}	h	2.29×10^{16}	
Fuel for excavators	Diesel			2.17×10^{9}	J	1.13×10^{5}	h	2.45×10^{14}	
Human work				1.76×10^{10}	J	1.24×10^{7}	I	2.18×10^{17}	2.03%
Total emergy for building manufacturing								1.07×10^{19}	100.00%

4.3. Index: building emergy/money ratio (em-building/money ratio)

In the *metrical computation* document edited by the legal director as introduced above, the economic costs of building manufacturing are reported in Euros. The ratio of total used emergy to money (sej/€) has been calculated as follows:

$$\underset{\text{(building emergy)}}{(1.07 \times 10^{19}\,\text{sej})} \,/\, \underset{\text{(building cost)}}{(993,300.00€)} = \underset{\text{(sej/€)}}{(1.08 \times 10^{13})}$$

This value will be used in the following section to assess the emergy flow due to building maintenance.

4.4. Emergy analysis of building maintenance

Maintenance has been assessed for those building elements that suffer with use and tend to run out, such as windows, sheet metal works, drainage systems, pavements and covering (floors and stairs), and plaster. In Table 3 the cost of their manufacturing and their lifetime is reported. A recovery cost

Table 2
Composition of a built m^3 and emergy per volume

Item	g	Emergy intensity (sej $\times 10^6$/g)	Emergy (sej $\times 10^9$/m^3)	Percentage
Concrete	263,665	1810	477,000	44.65%
Brick	75,759	3680	279,000	26.07%
Mortar	21,239	3310	70,300	6.57%
Steel	7,898	6970	55,100	5.15%
Plaster	11,383	3290	37,500	3.51%
Gres	7,521	4800	36,100	3.38%
Paint	1,138	25,500	29,100	2.72%
Decorative stone	10,871	2440	26,500	2.48%
Copper	89	104,000	9200	0.86%
Polystyrene and HDPE	1,025	8850	9080	0.85%
PVC	579	9860	5710	0.53%
Aluminium	149	21,300	3170	0.30%
Wood (fir)	486	2400	1170	0.11%
Glass	20	1410	28.4	0.003%
Human work *(in joule)	*1,757,280	*12.4	21,800	2.04%
Land use				
Lost of soil organic matter	1,824	2595	4734	0.44%
Building yard installation				
*(set of items)	–	–	3650	0.34%
Solar irradiation *(in joule)	*1,710,000,000	1.00	1.71	0.0002%
Total emergy per m^3			1.07×10^{15}	100%

has been calculated considering the annual cost of their manufacturing or total replacement (cost/lifetime). The recovery cost is the annual ordinary maintenance cost for the entire building's lifetime. The emergy/money ratio of the building has been applied to the cost of maintenance, which includes materials, human labour, machinery, and energy. Maintenance has been calculated relative to the first 50 years of the entire building's lifetime.

The emergy flow relative to the building's ordinary maintenance is equivalent to 1.53×10^{17} sej/year. The total emergy of maintenance for the first 50 years of the building lifetime is 7.65×10^{18} sej.

4.5. *Emergy analysis of building use*

An emergy assessment of building use is based on data of electricity, natural gas, and water consumption due to people living in the block. Consumption is therefore obtained through the consideration of average values of energy consumption per person in the block (which consists of 24 apartments with 58 inhabitants, and includes offices). In particular, electricity consumption is equivalent to 3230 kWh/year per apartment (this data is derived from an average electricity bill per apartment), water use is 20 L/day per person (sanitary use), and 7770 L/day is consumed for heating (the entire heating system in the block). Equivalent emergy flows have been assessed and presented separately in Table 4 for electricity, natural gas consumption, water use, and solar irradiation. Solar energy is a negligible quantity considering the irradiation on the southern façade and the roof, even if its role is very important in terms of energy saving for the building's lighting and heating. This renewable inflow of emergy likely corresponds to high emergy values that are saved because they would be otherwise provided by non-renewable sources. Water inflow is also significant, for it corresponds to an equivalent outflow of grey water. The transformity of water, furthermore, depends by almost 70% on the non-renewable resources used to build and supply aqueducts and other infrastructures from the source to the

Table 3
Emergy analysis of building maintenance

Consumed building elements	Manufacturing cost (€)	Lifetime (year)	Recovery cost (€/year)	Maintenance cost (first 50 years) (€/50 year)
Windows	42,000.00	28	1500.00	75,000.00
Sheet-metal works	3015.00	35	86.14	4307.14
Drainage system (PVC pipe)	35,350.00	40	883.75	44,187.50
Pavements and covering	73,205.00	33	2218.33	110,916.67
Plaster	142,020.00	15	9468.00	473,400.00
Total cost (€)			14,156.23	707,811.31
Total emergy (building sej/€ = 1.08×10^{13})			15.30 (sej $\times 10^{16}$/year)	765.01 (sej $\times 10^{16}$)

Table 4
Emergy analysis of building use

Building use housing	Input (unit × 10^6)	Unit	Transformity (sej/unit)	Ref.	Emergy (sej × 10^{16}/year)	Emergy per 50 years (sej × 10^{16})
Electricity	308,956.14	J/year	207,000	j	6.40	319.77
Natural gas (heating)	821.53	J/year	67,200	h	0.006	0.28
Water	182	g/year	1,950,000	k	0.35	17.71
Solar irradiation	6,836,266.08	J/year	1.00	Def.	0.0007	0.03
Total emergy for housing					6.76	337.79

building (Tiezzi et al., 2000 [24]). An energy assessment is also reported relative to a 50-year period of the building's lifetime.

References for transformities used in Table 3 are: h, Bastianoni et al. (2005) [20]; j, Odum (1992) [23]; k, Tiezzi et al. (2000) [24]. Values of specific emergy (transformities) are relative to the 15.83 baseline.

The emergy flow relative to the building use is equivalent to 6.76 × 10^{16} sej/year. The total emergy use due to housing for the first 50 years of the building's lifetime is 3.38 × 10^{18} sej.

4.6. Index: building emergy per person (em-building per person)

A new index can be calculated in order to give a measure of the environmental cost due to factors relative to the built environment per person. In the following assessment a period of 50-years has been considered as an appraisal of the entire building's lifetime. This value is assessed as follows:

$$[\underset{\text{(build. manufacturing/50years)}}{(21.47\times10^{16}\,\text{sej})} + \underset{\text{(build. maintenance)}}{(15.30\times10^{16}\,\text{sej})} + \underset{\text{(build. use)/(inhabitants)}}{(6.76\times10^{16}\,\text{sej})]/(58\,\text{persons})} = \underset{\text{(sej/pers.)}}{(7.50\times10^{15}\,\text{sej/pers.})}$$

The emergy per person (building inhabitants) is 7.50 × 10^{15} and represents the rate of emergy use of human systems relative to buildings, or specifically due to the building's use in a wider sense (including building manufacturing, maintenance and use).

5. Conclusion

The building industry is greatly concerned with environmental problems such as non-renewable materials and energy overexploitation. Housing involves chain processes that require inputs of materials and energy in different forms. An emergy synthesis has been applied to three phases, namely building manufacturing, maintenance, and use, in order to give a measure of the environmental impact due to buildings and, more in general, to the built environment. Results show the emergy content of a building conceived as a man-made emergy reservoir and the emergy flows for building maintenance and use.

- The emergy inflow to the building manufacturing process is 1.07 × 10^{19} sej. This value represents the emergy content in a built reservoir (the building) that persists during the building's entire lifetime (a building's lifetime is indefinitely long). Assuming a lifetime of 50 years, building manufacturing corresponds to 21.47 × 10^{16} sej/year.
- The annual emergy inflow due to the building maintenance is 15.30 × 10^{16} sej/year; this represents the emergy inflow to maintain the emergy content in the built reservoir constant in time, resisting its entropic degradation.
- The annual emergy inflow due to the building use is 6.76 × 10^{16} sej/year, which is equivalent to the electricity, gas, and water consumption of the building's inhabitants, besides solar irradiation, which is not relevant on its own, but is related in terms of energy saved for lighting and heating.
- In a final balance, Housing is equivalent to an emergy flow of 43.52 × 10^{16} sej/year due to building manufacturing (49%, considering a building's lifetime of 50 years), maintenance (35%) and use (15%).

Emergy-based indices specific for buildings have also been presented.

- Building emergy per volume is equivalent to 1.07 × 10^{12} sej/m^3.
- Building emergy/money ratio is 1.08 × 10^{13} sej/€.
- Building emergy per person (building inhabitant) is 7.50 × 10^{15} sej/person.

Referring back to Fig. 1, emergy values reported in the energy system diagram refer to emergy inflows per year for the processes of building manufacturing, maintenance and use for the presented case study, a building block with a reinforced concrete frame and brick walls. This case study appears to have many common characteristics, and has been chosen in order to provide general information on buildings as they have been constructed for the last 20 years in contemporary urban neighbourhoods of Italy and southern Europe.

A detailed appraisal has been provided specifically for the building's structural parts (basement, frame, floors, external wrapping, internal systems, windows, etc.), in order to evaluate the environmental concern of different processes, as well as for building materials. In particular, the *em-building volume* refers to the emergy content of a built m^3 considering quantity of building materials (mass) and their environmental cost (specific emergy).

Besides quantity (mass) and quality (specific emergy) of building materials, the emergy analysis of a building highlights how the durability of materials (lifetime) is also an important factor for sustainability, since a longer building lifetime (even considering ordinary maintenance) corresponds to lower emergy inflows per year for building manufacturing; a building is like a full emergy reservoir that persists in time.

Moreover, these outcomes provide a basis for future evaluations in the field of the building industry. Different building typologies, technologies and materials can be compared and contrasted with reference to different manufacturing processes, as well as to maintenance and use (a material's durability, thermal efficiency and energy consumption during its lifetime). For example, different scenarios can be compared considering the emergy investment for manufacturing a special façade with an augmented thermal insulation or a passive ventilation system and its effects in terms of energy saving (reduced thermal dissipation) in the phases of building maintenance (a material's durability) and building use (energy for cooling and heating). Also, different building types can be compared through the indices of emergy per volume (referring to the building technology) and emergy per person (i.e. number of inhabitants, population density). Furthermore, these em-building indices for different building types can be applied at the territorial level, giving a measure of the environmental impacts due to a whole urban setting. For example, emergy investments (for building manufacturing) and emergy inflows (for building maintenance and use) can be measured for a neighbourhood composed of common housing and compared to a neighbourhood of energy efficient eco-buildings with low environmental impacts (see, for example, the *BedZED—Beddington Zero Energy Development* Project in the London Borough of Sutton).

Environmental accounting methods and sustainability indicators, such as the emergy analysis, are powerful tools for evaluating housing and the building industry, providing measurements and information on building technologies and their environmental impacts. This research provides a reference work for monitoring and making choices towards sustainability.

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