# Potentialities of Lightweight Construction Solutions for Sustainability

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## ABSTRACT

The amount of waste produced every year, the exhaustion of resources and the construction solutions currently used in construction may not be sustainable in the future. All these issues lead to the research on new construction techniques, on recycling of waste into useful materials, on re-use of construction materials, etc. Most of the new and innovative solutions arise from the general feeling that something should be done to change the conventional way of construction in order to give an answer to current society concerns: the reduction of energy consumption, the minimization of pollution problems, the maximisation of the use of renewable and/or recyclable materials, etc. The aim of this study is to evaluate the potentialities of using more lightweight construction solutions with respect to functional comfort criteria (thermal, acoustic and visual comfort) and to assess the relative merits of this type of construction in view of maximising sustainability. Beyond the structural behaviour of a building, the demand of a better habitat requires also a good performance in terms of serviceability. In this work, the performance of lightweight construction solutions (optimized for reducing environmental impact) and conventional construction solutions were compared under the energy costs point of view (construction and heating). The other parameters have also been analysed but are not shown here since they were considered not relevant for this analysis.

## 1. INTRODUCTION

### *1.1 Historical evolution of housing construction systems in Portugal*

In the past centuries, at least until 50 years ago, in spite of an extremely heavy stone or massive brick envelope wall (it arrives to more then 1000 kg/m$^2$), some of the construction elements in housing buildings in Portugal were lightweight, mainly timber pavements (approximately 50-100 kg/m$^2$), timber/clay partition walls and timber covering structures (approximately 150- 200 kg/m$^2$). Recently, with the generalisation of steel reinforced concrete and industrialised hollow bricks, the more usual attitude is to generalise the use of the so called “lightweightened” concrete construction system (with approximately 350-400 kg/m$^2$ for a 0,22m pavement slab and a similar weight for a double pane hollow brick envelope wall, generally with insulation in the air gap) in conventional residential buildings. It is possible to conclude that, in spite of some relative increment in structural performance, the average weight of a residential building is very similar to 50 years ago, but the environmental impact costs per square metre have increased and the possibilities of recycling their components have decreased (Mendonça, 2003).

Reducing the specific weight of industrialised construction materials and systems can have a significant role on reducing environmental costs, namely by the use of prefabricated modular systems that require no cranes and other heavyweight equipment to erect and have smaller energy costs associated with transport and even with the construction materials themselves. One main problem is that lightweight buildings are usually characterised by a small thermal inertia that results in an excessive daily thermal temperature swing, and thus they are not usually considered on bioclimatic approaches on temperate climates.

### *1.2. Objectives*

The general objectives of this work are shown in Figure 1. There are several strategies that can lead to reduce the environmental impact of buildings. Recycle and re-use of the materials and even the buildings itself are possible, but are not the issues to be discussed in this paper. The strategy proposed here will be based on the reduction and how it can be achieved by optimizing the weight on architectural and construction systems. There will be focused two different aspects: one is a research on optimizing the total primary energy consumption (PEC) of construction materials and their transport, the other is based on reducing the energy operating consumptions for maintaining thermal comfort, using the maximum possible passive solar gains. In order to compare the relative influence of these aspects, measurements were carried out in two solar passive test cells.

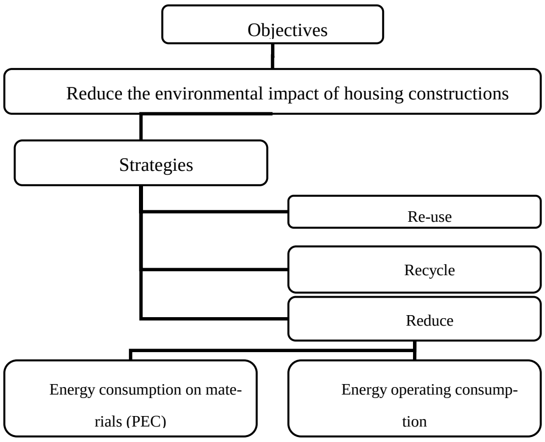


Figure 1. General objectives of this study.

## 1 ENERGY CONSUMPTION IN BUILDINGS

### *2.1 Reducing energy consumption in construction*

Reducing the weight of materials used implies smaller environmental damages due to the extraction of prime materials, to their transformation processes and to the work yards, with reduction of noise, dust, wastes and the consumption of energy during the construction and a proportional reduction on loss factors and especially on transport energy costs. The maximum use of local and less-transformed raw materials, or recycled ones, means reduction. But, it is important to minimize the use of those that are not locally available (such as steel for reinforcing concrete, cement or brick) and to optimize the use of those that, in spite of not being local or low energy, can compensate on savings over their lifespan, such as glass or insulation. It must be kept in mind that a road transport by truck implies 2890 kJ/t/km (802,78 kW.h/kg.km) (Energy Research Group, 1999), being one of the most pollutant ways of transporting construction materials, as it can be seen in Table 1. It must be said that in Portugal, this is the most common (practically the only one) way of transporting construction materials.

Table 1. Primary energy use by different modes of freight transport (Energy Research Group 1999).

| Emissions (g /T.Km) | Water | Rail | Road | Air |
|---|---|---|---|---|
| $CO_2$ | 30 | 41 | 207 | 1206 |
| $CH_4$ | 0,04 | 0,06 | 0,3 | 2 |
| $NO_x$ | 0,4 | 0,2 | 3,6 | 5,5 |
| CO | 0,12 | 0,05 | 2,4 | 1,4 |
| VOCs | 0,1 | 0,08 | 1,1 | 3 |
| Energy (kJ/T.km) | 423 | 677 | 2890 | 15839 |

### 2.2 *Reducing operating energy*

In what concerns the structure and the materials used, bioclimatic residential buildings in South European climates are even more heavyweight than conventional ones. Concrete and brick are used in the interior pane of double envelope walls and in pavements, in order to increase thermal storage capacity. But it could be questioned if the overall weight could not be reduced by introducing more accurate systems. When the materials and labour are locally available (as adobe or stone), the environmental cost is reduced, but the increase of the global mass of the building implies other problems, such as the high economical cost of an intensive labour or the difficulty for increasing density by the increment of floors (even to more than two). Thermal mass materials still should be used, but in a rational way, related to local availability and just to fit thermal storage necessities. Some construction elements cannot be always locally available (such as steel, concrete, ceramics and specially glass), and thus this is an area where optimisation can be even more effective (Mendonça, 2003).

In housing, the thermal gains could be higher in a direct gain strategy, with the concrete pavement slab, the interior walls and the interior pane of exterior walls taking the role of thermal storage, but the temperature and glare due to excessive solar radiation penetrating the interior occupied areas are a cause of discomfort. Apart from the degradation of the furniture and other equipment, a direct gain strategy is not a good solution, also due to the necessity of daily operating a night mobile insulation system. An indirect gain solution could, though, be a more effective solution in order to keep interior comfort standards within acceptable values.

## 3. TEST CELLS STUDY

### 3.1 *Characterization of the test cells study*

The proposed approach of reducing the overall environmental impact of buildings was based on the use, as much as possible, of local materials and on a mixed-weight housing principle, with a thermal zoning concept (where thermal mass is assured only in very specific building zones) and on a passive solar indirect gain strategy that was expected to lead to an overall reduction of the weight of construction but without increasing the operating energy. A research was undertaken using two test cells simulating areas of the architectural designs shown in Figure 2. The plan on the top is the proposed mixed weight and mixed use housing unit (working on North area with direct lighting and sleeping on South area with indirect solar gains). The bottom plan simulates a conventional residential unit (but it also has an optimized solar exposition and mixed direct / indirect solar gains).

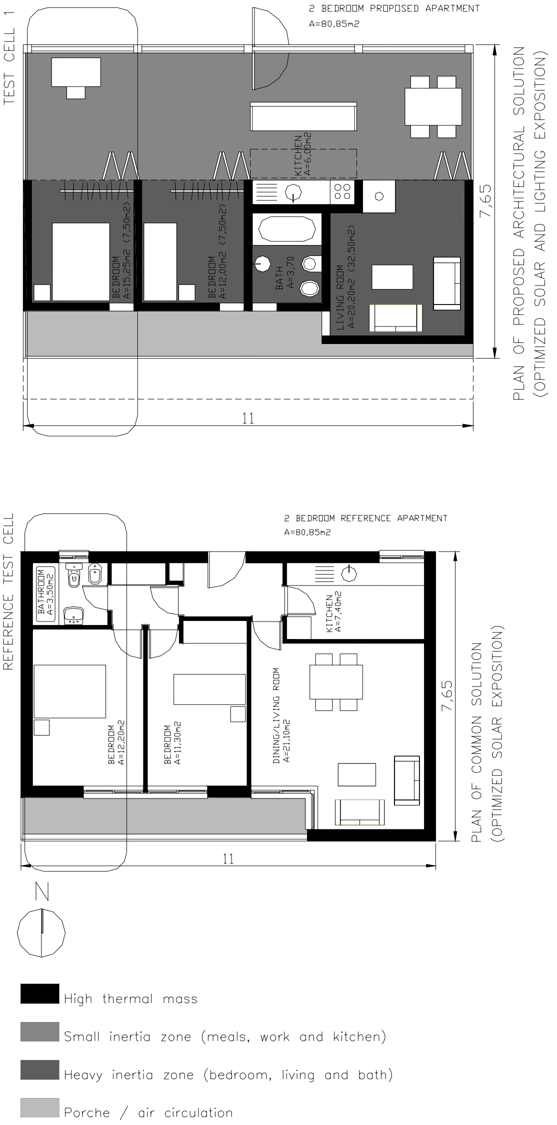
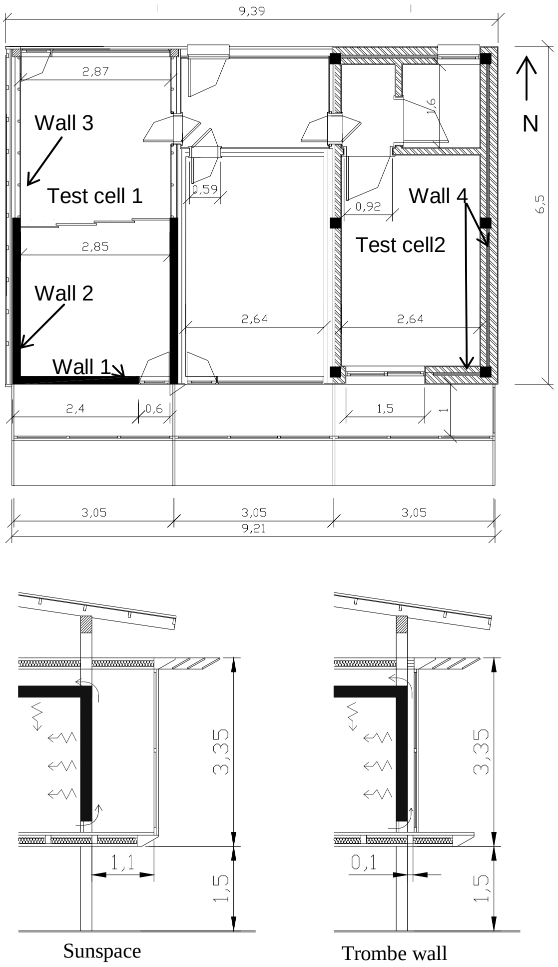


Figure 2. Plans of proposed and conventional housing units (Mendonça, 2003).

The Test Cells studied have a rectangular shape (approximately 6,5x3,1m), both are South oriented and have an horizontally moving glazed frame that is able to perform a sunspace or a Trombe wall as shown in the bottom of Figure 3.



Sunspace

Trombe wall

Figure 3. Test cells' plan and schematic vertical section of moving glazed frame (through wall 1) to create a Sunspace or a Trombe wall (distances in m).

Test Cell 1 is the non conventional cell, where the thermal performance of the mixed-weight construction was studied. This test cell is divided in two parts separated by a wood moving partition: an heavyweight South oriented zone (sleeping area) with concrete structure, pavement and ceiling slabs, adobe walls, and a North oriented lightweight zone with timber structure and sandwich pavement, ceiling and walls. In the heavyweight area, Wall 1 is an adobe thermal gaining wall without insulation and a black painting exterior finishing and Wall 2 is a double pane wall with a 15 cm adobe pane in the interior and a wood cement exterior board with a ventilated 15cm air gap with 5cm expanded cork insulation. The North oriented zone (working area) has sandwich lightweight pavement and ceiling made with wood cement board and expanded cork insulation and triple pane walls with an exterior ventilated 15 cm air gap and an interior super-insulated air gap with 8cm of expanded cork + 2cm of coconut fibre.

For comparative analysis, a conventional reference cell, named Test Cell 2 in Figure 3, with the same dimensional characteristics, but made with a conventional construction solution, was also studied. This cell corresponds to a conventional solution on contemporary Portuguese construction and has a construction system based on a steel reinforced concrete structure, with pavement and ceiling on pre-stressed concrete "T" beams and hollow brick and exterior double pane (15+11 cm) hollow brick wall with 4 cm of extruded polystyrene (XPS) placed in the air gap and finished with plaster on both sides.

Figures 4, 5 and 6 show the vertical schemes of the façades and a vertical section of each test cell.

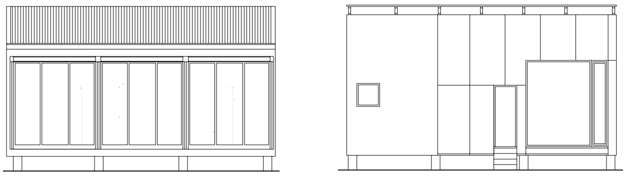


Figure 4. Test cells' vertical scheme of the North and South façades.

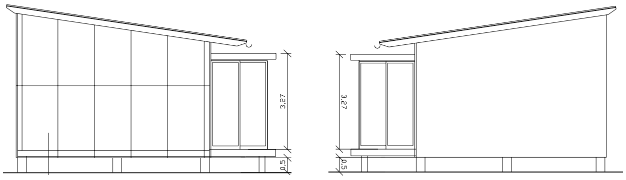


Figure 5. Test cells' vertical scheme of the East and West façades (distances in m).

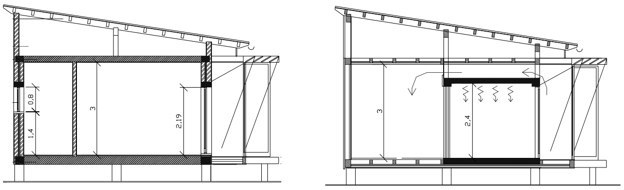


Figure 6. Vertical sections of test cells 1 and 2 – sunspace configuration (distances in m).

### *3.2 Energy operating consumption*

Long term energy savings implies more than a correct design of façades. In countries, such as Portugal, where the outdoor temperatures vary, in average, from a minimum value of –2,5°C and a maximum value of 35°C, with an average daily thermal amplitude of 10°C (Mendes et al. 1989), thermal inertia is even more important than insulation capacity. The absence of thermal mass can result in a night rapid drop of temperature and a resulting excessive daily thermal swing in the interior. Since the South facing walls can take the main role of thermal gains, the bet can be to optimise their performance, and so to use it mainly for indirect gain. The use of combined solutions of ventilation / heat storage, namely by the use of Trombe walls, is an effective method of natural heating during the cold season, when there is enough solar radiation. One problem is that the construction of these interior walls between the window and the occupied zones decrease interior light availability since they are opaque. The need of a great South oriented window surface with its major area closed by thermal gaining opaque walls, forces the building to open to other solar orientations. In the proposed solution, the working area for studying, receives natural illumination through a North oriented translucent window (in alveolar polycarbonate and timber frame). This North great light capture causes a greater fluctuation of the indoor temperature, but it also allows having a more uniform lighting environment for this area, that was expected to have a daytime occupation (working areas). The heavyweight area has a smaller fluctuation and when the partition door is closed, during night hours, the temperature swing in this area is lower than in the reference test cell. As shown in Figure 7, the Summer campaign measurements revealed that cooling needs were not relevant (the mean radiant temperature of the south compartment of test cell 1 and test cell 2 are always very near to the maximum summer comfort temperature – 25ºC), so they were not considered (the zone of this study was Guimarães and it is in a Northern temperate area of Portugal – not very far from sea so it still gets some maritime influence). The heating overall energetic needs were measured and calculated using the method proposed by CSTB (CSTB 1988) and these values were compared with the other energy aspects - primary energy of construction materials (PEC) and materials transport.

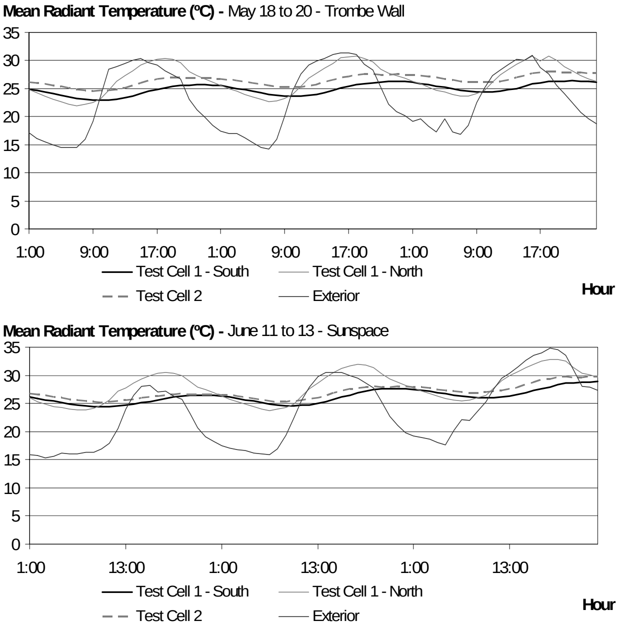


Figure 7. Comparisons of the mean radiant temperature of the test cells.

Observing Figure 7, it is possible to conclude that the south compartment of test cell 1 has a better performance in summer, because it has a slightly lower mean radiant temperature. But, when the sunspace was applied, this difference became smaller. It's possible to say that in what concerns thermal inertia, both cells show an appropriate performance for the zone under study.

## 4. ENERGY COST EVALUATION

Table 2 shows the numbers of the Embodied Energy of materials used in the proposed test cell (1) and in the reference test cell (2). As it can be seen from the analysis of this table, in Test Cell 1 and 2, the aluminium of the exterior window frames, in spite of being lightweight, has a very high PEC. Aluminium was the adopted solution just for the specific purpose of having a mobile window (with a telescopic movement in order to study the influence of the sunspace area in the thermal gains), since other solutions were not possible for this purpose. In a real situation, a wood frame in the frontal window of the sunspace or the Trombe wall would have a much smaller embodied energy (this situation is also considered in table 2). Through the analysis of this table, it can be seen that the proposed solution leads to a decrease of about 46% of the total PEC and of about 40% on the weight. On conventional construction, hollow brick and concrete take the greatest portion of the embodied energy.

Table 2. Embodied energy and weight of materials used in proposed and conventional test cells

| ***Test Cell 1 (Proposed)*** Materials Used | WEIGHT (kg) | kWh/kg | PEC (kWh) |
|---|---|---|---|
| Aluminium (30% recycled) | 200 | 44,5 | 8896 |
| Concrete | 18344 | 0,3 | 6053 |
| Particle board | 2161 | 1,1 | 2334 |
| Steel | 681 | 2,8 | 1894 |
| Insulation (expanded cork) | 884 | 1,1 | 982 |
| Stainless steel | 75 | 9,7 | 730 |
| Vulcanized rubber | 34 | 19,4 | 661 |
| Glass | 107 | 5,1 | 546 |
| Asphalt / carton shingle | 113 | 4,1 | 456 |
| Carton / plaster gypsum board | 398 | 1,1 | 418 |
| polycarbonate | 16 | 24,2 | 397 |
| Timber (local pine) | 1971 | 0,2 | 355 |
| Gypsum | 306 | 1,1 | 321 |
| Coconut fibre | 58 | 3,9 | 225 |
| Synthetic varnish | 10 | 21,5 | 205 |
| Timber floating pavement | 107 | 1,4 | 149 |
| Adobe | 4995 | 0,03 | 135 |
| Particle board | 84 | 1,1 | 90 |
| Lime painting | 144 | 0,3 | 40 |
| Expanded Polyethylene | 2 | 24,2 | 37 |
| Plastic painting | 4 | 5,6 | 20 |
| ***Total*** *(with aluminium frame on solarspace)* | ***30694*** | | ***24944*** |
| timber frame | 80 | 0,2 | 14 |
| ***Total*** *(with timber frame on solarspace)* | ***30574*** | | ***24930*** |
| **Total / m$^2$** (with timber frame on solarspace) | ***1799*** | | ***1466*** |

| ***Test Cell 2 (Conventional)*** Materials Used | WEIGHT (kg) | kWh/kg | PEC (kWh) |
|---|---|---|---|
| Clay | 9778 | 1,3 | 12320 |
| Aluminium (30% recycled) | 250 | 44,5 | 11120 |
| Concrete / Cement mortar | 32411 | 0,3 | 10696 |
| Steel | 955 | 2,8 | 2657 |
| Extruded Polystyrene | 54 | 27,9 | 1504 |
| Stainless steel | 75 | 9,7 | 730 |
| Glass | 127 | 5,1 | 650 |
| Asphalt / carton shingle | 113 | 4,1 | 456 |
| Gypsum | 270 | 1,1 | 284 |
| Alveolar polycarbonate | 9 | 24,2 | 216 |
| Particle board (cement / wood) | 154 | 1,1 | 166 |
| Timber (local pine) | 851 | 0,2 | 153 |
| Timber floating pavement | 95 | 1,4 | 131 |
| Plastic painting | 12 | 5,6 | 65 |
| Particle board (wood) | 40 | 1,1 | 44 |
| Synthetic varnish | 2 | 21,6 | 37 |
| Expanded Polyethylene | 1,4 | 24,2 | 33 |
| ***Total*** | ***45197*** | | ***41262*** |
| **Total / m$^2$** | ***3013*** | | ***2751*** |

For the comparative cost analysis presented in Table 3, a 50 years life span has been considered with a 2,5% inflation rate. It can be seen that the proposed solution is a little less expensive than the conventional one. The operating costs were considered just for the heating season, in a 18ºC base temperature and considering electric wall radiators for heating (as it is usual in Portugal). Table 3 also shows that a reduction of about 20% is achieved in the operating costs with the proposed solution. Note that in certain regions of Portugal, stone would have been preferable to Adobe masonry in interior heavyweight walls in the proposed solution, but the average final value would have been very similar, since stone has a similar PEC.

Table 3. Embodied energy, operating energy and energetic costs in a 50 years life span

| *Test Cell* | | Operating Energy Cost in Life Span (€/m$^2$) | Construction Cost (€/m$^2$) | Embodied Energy (kWh/m$^2$) |
|---|---|---|---|---|
| *1* | sun-space | 235 | 1111 | 1466 |
| | trombe wall | 369 | | |
| *2* | sun-space | 323 | 1267 | 2751 |
| | trombe wall | 417 | | |

| *Test Cell* | | Material Transport Energy (kWh/m$^2$) | Operating Energy Consumption (kWh/m$^2$) |
|---|---|---|---|
| *1* | sun-space | 121 | 2374 |
| | trombe wall | | 3729 |
| *2* | sun-space | 242 | 3262 |
| | trombe wall | | 4219 |

Figures 8 and 9 also show the referred comparison between the two test cells performance.

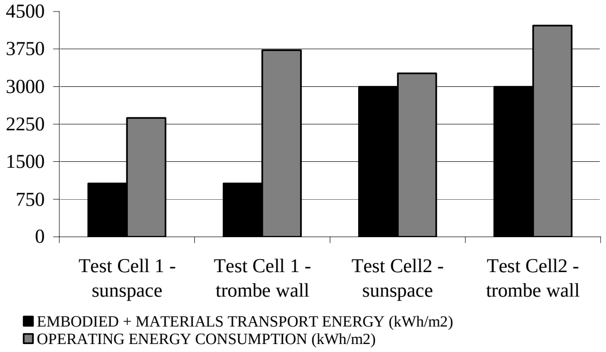


Figure 8. Comparisons between operating energy and embodied + transport energy for the two test cells.

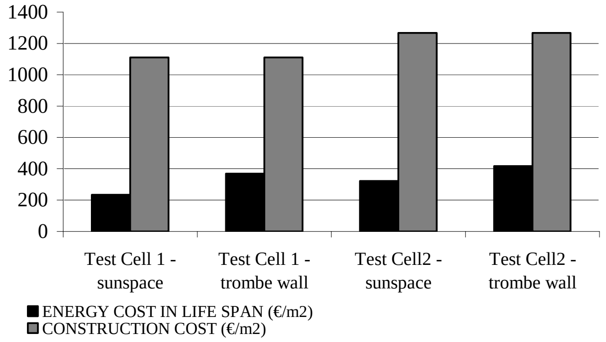


Figure 9. Energy and Construction costs for the two test cells.

Table 3 also shows that the materials transport energy was reduced in 50%. This is due to the effort of using, as much as possible, local materials. These local materials also had the advantage of being lighter in weight as it can be seen in table 2. So, the percentage of reduction associated with transport, mainly by truck, was significant. To this transport study it has been considered that all the industrialized materials had to make an average of 100 km. The average distance in the transport of adobe (compacted earth) was considered to be 0 km.

Berge says that "The amount of energy that actually goes into the production of building materials is between 6 and 20 % of the total energy consumption during 50 years of use, depending on the building method, climate, etc" (Berge, 1999). The percentage that most suits the Portuguese reality is maybe closer to 20 %, because of the particular amenity of the climate, but it is possible to state that the amount of energy that goes into the production of building materials can easily reach values between 30 to 48% of the total energy consumption during 50 years of use.

## 5. CONCLUSION

This paper shows the potentialities associated with the use of lightweight materials combined with locally available thermal mass materials, in order to achieve a good environmental profile. In the end of the life span of most contemporary housing buildings, the dismantling, treatment and transport of waste materials also have potential to represent energy savings. The proposed solution is also easy to dismantle and almost all of its materials are re-usable or recyclable, especially if compared with nowadays most common construction systems used in Portugal – steel reinforced concrete structure with clay hollow brick walls and pavements. The example presented in this paper shows how the environmental impact measured in the Primary Energy Consumption of materials in the proposed innovative mixedweight test cell can reach almost a 50% of improvement when compared with a conventional one and still having a similar economical cost (even a little lower). In spite of the increasing evolution that lightweight materials and systems achieved in the recent past, namely to their durability and stability, there is still a long way to go through, before these solutions can be widely accepted. Mixing them with heavyweight solutions, and proving the fact that this strategy is environmentally suitable to be used in bioclimatic constructions, even to temperate climates as the South European ones, can be a step forward. It could also be concluded that the solar passive optimized solution is more sustainable in a Sunspace configuration then in a Trombe wall configuration.

## 6. ACKNOWLEDGEMENT

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