Sustainability assessment of an energy efficient optimized solution

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ABSTRACT

In order to overcome the increasing energy demand in buildings and related environmental problems, new efficient energy technologies and new integrated building concepts, like solar passive and mixed-weighted thermal mass buildings, are being developed. The energy efficiency should not be the only parameter to consider in high-performance building design. Other parameters related to the three dimensions of the Sustainable Development (environment, economy and society) should also be considered, in order to obtain higher performance and more sustainable buildings.

The aim of this work is to assess the sustainability of a non-conventional solution using the methodology MARS-SC. The input parameters will be evaluated using energy simulation tools and experimental measurements. The study will focus on the performance comparison between a mixed-weight thermal mass test cell and a conventional one.

1. INTRODUCTION

Construction industry is one of the most important EU economical sectors, but it still relies too much on traditional construction methods and unskilled workmanship, being characterised by an excessive use of natural resources and energy.

This conflict between economic development and the environment lead to a state of environmental urgency. The building sector in the EU is responsible for 40% of the final energy demand and 1/3 of the greenhouse gases emissions. Globally, building sector accounts for 25% of wood, 40% of aggregates and 16% of water consumed worldwide (Dimson, 1996). This figures shows the large responsibility of building sector in the environmental pollution.

Different measures are necessary in order to improve the compatibility between buildings and the three dimensions of sustainable development.

Having this challenge in mind, it is during design phase that the sustainable building concepts should be applied, through the implementation of a strategic combined action that makes possible the reduction of the environmental impact by a judicious selection of materials, technologies and construction methods to be used. Analysing the evolution of the construction technologies, mainly in Portugal, it is possible to conclude that, in spite of some relative improvements on structural safety, the average construction mass of a housing building is very similar to 50 years ago. Although the environmental impacts per square metre have increased, building components reuse and recycling potential have significantly decreased (Mendonça, 2005).

More rational building processes can be implemented with the introduction of technologies that allow the reduction of mass in the construction. Such reduction becomes possible through the use of lightweight components, heavy insulated envelopes and punctual use of heavyweight materials for structural and anchorage functions or thermal storage. Besides that, the use of prefabricated modular systems that doesn't require cranes and other heavyweight equipment to build and that have small energy costs during transport and low embodied energy and environmental impacts should also be taken into account and selected, in most of the cases. This approach can therefore be associated to a better rationalisation of resources in construction.

In order to study the advantages of a mixed-weight housing principle that uses low embodied energy and environmental impact materials and to compare it with the conventional technology, two test cells were built (Fig. 1) in the Laboratory of Building Physics and Technology of the University of Minho (LFTC-UM). In this study it will be assessed and presented some environmental, social and economic advantages of a non-conventional design approach.

Figure 1.Test Cells.

2. DESCRIPTION OF THE BUILDING SOLUTIONS

2.1 Conventional Test Cell (CTC)

The CTC, as shown in Figure 2, contains three compartments. The CTC was built with a cavity hollow brick envelope wall with insulation on the air gap. This Test Cell represents the conventional Portuguese construction solution.

2.2 Proposed Test Cell (PTC)

The PTC, as shown in Figure 3, contains two compartment rooms. The compartment room 1 was built using compacted earth walls, in order to improve the environmental performance of the solution. The high thermal inertia combined with a south opening (equipped with exterior horizontal and vertical shading devices) is a passive solar solution. The compartment room 2 is a lightweight construction with insulation and a double glass window (1.4h x 0.4w m) in the north façade in order to promote daylighting and thus reduce the energy consumption with lightning.

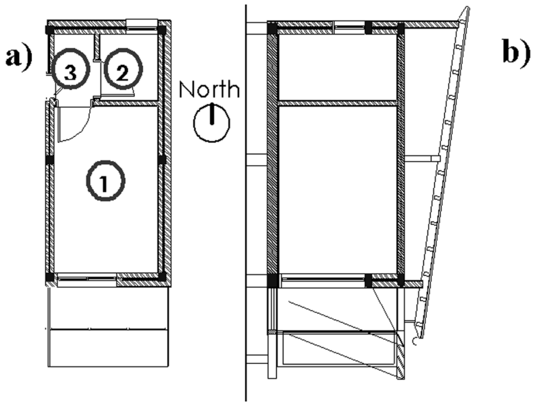

Figure 2. CTC drawings; a) floor plan; b) cross-section.

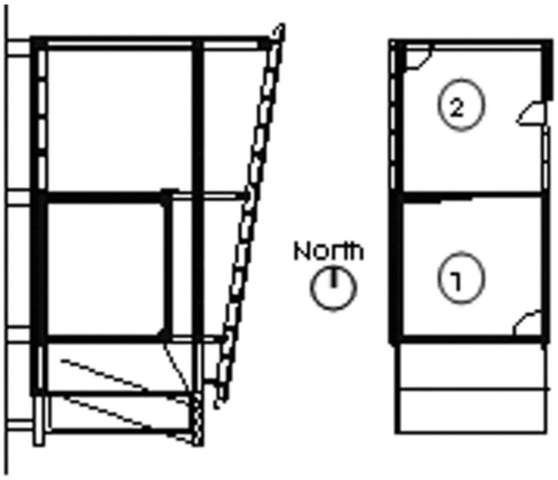

Figure 3. PTC drawings; a) floor plan; b) cross-section.

Both Test Cells were equipped with Sunspaces, in order to implement an indirect solar gain strategy

3. SUSTAINABILITY ASSESSMENT

The sustainability will be assessed considering some parameters related with the three dimension of the sustainable development. The parameters that will be used to compare the two solutions are presented in Table 1.

Table 1: Sustainability parameters

Dimensions		
Environmental	Societal	Economy
Global Warming Potential (GWP)	Summer thermal comfort (STC)	Construction costs (CC)
Acidification Potential (AP)	Winter thermal comfort (WTC)	Operating costs (OC)
Eutrophication Potential (EP)	Visual comfort (VC)	
Fossil Fuel Depletion Potential (FFDP)	Acoustic comfort (AC)	

3.1 Quantification of the parameters

i) Environmental dimension

Many of the environmental impacts in buildings are related to the materials and products' embodied energy and to the operating energy consumptions. The higher is the energy consumption during the raw materials extraction, processing and transport, and during building operations, the greater are the buildings' life-cycle environmental impacts.

The amount of energy needed to process the materials, their assembly in construction site, maintenance and demolition, can vary from 6 to 20% of the total energy consumed in building life-cycle. The major part of this value is linked to the materials Primary Energy Consumption (PEC) – energy resources spent for materials production, including the energy directly related to the raw materials extraction, their processing and the energy needed for the transportation (Berge, 2000).

Selecting lightweight materials generally results on smaller embodied environmental impacts. Besides that, other important achievements are the reduction of noise, dust and waste productions during extraction, transportation, building and dismantling or demolishing.

In general, the maximum use of local and less-transformed raw materials or recycled ones means reduction of embodied energy.

The assessment of the total embodied energy in building materials is one of the dimensions to consider in the environmental performance evaluation. Table 2 presents the construction mass (CM) and the embodied Primary Energy Consumption (PEC) of both test cells.

Comparing the results it is possible to see that the CTC's mass is 67% higher than the PTC's mass and that the embodied PEC in CTC is almost 88% higher than in PTC.

Some of the most important environmental impacts that are related to the energy consumption are: Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP) and Fossil Fuel Depletion Potential (FFDP). Table 3 presents the results found in the assessment of these parameters for both solutions. In Portugal, until now, there isn't a local life-cycle inventory (LCI) database related to building materials; therefore the results are based in values collected by Berge for central Europe (Berge, 2000).

Table 2. Construction mass (CM) and embodied primary energy (PEC) of both test cells (CTC & PTC).

	CTC		PTC	
Construction elements	CM (kg)	PEC(1) (kW.h)	CM (kg)	PEC(1) (kW.h)
Foundations	7211	2758	7211	2758
Floor	10194	4661	7010	3800
Walls(2)	17702	27917	9798	13526
Ceiling	8890	3669	5474	2604
Roof	1200	2255	1200	2255
Total	45198	41260	30694	24943
Total/m^2(3)	3013	2751	1806	1467

[1] Results based in life-cycle inventory values for Central Europe (Berge, 2000).

[2] Includes doors and windows

[3] This value is per net square meter

Table 3. Environmental impacts related to the materials and products used in the CTC and PTC.

	Environmental impacts			
Test Cell	GWP(1) (g.10^3/m^2)	AP(2) (g.10^3/m^2)	EP(3) (g.10^3/m^2)	FFDP(4) (MJ/m^2)
CTC	631	6	57	1135
PTC	366	3	28	606

[1] Global warming potential in grams CO_2 equivalents.

[2] Acidification potential in grams SO_2 equivalents.

[3] Eutrophication potential in grams N equivalents.

[4] Fossil fuel depletion potential in surplus MJ per functional unit of product. This value is according to the Portuguese primary energy supply structure.

Another important source of environmental impacts that takes place during construction and demolition phases is the production of pollutant gases. Many of these gases results from the fossil fuel combustion during building's materials, elements and residues transportation.

As higher is the distance of transportation, greater are the energy consumption and related environmental impacts. In Portugal the most used way of transportation in building processes is the diesel truck. The distance of transportation of building materials is difficult to evaluate due to the global scale market. Although, a recent survey made in the Portuguese construction market showed that the average distance of transportation from suppliers to construction site is about 50km (Oliveira, 2003). Table 4 shows the energy consumption and air pollutant emissions considering the average 50 Km of materials transportation.

Table 4. Air pollutant emissions and primary energy consumption during transportation from suppliers to construction site (Energy Research Group 1999).

		Emissions (g/t.km) - Energy (kW.h/t.km)	CTC Emissions (g/m^2) - Energy (kW.h/m^2)	PTC Emissions (g/m^2) - Energy (kW.h/m^2)
Emissions	CO_2	207	31186,62	18687,23
	CH_4	0,3	45,20	27,08
	NO_x	3,6	542,38	324,99
	CO	2,4	361,58	216,66
	VOCs	1,1	165,73	99,30
	Energy	0,8	121,7	72,9

The environmental impacts related to the energy consumption and air pollutants emissions during transportation phase are presented in Table 5.

Table 5. Environmental impacts related to the materials and products transportation from suppliers to construction site.

	Environmental impacts			
Test Cell	GWP(1) (g.10^3/m^2)	AP(2) (g.10^3/m^2)	EP(3) (g.10^3/m^2)	FFDP(4) (MJ/m^2)
CTC	193	28	0,02	62
PTC	116	17	0,01	37

[1] Global warming potential in grams CO_2 equivalents.

[2] Acidification potential in grams SO_2 equivalents.

[3] Eutrophication potential in grams N equivalents.

[4] Fossil fuel depletion potential in surplus MJ per functional unit of product.

Besides the embodied environmental impacts, the environmental impacts related to the energy consumption during operation phase are accessed. In this case, it will only be considered the GWP since there isn't any Portuguese's LCI data related to the other parameters. Data shows, according to the Portuguese energy mix, that 500 grams CO_2 equivalents are produced per each kW of delivered energy. In this way and according to the results obtained in the energy simulations (Table 8) the GWP related to the operational energy use is: 3547 g.10^3/m^2 for CTC and 3217 g.10^3/m^2 for PTC.

Results of the environmental assessment show that CTC has higher environmental impacts than PTC, due to the CTC's higher construction mass and operational energy demand.

ii) Social dimension

The most important parameters to evaluate the buildings indoor environment are the thermal comfort, the visual comfort and the acoustic comfort.

The most used parameters to assess the thermal comfort are the PMV – Predicted Mean Vote and the PPD – Predicted Percentage Dissatisfied (Fanger, 1982).

Table 6 presents the PMV and PPD of the PTC and of the CTC calculated according to ISO 7730.

Table 6. Thermal comfort of the Test Cells.

Test Cell	Winter		Summer	
	PPD (%)	PMV	PPD (%)	PMV
CTC	80,8	-2	6,8	0,2
PTC	77,3	-2	7,7	0,3

For the summer period the thermal comfort is better in CTC, however for the winter period the PTC has a better performance than the CTC.

The natural lightning performance evaluation was carried out using the software tool Desktop Radiance. The Iluminances (lux) where estimated for two critical dates: 21 December – the winter solstice and 21 June – the summer solstice. The results are presented in Figures 4 and 5. Figures 4 and 5 show a better daylightning distribution in PTC and also an excessive illuminance in CTC that should force the occupants to close the blinds. In one hand, this situation will reduce the solar heat gains and in the other hand it will increase the use of artificial lightning. The acoustic comfort was evaluated using only the façade's airborne sound insulation index (R_{45}). The results are based in "in-situ" measurements that follow the ISO 140 and 717 Standards. The results are presented in Table 7. As the acoustic insulation is directly related to the mass of the solution, the CTC has a better performance, even though the PTC has a very similar performance.

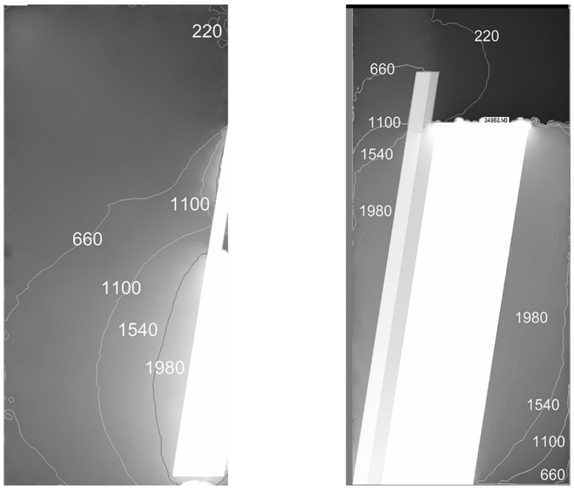

Figure 4. Illuminances on winter solstice with clear sky (isolines in lux) (12h) – PTC (left); CTC (right).

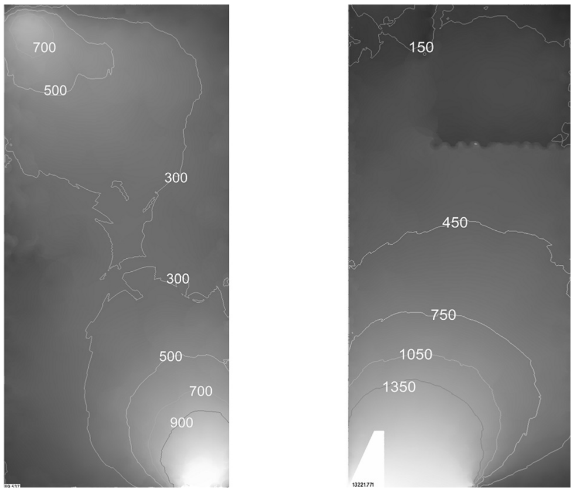

Figure 5. Illuminances on summer solstice with clear sky (false color) (12h) – PTC (left); CTC (right).

Table 7: Noise insulation of façades measured "in situ".

Test Cell		R_{45} (dB)
CTC	South Façade	30
	East Façade	47
PTC	South Façade	34
	West Façade	41

iii) Economic dimension

From the economic point of view the most important aspects are the construction cost and the energy consumption cost in the buildings' whole life-cycle. The construction cost was obtained directly from the construction company that built the Test Cells. However, as there is no heating or cooling system installed in the Test Cells, the energy consumption was obtained using a simulation tool – VisualDOE.

In order to achieve a good precision in the simulation, it was necessary to calibrate the model of the Test Cells used in the simulation tool. This task was done using: i) a climatic file created specifically for this test; ii) envelope thermal resistance calculated "*in-situ*"; iii) matching up the interior temperature measured "in situ" with the one calculated by VisualDOE (Silva, 2006).

The heating and cooling set points used for the HVAC system in VisualDOE were the ones recommended by the Portuguese thermal regulation – 20ºC for winter and 25ºC for summer. The results of the simulation are presented in Table 8.

Table 8: Energy consumption for the Test Cells.

Test Cell		Energy consumption (kwh/m^2.year)
PTC	Heating	102,1
	Cooling	26,6
	Total	128,7
CTC	Heating	126,8
	Cooling	15,1
	Total	141,9

The energy consumption cost was calculated for a life span of 50 years and with an inflation rate of 2,5%. In order to convert the Energy consumption in Product cost (energy cost) it was applied the tax stipulated by the Portuguese electricity provider – EDP – 0.1107 €/kWh. Table 9 shows that the total cost of the CTC is 11% higher than the PTC, mostly due to higher heating needs.

Table 9: Economic dimension of the Test Cells.

Test Cell	Energy Cost in life span (€/m^2)	Construction Cost (€/m^2)	Total Cost (€/m^2)
CTC	805	1267	2072
PTC	730	1111	1841

3.2 Representation and global assessment

The global assessment is done using the methodology for the relative sustainability assessment of building solutions (MARS-SC) that was developed in order to support the design teams in sustainability assessment of new buildings (Mateus, 2006). This methodology compares the performance of the solutions under analysis to the performance of the conventional solution within the three dimensions of the sustainable development. In the assessment are considered the parameters presented in Table 1 and the weights presented in Table 10.

Table 10: Weights considered in the assessment.

Dimension	Parameter	Parameter's weight (%)	Dimension's Weight (%)
Environmental	GWP	49,9	30
	AP	16,7	
	EP	16,7	
	FFDP	16,7	
Social	TC	33	50
	VC	33	
	AC	33	
Economic	TC	100	20

Table 11 resumes the results found in the sustainability assessment of both test cells. Figure 6 presents the sustainable profile of both solutions.

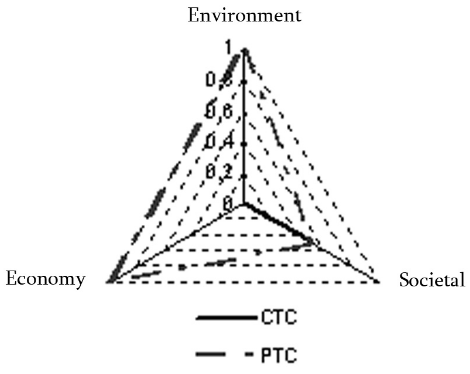

Figure 6 – Sustainable profile of both solutions.

Table 11: MARS-SC results.

Solution	Dimension			Sustainable Score (SS)
	Environ. (I_{Env})	Soc. (I_{soc})	Econ. (I_{Eco})	
CTC	0,0	0,5	0,0	0,25
PTC	1,0	0,5	1,0	0,75

Even without using the methodology MARS-SC, the clear cut results obtained in the quantification of parameters, shows that the most sustainable solution is the PTC. This solution is the one that best compromises the three dimensions of the sustainable development. PTC's limitations are only linked to societal parameters. The lower PTC's construction mass contributes to the lower airborne sound insulation of the external envelope. The worst summer thermal performance of PTC can be explained by the lowest thermal inertia and an unfavourable orientation.

The proposed solution (PTC) is also easy to dismantle and almost of its materials have high reuse and recycling potential, especially if compared to the most common construction system used in Portugal nowadays – reinforced concrete structure with clay hollow brick walls and concrete floors (CTC).

4. CONCLUSIONS

Project teams have big responsibilities in searching the sustainability in the building and real estate sectors, through the selection and use of building solutions with improved environmental, functional and economical performances, during their whole life-cycle. The development and use of building sustainability assessment methods and tools are fundamental aspects for those goals. This paper shows the potentialities associated with the use of lightweight materials combined with locally available thermal mass materials, in order to achieve a more sustainable construction.

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