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RESEARCH COMMUNICATION

A THERMODYNAMICS-BASED MEASUREMENT OF ENVIRONMENTAL RESOURCE USE IN BUILDINGS AND CULTURAL HERITAGE

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ABSTRACT

This paper presents a theoretical thermodynamics-based viewpoint on buildings that is synthetically explained through an energy systems diagram. Considering that buildings, and also historical buildings, can be conceived in terms of energy and material flows and stocks, we discussed here two methods for assessing environmental resource use due to building construction, maintenance and use. In a sustainability framework, outcomes provide information about some common activities and practices related to buildings and housing – such as planning practices based on physical limits to the construction of new buildings or more practical activities of restoration of existing buildings, including cultural heritage – in terms of energy, emergy and ecological footprint. A new research is thus needed in order to stimulate good practices such as conservation of historical buildings and the definition of new thermodynamics-based urban indexes for regulating building construction in contemporary cities.

Keywords: construction, ecological footprint, embodied energy, emergy evaluation, global warming potential, historical buildings, maintenance.

1 INTRODUCTION

When Le Corbusier composed the *modulor* in the 1950s, he wanted 'to find the ideal proportions that would enable designers to keep the human scale in mind in the age of machines'. He was looking for the consonances existing between ourselves and our environment since, as he said, 'we are more likely to choose the best measurements if we can see them, appraise them with outstretched hands, not merely imagine them'.[1]

In the age of machines, Le Corbusier proposed the solution to a need of the time, namely to render uniform the use of space and the new accessories that technology offered in the realm of housing. The aim was to offer performance that met the needs of every function, attempting to solve the main problem (efficiency and optimization of space and operating times) for production as well as use of goods. His proposal consisted in identifying the relations between human activities and the context in which they were exercised, by defining *proportions and consonances*.

Whatever we call the age of today (post-industrial, electronic or the age of globalization), the problems have certainly changed. However, they still concern the *proportions* and *consonances* between human activity and the setting in which it occurs, albeit in a broader sense. Indeed, we have to consider the movements of our daily lives and evaluate their effects on the environment, i.e. the source of resources and the receptacle of wastes. If in Le Courbusier's day it was necessary to find a common procedure for designing efficient living space, today it is necessary to coordinate efforts towards rational use of energy and environmental resources in order to reconcile human activities and natural cycles, resource withdrawal rates and rates of regeneration: two problems (that of Le Courbusier and our problem today) with different terms but a common conceptual matrix [2]. The same principle holds for both, the principle according to which *we are more likely to choose the best measurements if we can see them, appraise them with outstretched hands, not merely imagine them* [1].

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1 A THERMODYNAMICS-BASED REPRESENTATION OF BUILDINGS

To know the relations between humans and the built or natural environment, it is necessary to find a functional scheme and try to see and measure it [2]. According to Howard Odum's theory [3, 4], energy systems diagrams can be drawn in order to visualize relations existing between flows and stocks of energy.

By this approach, we can make a diagram of the processes of construction, maintenance and use of a building and quantify them. In this way, we derive a more complete interpretation of architecture and we can then extend our thought to historical buildings and cultural heritage.

A building is an artificial stock of resources coming directly or indirectly from the environment. Construction of a building requires intensive use of materials and energy, i.e. flows that form a permanent stock. In other words, in the phase of construction, flows of energy and matter converge on the site where they are used to make order, to give form to a structure, to assemble parts. In Fig. 1, the building is represented by the tank symbol to indicate a stock of resources that persists in time. Construction, when materials are assembled by exploiting energy, is indicated by the interaction symbol. The flows involved in construction indicate an initial investment of natural capital that persists during the entire lifetime of the building.

Historical buildings are like stocks that were maintained for a long run and their long life made their construction a very profit-bearing deal (in terms of an initial investment of environmental resources) since the initial investment was enough amortized over time.

The second interaction symbol represents maintenance of the building that absorbs a certain quantity of flows each year. The flows may be discontinuous, according to necessity. The resources used in this stage are needed to prevent entropic degradation of the building. In theory, the input to the tank compensates the output flow (arrow to heat sink) and maintains the quality and functionality of structural organization. Without this input, the building would fall to ruin, which amounts to an increase in entropy. This spontaneous process by which order degenerates into disorder is described in the second law of thermodynamics and is evident in buildings abandoned.

Use of the building also calls for resources. Other flows, such as water, electricity and natural gas, obtained by connection to various networks, sustain the activity carried on inside, without considering food, clothes, furniture, books, appliances and so forth.

2 ENERGY AND MATERIAL FLOW AND STOCK ASSESSMENT

In a recent study [5], researchers at the University of Siena did an emergy analysis of the construction, maintenance and use of a four-storey residential building. The most common current building

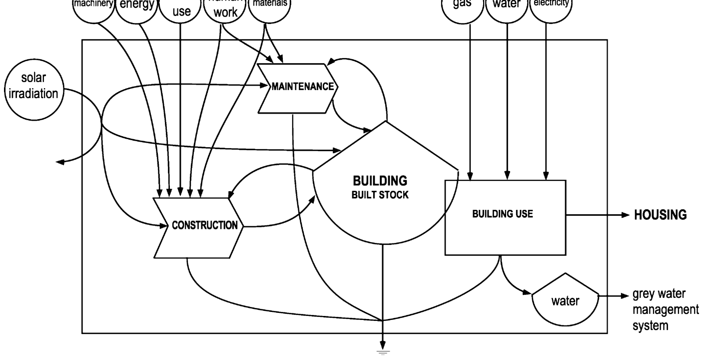

Figure 1: Emergy diagram of the construction, maintenance and use of a building.

methods in Europe were considered: foundations and frame in reinforced concrete, floors in brick and concrete, walls in hollow bricks, exterior in stone and aluminium windows.

The emergy use for the construction of a building of this type was expressed per cubic metre and corresponds to 1.07×10^{15} sej/m^3. This value included all the flows of materials and energy needed for construction. Foundations and frame took 41% of this quantity, the walls, ground floor and roof took 20% and the other floors and internal work and finishing 35%.

The percentage of emergy attributed to materials was also calculated and expressed per cubic metre of building. Every material has a specific emergy (in sej/kg), an intrinsic quantity that expresses its environmental weight. For example, 1 kg of cement has an emergy of 3.04×10^{12} sej [6], while specific emergy of concrete corresponds to 1.81×10^{12} sej, aluminium to 21.3×10^{12} sej, bricks to 3.68×10^{12} sej and wood to 2.4×10^{12} sej. The quantity of materials used for construction is another essential aspect for emergy analysis since sustainability analysis is based on extensive quantities [7]. In the case of modern buildings, the most widely used material is concrete. In a cubic metre of building, there is about 260 kg of concrete, 76 kg of bricks/tiles, 21 kg of mortar, 11 kg of plaster, 10 kg of stone, 8 kg of steel and about 10 kg of other materials. In terms of emergy, the concrete amounts to 4.8×10^{14} sej/m^3 (about 45% of the total), bricks/tiles 2.8×10^{14} sej/m^3 (about 26%), mortar and plaster 1.1×10^{14} sej/m^3 (about 10%), steel 5.5×10^{13} sej/m^3 (5%), stone 6.3×10^{13} sej/m^3 (6%) and paint 2.9×10^{13} sej/m^3 (3%). Human work accounts for 2.2×10^{13} sej/m^3 (about 2%), land use 4.7×10^{12} sej/m^3 (0.5%) and setting up the building site 3.6×10^{12} sej/m^3 (0.4%).

Emergy assessment extended to the subsequent phases of maintenance and use of buildings has also shown that the emergy equivalent of resources used per year is 15.3×10^{16} sej and 6.76×10^{16} sej, respectively.

In the overall balance, housing is sustained by an emergy flow of 43.52×10^{16} sej/year (assuming a mean building life of 50 years), 49% of which is invested in construction, 35% in maintenance and 15% in use.

About historical buildings, we know that the longer the life of a building, the lower the percentage ascribed to construction. This makes conservation of buildings a bargain, from a sustainability point of view.

Similarly, ecological footprint due to the appropriation of ecosystem resources and services in the construction of a building was calculated [8]. In particular, the calculation of ecological footprint was indirectly obtained by assessing the embodied energy of each material and the corresponding carbon dioxide emission through a standard global warming potential. Then the ecological footprint was assessed considering global area needed for absorbing the total CO_2 emission due to building construction.

Since the ecological footprint calculates the area of ecosystems committed to construction of the building with respect to area occupied by the building, here we apply this methodology to the above case study and we found that a four-storey residential building with a floor plan of 160m^2 has a footprint of about 9400 global m^2 (gm^2) per year, calculated considering the mean life of the various materials (that means including maintenance) as in Table 1.

The building's footprint indicates the area occupied indirectly for its construction and maintenance, i.e. the area of land necessary to produce the goods and services needed for construction and substitution (since it considers the materials life span). Similarly, we assessed the ecological footprint due to building use as in Table 2.

This information could be used to develop a new index. The definition of new standards based on sustainability indicators that consider consumption of natural resources could regulate city expansion by posing a physical limit to its footprint. For example, a building constructed using low impact techniques would have a lower footprint and could be incentivated by permitting larger volumes. Buildings with high footprints could be penalized by volume limits [2].

Table 1: Ecological footprint of building construction and maintenance.

Material	g/m^3	Embodied energy (MJ/kg)	ENergy (MJ/m^3)	Life span	Energy (kW h/year)	Emission (t CO_2)	Energy land (gm^2)	Forest (gm^2)	Built up areas (gm^2)	Total footprint (gm^2/m^3)	Footprint (%)
Concrete	263,665	1.2	316.40	75	1.17	5.62×10^{-4}	1.52	–	–	1.52	15.91
Brick	75,759	2.7	204.55	75	0.76	3.64×10^{-4}	0.99	–	–	0.99	10.29
Mortar	21,239	0.1	2.12	75	0.01	3.78×10^{-6}	0.01	–	–	0.01	0.11
Steel	7,898	32.0	252.72	75	0.94	4.49×10^{-4}	1.22	–	–	1.22	12.71
Plaster	11,383	7.8	88.78	25	0.99	4.74×10^{-4}	1.28	–	–	1.28	13.39
Gres (and similar)	7,521	18.9	142.14	75	0.53	2.53×10^{-4}	0.68	–	–	0.68	7.15
Paint	1,138	60.2	68.52	15	1.27	6.09×10^{-4}	1.65	–	–	1.65	17.23
Decorative stone	10,871	18.9	205.46	75	0.76	3.65×10^{-4}	0.99	–	–	0.99	10.33
Copper	89	71.6	6.34	20	0.09	4.23×10^{-5}	0.11	–	–	0.11	1.20
Polystyrene	1,025	94.4	96.79	75	0.36	1.72×10^{-4}	0.47	–	–	0.47	4.87
PVC	579	70.0	40.54	75	0.15	7.21×10^{-05}	0.20	–	–	0.20	2.04
Aluminium	149	191.0	28.38	75	0.11	5.05×10^{-05}	0.14	–	–	0.14	1.43
Wood-cork	486	10.8	5.24	25	0.06	2.80×10^{-05}	–	0.08	–	0.08	0.79
Glass	20	6.8	0.14	75	0.00	2.43×10^{-07}	0.00	–	–	0.001	0.01
Soil erosion	1,824	–	3.82	75	0.01	6.79×10^{-06}	0.02	–	–	0.02	0.19
Energy	J/m^3	–	MJ/m^3	–	–	–	–	–	–	–	–
Human work	1,760,000	–	1.76	75	0.01	3.13×10^{-6}	0.01	–	–	0.01	0.09
Building yard	24,600,000	–	24.60	75	0.09	4.37×10^{-5}	0.12	–	–	0.12	1.24
Land	m^2	–	–	–	–	–	–	–	–	–	–
–	0.036	–	–	–	–	–	–	–	0.10	0.10	1.05
–	–	–	–	–	–	–	–	–	–	–	–
Total	–	–	–	–	–	–	–	–	–	9.58	–

Table 2: Ecological footprint of building use.

Building use housing (m^3)	Consumption	Unit	Energy land (gm^2)	Footprint (%)
Electric energy	9	KW h/year	11	98.30
Gas (heating)	0.002	m^3/year	0.01	0.10
Water	0.18	m^3/year	0.18	1.60
Total	–	–	11.36	–

3 CONCLUSION

A building is itself a resource. Its representation as a stock suggests that the building can be treated as a reserve of non-renewable resources. Non-renewability is deduced from the use of non-renewable construction materials, such as concrete and brick, including the fuels burnt to make them, and stone, including the energy needed to extract it. In these cases, the natural regeneration times (sedimentary cycles) are infinitely long compared to extraction times. Moreover, current practices were not conceived to recycle or dismantle and re-use parts of buildings at the end of their lives.

The idea that a building is a reserve of invested natural capital that can be maintained in time is an important conceptual novelty. Maintenance and restoration, changes in use, modifications and additions are ways of conserving and renewing the function of a building, in the sense of structure and urban function. In the case of restoration of an historical building or a disused building, a moderate quantity of energy and materials is theoretically invested to reactivate a non-depleted resource that can continue to be exploited. In a future perspective, it is possible to consider any building already existing in a potentially renewable resource that can be conserved indefinitely.

This also emerged from our calculations: the conservation of a building is a bargain from a sustainability viewpoint.

Furthermore, traditional planning control is based on the definition of limits. These are generally established on the basis of formal criteria, such as fractions of allotments that can be built on, number of storeys or proportions related to land zoning type. This research set out to measure human impact on the environment in a tangible way, through emergy, the ecological footprint or other indicators. The need to do this felt by modern architecture remains a priority among contemporary needs and problems, as it was for Le Corbusier, albeit in a new form.

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