Performance-based selection of sustainable construction solutions for external walls

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Abstract

This research is focused on the integration of sustainability and functional performance in architecture. While having an important contribution in terms of environmental impact, construction solutions also play a significant role in the reduction of energy use of buildings. Therefore, a careful, although simple, analysis of construction solutions integrating environmental and functional performance is needed to support the decision process in architectural design. A simplified methodology, using an environmental indicator and an energy-related functional indicator is implemented to assess how a set of construction solutions for external walls would perform in face of different objectives. The environmental indicator is obtained through the aggregation of the individual normalized values for the embodied energy and the carbon footprint. The functional indicator characterizes the energy performance of the wall, by aggregating the individual normalized values of the heat transfer coefficient and the net superficial thermal mass. These indicators are then integrated in a final weighted index to allow for a straightforward, yet effective understanding of the environmental impact of functional construction solutions. The set of construction solutions comprises different materials for cavity as well as single walls that are common in the building construction sector: ceramic brick masonries, reinforced concrete, mortar render and plasterboard as internal coating, synthetic or natural materials applied in two thicknesses for thermal insulation. Different combinations of these materials form the set of 90 heavyweight external walls that were calculated. Results show that it is possible to select construction solutions with a good environmental and functional performance. There is however a conflict between the objectives of reducing embodied environmental impact and increasing thermal inertia. This later may be an important comfort factor in the cooling season in residential architecture. The proposed methodology can be a comprehensive support tool to architects at the moment of selecting construction

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solutions, so that the principles of a sustainable construction are increasingly becoming a reality in architectural design.
Keywords: sustainable architecture, material selection, external walls.

1 Introduction

The construction sector remains one of the main consumers of energy and materials worldwide. The United Nations Environment Programme reports that the environmental footprint of the building sector consists of 40 percent energy use, 30 percent raw materials use, 25 percent solid waste, 25 percent water use and 12 percent land use [1].

People working in the sector have an important responsibility when choosing the materials for the construction of buildings, and due consideration about the impact these can have on the environment is crucial. There is frequently a conflict in combining the right material for architectural design, and the material which has the best environmental and functional performance for a specific situation. This happens for two main reasons: on the one hand, industry lacks reliable information about the environmental impact of materials, although it should be acknowledged that recent improvements allow for a more optimistic perspective; on the other hand, Life Cycle Assessment (LCA), which was originally designed to evaluate the life cycle of manufactured products in terms of its environmental impacts, cannot be directly applied to buildings [2].

A full LCA study is very time consuming, expensive and requires a great amount of detail. Its full implementation may therefore be compromised in smaller scale projects, because the quantity and quality of resources available are not comparable to those that are mobilized in large scale real estate developments. Besides this scale issue, even in projects with enough financial capacity, it is very difficult to have the necessary level of detail needed for a full LCA analysis in early stages of the design process. Whereas 80 percent of the environmental impact of a product is decided at an early stage of design [3], it is crucial to have the opportunity to develop simple and expeditious methods allowing a viable and early assessment, even if losing some of the degree of detail comparing to the results obtained with a complete analysis.

The external walls of a building are the most crucial elements with respect to the comfort of those who live in the space, influencing directly the energy performance of the building. The environmental impacts of each type of external wall are a direct result of the materials used and of the way they were assembled. The initial embodied energy and the thermal properties play a very important role in the global integrated energy performance of the building. This is why this study is focussed on the development of a simple methodology to select external walls, trying to contribute to the decrease of energy and materials on the construction sector.

2 Methodology

The main objective of this study is to develop a methodology to compare different construction solutions of external walls, in a simple way that can be used at any stage of an architectural project. This simplified methodology aims at more informed choices from those working in the construction sector, in order to understand the real impact of the selected construction solutions.

The methodology that is proposed establishes a simplified analysis of external heavyweight walls, based on two indicators that characterize the environmental and the functional performances. The process simplification lies on the reduced number of parameters considered for each indicator, as well as in the calculation process. The end result for each wall, attributes a global indicator – a sustainability indicator – that considers both performances in an aggregated form, making it easier to analyse and compare alternatives. The aggregation method [4] allows varying the relative importance of each type of performance by providing the user with a personal selection criteria adapted to various circumstances related to design scenarios.

Each one of the two indicators integrates two parameters. The environmental sustainability is assessed by the embodied energy and carbon (EE_s [MJ/m^2] and EC_s [kgCO$_2$e/m^2], respectively); the functional performance is assessed using the heat transfer coefficient (U [W/m^2.K]) as well as the net superficial thermal mass (M_{tsu} [J/m^2.K]).

In what concerns the life cycle boundaries of this study, it should be noted that the environmental indicator considers the cradle-to-gate range, i.e., from the extraction of raw materials to the end of the production process of the material units that compose each construction solution. This range therefore includes the extraction, processing and packaging of materials. The phases of construction, operation, maintenance, rehabilitation and end of life are therefore excluded. This option is the result of two main aspects. On the one hand, the inventory database that was used [5] considers the cradle-to-gate boundaries. The option for this set of information is related to the ease of access and use. On the other hand, to extend the life cycle boundaries implies considering factors which are highly variable depending on the case, as the distance from the factory to the construction site, the construction process, the use of the building, the operation mode and the types of rehabilitation. It should however be noted that the methodology allows an easy incorporation of additional information if the user wishes to do so.

The functional indicator represents the potential for energy efficiency and thermal comfort in what may be the contribution of an external wall. In this way, this functional information may assist in assessing the performance of the building in the operational phase. It may therefore be said that this functional indicator is an indirect environmental indicator for the operational phase.

Overall, the integrated analysis of the environmental and the functional performances, through a sustainability indicator, allows for the comparison of the external walls considering its direct environmental impact and the potential for comfort and energy efficiency.

2.1 Environmental parameters

The environmental impact assessment of products or processes has today a key role in the management of finite resources and environmental conservation.

In a complete LCA study, the environmental impact category is normally very detailed. Factors such as the global warming potential, the degradation of the ozone layer, acidification of soil and water, the potential for eutrophication, the production of photochemical ozone (low level) and the consumption of non-renewable natural resources are normally determined for a single product [3]. It is difficult to incorporate this kind of information in the decision process about what product or material to select. Among many other decisions that the design team has to take for a building, simplifying the set of information may contribute to a more persistent consideration of these crucial aspects especially in small scale developments. By providing more simple and flexible information, the environmental impact and the energy performance of construction assemblies will be more effectively compared resulting in a more accurate selection.

The choice should focus on materials with low embodied energy and low embodied carbon to minimize the overall environmental impact. Extraction of raw materials should also be as minimized as possible by selecting materials with a high rate of recycled content, whenever possible and reliable information is available.

This study focuses on the superficial embodied energy (EE_s) and the superficial embodied carbon (EC_s). These parameters characterize the amount of energy and the related carbon dioxide emissions that were needed from the very extraction of raw materials to the final product availability at the factory gate. Whenever available in the inventory dataset, the unit values for the embodied carbon take into account carbon dioxide equivalent information thus covering all the greenhouse gas emissions and not only carbon dioxide.

Values of embodied energy and carbon are taken from the database produced by Geoff Hammond and Craig Jones [5] under the *Carbon Vision Buildings Program* at the University of Bath, United Kingdom. In this inventory values are calculated and provided by unit mass of material (kg). However, as part of a research that is primarily intended to the practice of architecture, it would not make sense to characterize the performance of construction solutions per unit mass. The basic unit within the scope of architectural design is unit surface area, and the resulting weight of each building element depends on the thickness of each layer. In its turn, the thickness will depend on the performance requirements in relation to the properties of materials. Therefore, the calculations presented in this paper are results per unit surface area of external wall (m^2).

The embodied energy per wall unit surface area, EE_s [MJ/m^2], is obtained from eqn (1):

$$EE_s = \sum_i \left(M_{si} \cdot EE_i\right) \tag{1}$$

where M_{si} : superficial mass of layer i [kg/m^2]; EE_i : embodied energy per unit mass of layer i [MJ/kg].

Similarly, embodied carbon per wall unit surface area, EC_s [$kgCO_2e/m^2$], is the result of eqn (2):

$$EC_s = \sum_i \left(M_{si} \cdot EC_i \right) \tag{2}$$

where EC_i : embodied carbon per unit mass of layer i [$kgCO_2e$ /kg].

Superficial mass M_s [kg/m^2] is calculated by eqn (3):

$$M_s = e \cdot \rho \tag{3}$$

where e : thickness [m]; ρ : density [kg/m^3].

2.2 Functional parameters

The functional performance assesses the potential for thermal comfort and energy efficiency associated with each construction solution. The parameters chosen to evaluate this performance are the heat transfer coefficient (U) and the net superficial thermal mass (M_{tsu}).

The heat transfer coefficient gives information about the unidirectional heat transfer in steady state conditions. It may seem at a first glance that the objective would be to have the lowest possible U-value. However, this will depend on the type of climate and the use of the building. Very low U-values may contribute to the risk of overheating in buildings with a high occupation rate located in moderate and hot climates.

The heat transfer coefficient U [$W/m^2.K$] is calculated by eqn (4) [6]:

$$U = \frac{1}{R_{si} + \sum_i \frac{e_i}{\lambda_i} + R_{se}} \tag{4}$$

where R_{si} : internal surface thermal resistance [$m^2.K/W$]; e_i : thickness of layer i [m]; λ_i : thermal conductivity of layer i [W/m.K]; R_{se} : external surface thermal resistance [$m^2.K/W$].

The summation indicated in the denominator of eqn (4) is the total thermal resistance of the wall, R_T.

When the layer i is not homogeneous, i.e. when the heat transfer also occurs by convection and/or radiation and not just by conduction (e.g. air cavities or hollow bricks), the thermal resistance is obtained from laboratory testing and not through the values of thickness and thermal conductivity. These values of thermal resistance are available in reference technical publications [6].

The net superficial thermal mass measures the capacity of the wall to absorb and retain heat. It is an indirect measure of thermal inertia. In general cases of residential buildings in moderate and hot climates with significant daily thermal amplitude, it is useful to have a high thermal inertia to reduce the temperature variation of the internal environment. More stable thermal comfort conditions are thus obtained in winter and especially in summer. It should be noted that this passive design strategy applies mainly to hot dry climates. In hot humid climates, thermal comfort also depends on reducing the relative humidity levels, which in turn is hardly obtained without the use of mechanical systems. The thermal mass of a construction element depends on the mass and the specific heat of each of its layers. However, the extent to which the thermal mass indeed contributes to the internal environment conditions is also the result of the sequence of those layers. For instance, to apply thermal insulation in the internal face of a reinforced concrete wall will annul the effect of the concrete high thermal mass because the thermal energy will not reach the concrete mass. Therefore, the actual contribution of the construction element to the internal thermal inertia is calculated through the net superficial thermal mass, M_{tsu} [J/m^2.K] from eqn (5) [7]:

$$M_{tsu} = \frac{CT_s}{R_T} \tag{5}$$

where CT_s : surface thermal constant of the wall [s]; R_T : total thermal resistance of the wall [m^2.K/W].

The surface thermal constant CT_s [s] of a construction element with n layers, is determined through eqn (6) [7]:

$$CT_s = \left(R_{se} + \frac{R_1}{2} \right) \cdot M_{ts_1} + \sum_{i=2}^{n} \left[\left(R_{se} + \sum_{j=1}^{j=i-1} R_j + \frac{R_i}{2} \right) \cdot M_{ts_i} \right] \tag{6}$$

where R_1 : thermal resistance of layer 1 [m^2.K/W], the most external one; M_{ts_1} : superficial thermal mass of layer 1 [J/m^2.K]; R_j : thermal resistance of layer j [m^2.K/W], located between layer 1 and layer i; R_i : Thermal resistance of layer i [m^2.K/W]; M_{ts_i} : Superficial thermal mass of layer i [J/m^2.K].

The superficial thermal mass M_{ts} [J/m^2.K] is obtained through eqn (7):

$$M_{ts} = M_s \cdot c \tag{7}$$

where c : specific heat [J/kg.K].

2.3 Calculation of an integrated index

The above described environmental and functional parameters are now used to calculate an environmental indicator, IS_E, and a functional indicator, IS_F. These individual indicators are then combined to produce a single integrated sustainability index, IS_G, which characterizes each of the construction solutions.

The environmental indicator (IS_E) is the result of a weighted average of the superficial embodied energy (EE_S) and the superficial embodied carbon (EC_S). Similarly, the functional indicator (IS_F) is calculated through a weighted average of the heat transfer coefficient (U) and the net superficial thermal mass (M_{tsu}).

The process needs a prior normalization because the absolute values are very different from parameter to parameter. This normalization leads to a single scale, reversing the effect of different units.

The normalized value $\overline{P_i}$ of each parameter for each construction solution is calculated by eqn (8) [8]:

$$\overline{P_i} = \frac{P_i - P_{*i}}{P_i^* - P_{*i}} \forall_i \tag{8}$$

where P_i : value for parameter *i*; P_{*i} : worst value for parameter *i* in the complete set of solutions; P_i^* : best value for parameter *i* in the complete set of solutions.

At this stage, each type of performance, environmental and functional, is defined by two parameters, which values are normalized. In order to combine the two parameters into a single indicator, an aggregation method is used.

The aggregated value IS_j of each indicator is calculated by eqn (9):

$$IS_j = \sum_{i=1}^{n} \left(\overline{P_i} \cdot w_i \right) \tag{9}$$

where w_i : weighting factor for parameter *i*.

The above eqn (9) shows that the aggregation of each performance indicator includes a weighting factor of the parameters in cause. It is therefore possible to easily vary the relative importance of the individual parameters that compose the indicators, to consider specific circumstances of a particular project.

The overall assessment finally reveals a global sustainability indicator characterizing each construction solution. This indicator, IS_G, is obtained through the weighted aggregation of the two individual indicators, through eqn (10):

$$IS_G = IS_E \cdot w_E + IS_F \cdot w_F \tag{10}$$

where IS_E : weighted aggregated environmental indicator; w_E : weighting factor for the environmental indicator; IS_F : weighted aggregated functional indicator; w_F : weighting factor for the functional indicator.

It is thus possible to order each construction solution, in relation to the complete set, according to the importance that is assigned to each of the two indicators (environmental and functional). This significance is the result of specific design conditions and may differ from case to case.

3 Construction assemblies

The selection criteria for the definition of construction solutions took into account the Portuguese common practice. Ninety construction solutions for heavyweight external walls were analysed, comprising single and cavity walls. Both kinds of wall consider two thicknesses for the thermal insulation, 4 and 6 cm. The insulation materials are cork, extruded polystyrene and rock wool; this latter was only considered in cavity walls.

In the case of single walls, the thermal insulation is always on the external side of the wall with a mortar render as finishing. The main component of the wall (letter “A” in Figure 1) may be reinforced concrete (thickness of 20 cm); common horizontally perforated hollow ceramic bricks (hollow bricks, thickness of 20 cm); or vertically perforated hollow ceramic bricks (known as “thermal bricks” because of the higher thermal resistance, thickness of 19, 24 and 29 cm). The internal coating may be a mortar render or plasterboard, except for the concrete walls where it was decided to leave the material’s natural appearance.

In the case of cavity walls, the cavity is partially occupied by the thermal insulation material and an air gap of 5 cm is left to solve humidity and condensation issues. Combinations of components B and C of Figure 1 are described in Table 1.

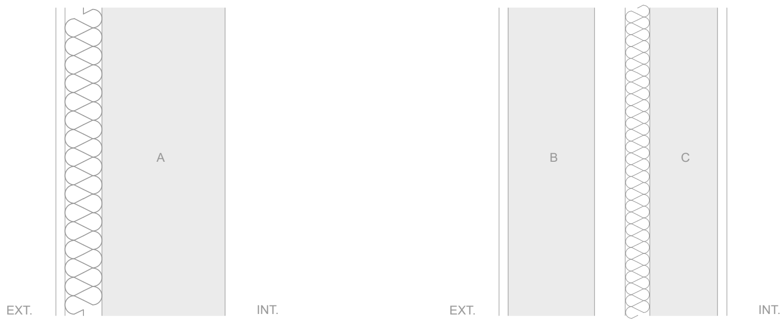

Figure 1: Design templates for single and cavity walls construction solutions.

Table 1: Combinations of the materials used in the cavity walls.

B	**C**
Reinforced concrete (20 cm)	Hollow brick (11 and 15 cm) Thermal brick (14 cm)
Hollow brick (20 cm)	Hollow brick (11 and 15 cm) Solid brick (11 cm)
Hollow brick (15 cm)	Hollow brick (11 cm) Solid brick (11 cm)
Thermal brick (19 cm)	Thermal brick (14 cm)

4 Results and discussion

The analysis of the results, by means of the calculation of the sustainability index, considers two basic design scenarios related to the climate within the scope of residential buildings. Scenario 1 is intended for cold climates where the need for a low heat transfer through the walls prevails over the need for thermal energy retention. In this case, the functional indicator is calculated with a weighting factor of 0.90 for the U-value and a weighting factor of 0.10 for M_{tsu}.

Scenario 2 addresses hot dry climates where the need for thermal inertia should prevail provided that the U-value is not too high (what may be assessed by comparison with national regulations). In this case, the weighting factors are reversed: 0.10 for the U-value and 0.90 for M_{tsu}. In both cases, the environmental parameters, EE_s and EC_s, are weighted at 0.50 for the calculation of the environmental indicator.

In each design scenario, two alternatives are considered in the weighting of the environmental and the functional indicators for the calculation of the final sustainability index. These alternatives represent a progressively higher priority given to the environmental concern. In addition, a scenario that gives full priority to the reduction of the environmental impact is considered. A total of five sets of results are therefore analysed according to Table 2.

Table 2: Weighting factors for the five sets of results.

<table>
<tr><th rowspan="2"></th><th colspan="3">Environmental</th><th colspan="3">Functional</th></tr>
<tr><th>IS_E</th><th>EE_S</th><th>EC_S</th><th>IS_F</th><th>U</th><th>M_{tsu}</th></tr>
<tr><td>Scenario 1.1</td><td>0.50</td><td rowspan="5">0.50</td><td rowspan="5">0.50</td><td>0.50</td><td rowspan="2">0.90</td><td rowspan="2">0.10</td></tr>
<tr><td>Scenario 1.2</td><td>0.75</td><td>0.25</td></tr>
<tr><td>Scenario 2.1</td><td>0.50</td><td>0.50</td><td rowspan="2">0.10</td><td rowspan="2">0.90</td></tr>
<tr><td>Scenario 2.2</td><td>0.75</td><td>0.25</td></tr>
<tr><td>Scenario 3</td><td>1.00</td><td>0.00</td><td>-</td><td>-</td></tr>
</table>

4.1 Cold climates

Scenarios 1.1 and 1.2 address cold climates giving priority to a low heat transfer coefficient. If equal importance is given to the environmental concern and the functional performance (scenario 1.1), the results indicate that the best choice is a single thermal brick masonry wall, with 6 cm of thermal insulation. In this case, there is no difference in applying a mortar render or instead plasterboard as internal finishing. Preferred thicknesses for the thermal brick are, by order, 19 cm, 24 cm and 29 cm.

If the environmental concern is given a priority of 75 percent (scenario 1.2), two main differences arise from the results. On the one hand, 20 cm common hollow bricks are now an important part of the first selection set, together with 19 cm thermal bricks. On the other hand, construction solutions with a thermal insulation thickness of 4 cm are now among the preferred construction solutions together with the ones with 6 cm of thermal insulation.

4.2 Hot dry climates

Scenarios 2.1 and 2.2 address hot dry climates giving priority to thermal inertia. If equal importance is given to the environmental concern and the functional performance (scenario 2.1), the results indicate that the best choice is the set of the four reinforced concrete walls considered in this study. These have indeed the highest values for the net superficial thermal mass. After this first set of four options, the next preferred choices become more diffuse including single 20 cm hollow brick masonries and single thermal brick masonries with a brick thickness of 19 and 24 cm. If the environmental concern is given a priority of 75 percent (scenario 2.2), there is no reinforced concrete wall between the best options. This is due to the fact that these walls have high embodied energy and embodied carbon. In this scenario, the set of preferred options is similar to the one of scenario 1.2, i.e., single common hollow brick masonry walls and single thermal brick masonry walls, with 4 cm or 6 cm of thermal insulation.

4.3 Optimizing the environmental impact

In scenario 3, where full priority is given to the lowest possible environmental impact, the results do not differ significantly from the ones for scenarios 1.2 and 2.2 although it may be observed that construction solutions with common 20 cm hollow brick masonry and a 4cm cork thermal insulation are slightly higher in the list of preferred choices.

4.4 Discussion

The results show that, within the complete set of construction solutions analysed in this research, the most suitable for cold climates are single brick masonry walls. Depending on the relevance attributed to the environmental impact, the type of brick may differ. If a moderate relevance is considered, thermal bricks are preferred because they lead to a lower U-value. However, if a high relevance is given to the environmental aspect, then common hollow bricks are a better choice because they have less embodied energy and carbon due to the lower material usage.

In hot climates, reinforced concrete leads to a good overall ranking of these walls due to the high thermal inertia, but only if a moderate relevance is given to the environment. The also high embodied energy and carbon of the material take these construction solutions out of the best options if a higher relevance is attributed to this indicator. In this case, single brick masonry walls are again the preferred options.

It is interesting to note that in all of these results, cavity walls never show among the top ranked solutions. This is due to the higher level of material incorporated (due to the second masonry) which, in turn, increases the embodied energy and carbon. On the other hand, these cavity walls have a lowest environmental impact than the concrete walls. However, their thermal inertia is roughly half of the thermal inertia of the concrete walls. This is why the cavity walls do not show in the best ranked solutions in hot climates considering a moderate relevance for the environmental concern.

The scenario which would lead to a high rank of some of the cavity wall solutions is one for cold climates (weighting factor of 0.90 for the *U*-value and a weighting factor of 0.10 for M_{tsu}.) and a priority of 70 percent given to the functional parameter, thus implying a low relevance given to the environmental impact (30 percent).

The need for thermal inertia, which may be quite important in hot climates, seems to be conflicting with the objective of reducing the environmental impact of construction solutions. This may be assessed by comparing the average rank of the solutions included above the third quartile (Q_3) of the global set. In scenario 2.1 (hot climates with moderate relevance given to the environment), the average rank for subset above Q_3 is 0.53. This same calculation leads to values of 0.77, 0.81 and 0.68 respectively for scenarios 1.1, 1.2 and 2.2.

5 Conclusions

This study intends to contribute to a more informed selection of building materials in architectural design. Designers have to integrate different and frequently contradictory objectives. To combine architectural conceptualization with functional performance and environmental impact, within the scope of project-specific constraints, requires structured information. A simplified methodology to select heavyweight external walls is proposed, integrating two environmental parameters and two functional parameters related to energy efficiency and thermal comfort. The methodology has the flexibility to allow for the consideration of different design scenarios.

A set of 90 construction solutions was analysed with the proposed methodology for two climate-related design scenarios in residential buildings.

Results show that it is possible to have effective data obtained through a simple method to support designers in a more informed, and thus accurate selection of building materials and construction solutions.

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