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Life cycle environmental assessment of temporary building constructions

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Abstract

The paper analyses the impact of embodied energy over a building's life cycle as an important factor in construction planning, particularly for temporary structures. In fact, a choice of low-embodied energy construction materials, technological components, and construction systems is essential to guarantee a very high-energy performance of those constructions. Temporary buildings are exempted from the application of the minimum requirements to reduce energy in use as set by the European directive 2010/31/EU due to their short expected service life. Hence, it becomes even more important to consider the impact of their embodied energy and the one of their end of life. Results from a case study, a temporary building designed for Milan Expo 2015, are presented to compare embodied energy of construction materials, including scenarios for their end-of-life, and predicted energy consumption at use stage.

Keywords: eco-efficient temporary buildings; low-impact materials; life cycle assessment; embodied energy; service life.

1. Introduction

The paper is focused on the issue of sustainable construction with respect to expected service life of a building. The building sector is a large energy consumer and carbon releaser responsible for almost 40% of Europe's total energy consumption and carbon emissions [1]. Estimates of energy performance of a building during its life cycle

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include the amount of energy needed for heating, cooling, ventilation, hot water and lighting as well as the embodied energy of construction materials [2]. In this perspective, building expected service life must be taken into account since the earlier design phases.

Very often designers ignore the expected duration of the buildings they are designing while it can be very impactful on the environment and on the cost-effectiveness of construction. As a matter of fact, the relative impact of up-to-gate phases of the life cycle of a building is as much higher than the one of use phases as shorter is its service life. For example, the life cycle impact of a residential building, usually 80 years, it is very different from the one of a temporary structure, which has a very short service life. In the former, the largest impact (up to 90% of the total) is due to operational actions during the use phase, while in the latter the up-to-gate phases (raw material extraction, pre-industrial processing, manufacturing, and delivery to the construction field) have a much higher contribution (even more than 50%). The properties of a material such as weight, durability, cost, thermal performance, embodied energy, air emission, must therefore be taken into account in relation to the function of the building but also to its expected service life. In addition, at the design stage, an accurate LCA, particularly for short service life buildings, can reduce the uncertainty associated to the definition of future scenarios associated to the operational and end-of-life phases.

1.1. Temporary structures

In the last decade, the demand for temporary structures is expanding because of the growing of world events, artistic and sport programmes, festival, fairs, etc. [3]. These buildings had to respond to sustainable design rules in term of flexibility, speed of execution and low budgets. At the same time, they must fit the architecture point of view and satisfy thermal, acoustic and other performances to guarantee high level of climate comfort. Many times, there are some limits to achieve good results (no thermal and acoustic insulation, use of multifunctional structure not suitable for a special function, etc.). Since temporary buildings are exempted from the application of minimum requirements to reduce energy in use as set by the European directive 2010/31/EU due to their short expected service life, it becomes even more important to consider the impact of their embodied energy and the one of their end of life.

The case study is a temporary building designed for Milan Expo 2015 with a design expected life spanning from 1 to 20 years. Here, building technologies were selected using the Embodied Energy method combined with the 50:50 method in accordance with ICE database developed by the University of Bath [4, 5] in order to evaluate both the impact of energy consumption and the recycling potential of building components in relation to the building life cycle. Furthermore, the impacts of pre-use/end-use stages are compared to energy consumption for HVAC in the operational stage. Results show that the expected service life of the building is an assessment key point: using kWh/m^2 year as a functional unit, construction/end-of-life impacts can be normalised to the expected service life allowing for assessing the environmental impact of several life cycle scenarios.

2. Life cycle environmental assessment of a temporary building design for EXPO 2015

2.1. Short description of the case study

The company Expo 2015 S.p.a. launched a design competition for the services buildings in support of the Milan 2005 world exhibition. Main objective of the competition was to get innovative, sustainable and high architectural quality design proposals. In particularly, competitors had to consider the following design strategies to reach sustainability:

- speed and ease of construction;
- low environmental impact of construction materials;
- low energy requirements during operation;
- innovation.

The case study reported in this paper is one of the temporary building modules included in a proposal submitted to the design competition (fig. 1). It is a two-storey structure of 16.038 m^3 net volume and 4.860 m^2 of net floor area. It comprises several functional spaces: commercial, restaurant and bar, visitor services including info-point and toilets. Construction characteristics are high-speed assembling and flexible prefabrication, use of low environmental impact materials, HVAC systems integrated with passive cooling techniques. Except for the reinforced concrete foundations, building components use materials based on renewable resources (mainly wood) and recycling processes; the former representing 32% of total embodied energy and the latter leading to a 60% reduction of total embodied energy as compared to the use of virgin materials or components potentially not recyclable.

Regarding operation phase, the predicted use of the module is from May through September; hence, the largest amount of energy consumption is related to air conditioning and was calculated to be 127.662 kWh, considering the contribution of passive techniques such as ventilative cooling and earth-to-air heat exchangers. This corresponds to a delivered energy intensity of 7.96 kWh/m^3-year or 26.27 kWh/m^2-year.

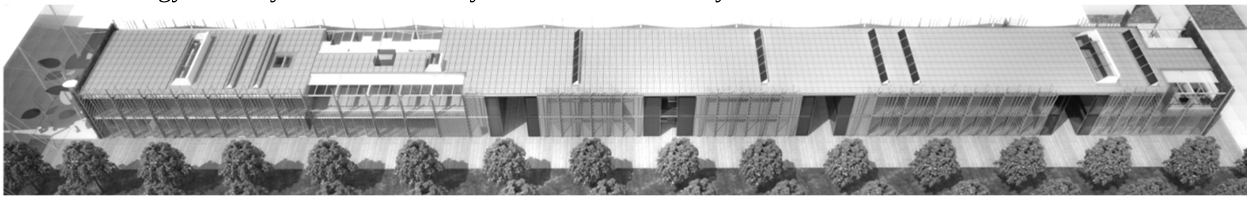


Figure 1. 3-D aerial simulated view of the case study building module.

2.2. Embodied Energy calculation method

The “cradle-to-gate” energy impact assessment related to foundations, structure and envelope of the building is based on the Embodied Energy calculation method. Embodied Energy (*EE*) is the quantity of energy required to process buildings materials, as a sum of the energy consumed over the material supply chain. *EE* includes raw material extraction and supply to the plant site and processing and is calculated through the following equation:

$$EE = E_{ind} + E_{dir} \tag{1}$$

where:

EE = embodied energy [MJ]

E_{dir} = direct energy consumption of the manufacture material process

E_{ind} = indirect energy, the sum of energy required to manufacture feedstock materials and energy required to manufacture machines

Considering the temporary use of the building, and a great possibility of reusing and recovering the entire building or part of it, *EE* is recalculated introducing both the recycled content of initial material and the benefit for recyclability. The method applied for calculating *EE* including recycling ($EE_{recycle}$), called 50:50, represents a logical choice [6] as it presents the results as a single value, yet comparable to the operational energy in the first design phase, and it can accommodate sustainability complex needs [5, 7].

The functional unit is 1 square meter of gross floor area of the building. Its service life is 1 year, but considering the hypothesis of reuse, the expected service life of some building components raises to 10, 15 or 20 years.

The life cycle environmental assessment of the building has followed the steps below:

1. Analysis of physical and dimensional characteristics (area, thickness, volume, density, mass) of materials constituting layers and functional parts of building components types such as bearing structure, opaque envelop, and partitions , which have a significant impact in terms of area and/or specific weight.
2. Evaluation of total Embodied Energy (EE_{TOT}) and the fraction derived from renewable sources (EE_{FR}) for each material identified in the first step. For calculating EE_{TOT} and EE_{FR} the Boustead Model European database was used.
3. Addition of the recycled content and the recyclability potential of single materials/elements of step 1 to the total Embodied Energy ($EE_{TOTrecycle}$). This calculation was performed using the method called 50:50 [5], which allocates half of the benefits of using recycled materials (pre-cycle) and half of the benefits of creating recycled materials (post-cycle), according to the following equation:

$$EE_{recycle} = 0.5(1-R)EE_V + 0.5R*EE_R + 0.5r*EE_R + 0.5(1-r)EE_V + (1-r)EE_D \quad (2)$$

where:
R = Recycled content
R = Recyclability potential
EE_{recycle} = embodied impacts, per unit of material
EE_R = embodied impacts arising from recycled material input, per unit of material
EE_V = embodied impacts arising from virgin material input, per unit of material
EE_D = embodied impacts arising from disposal of waste material, per unit of material

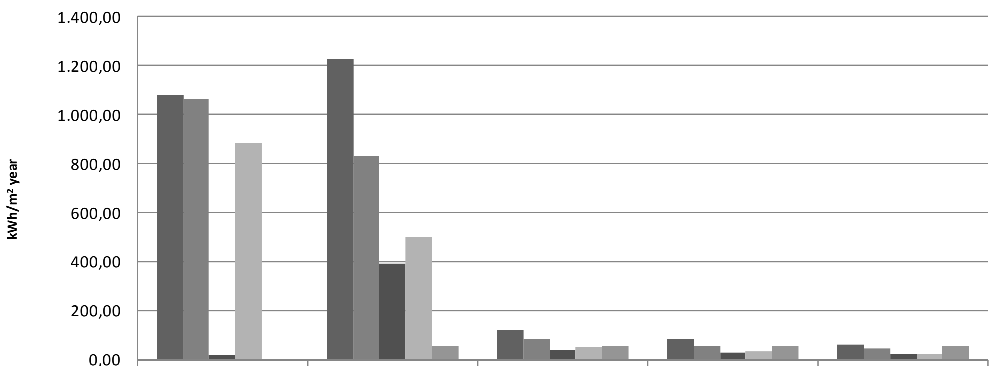
4. Parameterisation of calculation results with respect to:
- net floor area of the building (NFA = 4860 m^2);
- different hypotheses of expected service life (*SL*) of the elements constituting the above-grade level components, in relation to disassembly, recovering and recycle (*SL* = 10, 15 and 20 years).

2.3. Results

Table 1 shows the results of step 1, 2 and 3. Firstly, the mass of each building component is combined with its energy content (MJ/Kg) to evaluate the EE_{TOT} and its renewable part (EE_{RR}). The five columns under $EE_{TOTrecycle}$ show data drawn from application of equation (2).

In order to enhance the transparency of the impacts assessment, the results are been converted from MJ into kWh and normalised to the net floor area as indicated in step 4. Finally, the Embodied Energy was compared to the operational energy (*OE*) for HVAC, converted into primary energy by applying a conversion factor of 2.18.

Figure 2 reports four service life scenarios and the related annual energy intensity (kWh/m^2-year). Although the embodied energy of building components remains significantly high per unit of surface area in relation to the time-limited predicted use of the building (1 year), it can be drastically reduced depending on the extended number of years of their expected service life outside the boundary conditions of this project. The *EE* intensity (kWh/m^2-year) – total (EE_{TOT}), non renewable (EE_{RNR}), renewable (EE_{RR}), and recycle ($EE_{TOTrecycle}$) – over a perspective building components life cycle was calculated in relation to four service life scenarios and compared to operation energy ($OE_{cooling}$) which is only related to cooling and is kept constant over the years (Figure 2).



	basement (SL = 1 year)	upper-ground level (SL = 1 year)	upper-ground level (SL = 10 years)	upper-ground level (SL = 15 years)	upper-ground level (SL = 20 years)
EE TOT	1.077,10	1.222,78	122,28	81,52	61,14
EE RNR	1.061,33	832,34	83,23	55,49	41,62
EE RR	15,78	390,43	39,04	26,03	19,52
EE TOTrecycle	882,15	496,56	49,66	33,10	24,83
OE cooling	0,00	57,27	57,27	57,27	57,27

Figure 2. Embodied Energy and Operational Energy of the case study building over installation and four service life scenarios

Table 1. Embodied Energy of the case study building).

Building parts	**Building components**	**Material**	**Mass**	**EE_{TOT}**		**EE_{RR}**	**$EE_{TOTrecycle}$**				
			kg	**MJ/kg**	**MJ**	**MJ**	**R**	**r**	**EE_V (MJ)**	**EE_R (MJ)**	**$EE_{recycle}$ (MJ)**
horizontal structure	foundation	reinforced concrete	3390480	2,75	9323820	135619	10%	10%	8391438	839144	7636209
	slab	reinforced concrete	2079000	2,07	4303530	64449	10%	10%	3873177	387318	3524591
	screed	concrete	930978	0,75	698233	10241	10%	10%	628410	62841	571853
	beams	glued laminated timber	136180	12	1634160	1029521	20%	90%	1307328	261466	732104
vertical structure	prefabricated load-bearing wall	reinforced concrete	1643420	2,75	4519405	65737	10%	10%	4067465	406746	3701393
	posts	steel	122490	13,1	1604628	116366	80%	90%	320926	256741	266368
roof	top plates	solid wood	7902	10,4	82181	51758	50%	95%	41090	20545	26195
	wooden slab	solid wood	159192	10,4	1655597	1042708	50%	95%	827798	413899	527721
	pallet cladding	hardwood	27783	10,4	288943	181979	50%	95%	144472	72236	92101
	waterproofing	PVC	5350,8	67,71	362303	7223	30%	80%	253612	76084	155971
	sub-structure	*Populous* wood	414032	10	4140320	2608401	40%	50%	2484192	993677	1813460
external walls	external panel	polycarbonate	49349	112,9	5571480	167292	30%	95%	3900036	1170011	2193770
	insulation layer	glass wool	2352	28	65856	1559	20%	20%	52685	10537	44255
	wooden layer	OSB	5049	14,5	73204	46119	30%	70%	51243	15373	33308
	internal panel	plasterboard	11540	6,75	77892	39142	30%	70%	54525	16357	35441
	solar shading (slats)	hardwood	7336	10	73360	462177	50%	80%	36680	18340	24759
	solar shading (frame)	aluminum	9904	84,89	840717	177473	90%	90%	84072	75664	76505
internal parts	core slab	solid wood	146889	10,4	1527646	962123	50%	95%	763823	381911	486937
	fooring	polyester, granite and sand conglomerate	164080	15	2461200	32324	20%	20%	1968960	393792	1653926
		glazed tiles	18704	11	205744	2712	10%	10%	185170	18517	168504
		larch deck	29522	10,4	307027	193368	50%	95%	153513	76757	97865
	partition wall	plasterboard	30976	6,75	209089	105071	30%	70%	146362	43909	95135
		fiber cement	14832	12,85	190591	5933	10%	10%	171532	17153	156094
	doors	softwood	1499	14,5	21741	13697	50%	80%	10871	5435	7338
TOTAL					**40.238.667**	**7.107.032**					**24.121.805**

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The relative incidence of EE_{TOT} intensity on the overall life cycle energy balance ($EE + OE$) over the four service life scenarios is: 96% for SL 1; 68% for SL 10, 59% for SL 15, and 52% for SL 20 (Figure 3). The same figure for $EE_{recycle}$ is: 90% for SL 1, 45% for SL 37% for SL 15, and 30% for SL 20. The percentage values reported in Fig. 3 include only Embodied Energy related to the building above-grade level. Energy needs for foundations are excluded since they are site-specific and, therefore, have to be recalculated in the case of disassembly and reuse of the above-grade part in another place. In addition, operation energy does not apply for foundations.

Assumption is made that operational energy for HVAC is constant over the expected building service life. Hence, paying attention to embodied energy of material becomes as more important as the end-use energy decreases.

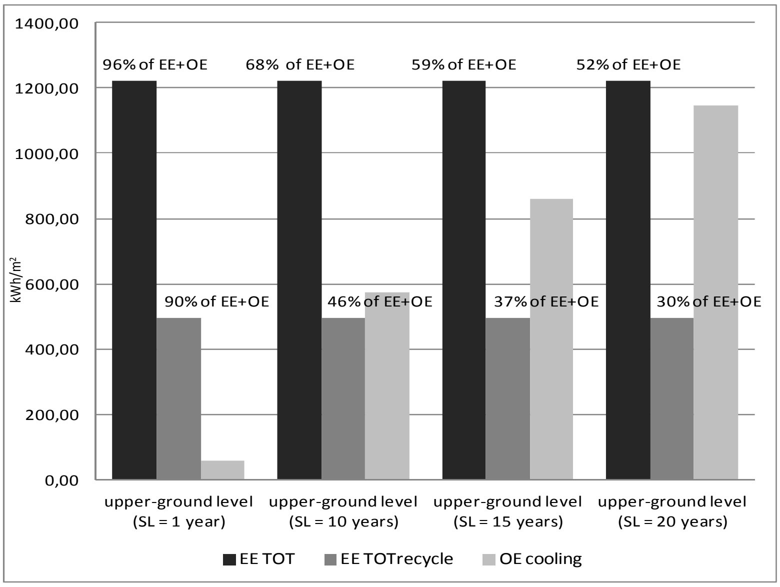

Figure 3. Incidence of EE_{TOT} and $EE_{TOT\ recycled}$ intensity on the overall life cycle energy balance in four building service life scenarios.

3. Conclusions

The study's results show that assessment of Embodied Energy is an essential part of the overall energy balance evaluation of a building over its service life, and its relative incidence is as higher as shorter is the service life of the considered building and/or as lower the predicted energy consumption for building operation. Hence, the importance of assessing Embodied Energy since the early design phase is particularly strong for temporary pre-fabricated structure as well as high energy efficient and low environmental impact buildings such the ones that are expected after 2020 in application of EPBD/2010/31/EU. Efforts should be made, therefore, to enhance the availability and accuracy of EE data, possibly through a European-validated data bank.

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