The role of Life Cycle Assessment (LCA) in the design of sustainable buildings: thermal and sound insulating materials

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ABSTRACT
Life Cycle Assessment procedures are being used more and more by designers and consultants in the evaluation of the overall environmental impacts of a building throughout its entire life (“from cradle to grave”). Though many studies have demonstrated that the highest impacts of a building are due to its space heating, air-conditioning and electrical consumption, the impacts due to the construction phase and therefore the choice of materials are not negligible. The University of Perugia is carrying out a research, funded by the Italian Ministry for Environment, on the role of the building sector on greenhouse gas emissions; within this research, data on building materials is being collected and methodologies are being tested to help spread the knowledge of LCA procedures in Italy.

First of all, the paper illustrates the aims and methodologies of LCA studies, gives the definition of embodied energy for a building material and presents related data of thermal and sound insulating materials. Finally, the paper presents the results of some simulations carried out on some typical buildings (an independent house, an office building, a block of flats), whose energy and environmental performance was optimised also thanks to a LCA approach. Particular attention was paid to the choice of thermal and sound insulating materials.

1. INTRODUCTION
Energy consumption in the building sector can reach up to 40% of the total energy demand of an industrialized country. For this reason, green building strategies can be extremely effective as far as fossil fuel savings and greenhouse gas reduction. Sustainable materials can play an important role, since less energy is generally required for their production than that needed for conventional materials.

According to the definition of sustainability of the Brundtland Report¹, “Sustainable development meets the needs of the present without compromising the ability of future generations to meet their own needs” a material can therefore be considered sustainable if its production enables the resources from which it was made to continue to be available for future generations and has the lowest possible impact on human health and on the environment. A sustainable material is generally made from natural or recycled materials and its production requires a small amount of energy, makes limited use of non-renewable resources and has a low environmental impact.

According to this definition, many currently used thermal and sound insulating materials can not be considered sustainable, at least as far as energy consumption and greenhouse gas emissions; moreover, some of them can be harmful for human health. For example, mineral wools are widely used because of their good performance and low cost, but their fibres, when inhaled, can accumulate in the lung alveoli, and can cause skin irritation.

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In the last years a great attention has been focused on “green” materials, especially in the building sector. Many research centers have developed new sustainable materials, in many cases with interesting thermal and acoustical properties. Also the public sector started to consider these materials; in Italy, for instance, many Municipalities have introduced into Building Regulations specific recommendations to increase the use of ecological materials in new constructions, allowing a reduction of construction taxes.

In particular, an increasing attention has been turned to natural fibres as alternatives to synthetic ones, in order to combine high acoustic and thermal performance with a low impact on the environment and human health. Recycled materials, such as recycled plastic fibres and recycled rubber mats, can even be regarded as a sustainable alternative, as they contribute to lower waste production and use of raw materials.

It is however very important to assess the real sustainability of a natural or recycled material, and to verify the total energy use in its production process. To this extent, the parameter called “embodied energy” can be of help, but it is only thanks the approach of Life Cycle Assessment procedures (LCA) that a final judgement on the sustainability of a material can be drawn.

2. LIFE CYCLE ASSESSMENT AND ENVIRONMENTAL EVALUATION PROCESS

There are many different procedures and tools to perform the Environmental Performance Evaluation (EPE) of a material or product; the ones most commonly used are the Environmental Indicator Systems (EPI), the Environmental Management Accounting (EMA), the Environmental Management Systems (EMS), the Life Cycle Analysis (LCA) and the Eco-labelling. The most complete tool is for sure LCA. The concept of LCA is based on:

- the consideration of the entire life cycle which includes raw material extraction and processing, production and use, up to recycling and disposal;
- the consideration of all environmental impacts connected with the life cycle such as air, water and soil emissions, wastes, raw material consumption or land use;
- the aggregation of the possible impacts of the environmental effects in consideration and their evaluation in order to give environmental oriented support to decisions made.

The LCA methodology is implemented by ISO 14040 standard guidelines. The main steps followed within the LCA frame are:

Goal definition, System’s boundaries, Inventory Analysis, Evaluation of the impacts, Interpretation.

There are many evaluation methods used within LCA studies and various different commercial codes which implement the methods. The code Sima Pro was used in the present paper; within SimaPro the three methods of Cumulative Energy Demand (CED), IPCC (International Panel on Climate Change) and Eco-Indicator 99 were chosen.

IPCC method classifies the different emissions according to their contribution to greenhouse effect; the indicator is Global Warming Potential (GWP), the unit is kg CO₂-eq. The energy used during the entire life cycle of the building is calculated by the method of Cumulative Energy Demand (CED), the unit is MJ-eq. Finally, Eco-Indicator 99 is one of the most complex and complete methods. It allows the evaluation of the emissions and the use of resources according to 11 impact categories (carcinogenic substances, respiratory diseases, climate changes, ozone depletion, radiation that causes ionisation, acidification/eutrophication, ecotoxicity, land use, mineral resource depletion and fossil fuels), grouped into three damage categories:

1. damage to human health, expressed as the number of years of human life lost or in suffering from diseases;
2. damage to the quality of ecosystems, expressed as the loss of living species in a certain area over a certain period;
3. damage to resources, expressed as the surplus of energy necessary for the further extraction of minerals and fossil fuels.
3. SUSTAINABLE MATERIALS FOR THERMAL AND SOUND INSULATION IN BUILDINGS

These materials can be divided into two main categories:

- natural materials: cotton, hemp, wool, flax, clay, etc..
- recycled materials: rubber, plastic, cellulose, carpet, etc..

Recent Literature reports a wide variety of materials, from the most common to the least conventional solutions. Sustainable materials are in many cases comparable to traditional ones as far as thermal and acoustic performance is concerned. Though for many products physical properties have not been analysed in depth and are not yet certified, they have already reached a certain technical and commercial maturity.

A. Natural materials

As for natural materials, the less they are treated, the higher they perform in energy saving; native materials need to be used in order to reduce transport energy. Moreover natural fibres have positive impacts as far as climate change (CO₂ absorption). Nevertheless other performances have to be considered: vegetal fibres are more subject to fungal and parasitic attack and are less resistant to fire than mineral fibres. The toxicity of the chemical products used for cultivation must also be taken into account.
B. Recycled materials
Many recycled materials, such as waste rubber, metal shavings, plastic, textile agglomerates can be used to prepare thermal and acoustic materials. It could be useful to mix various recycled materials of different granular sizes to obtain the desired performance; in these cases a binder or glue has to be added in the appropriate proportion 11.

4. EMBODIED ENERGY
Embodied energy is defined as the available energy that was used in the work of making a product. Embodied energy is an accounting methodology which aims to find the sum total of the energy necessary for an entire product lifecycle, including raw material extraction, transport, manufacture, assembly, installation, disassembly, deconstruction and/or decomposition. Different methodologies produce different understandings of the scale and scope of application and the type of energy embodied. International consensus on the appropriateness of data scales and methodologies is pending. Embodied energy is a new concept for which scientists have not yet agreed absolute universal values because there are many variables to take into account, but most agree that products can be compared to each other to see which has more and which has less embodied energy. Typical embodied energy units used are MJ/kg (megajoules of energy needed to make a kilogram of product), tCO2 (tonnes of carbon dioxide created by the energy needed to make a kilogram of product).

In particular, the energy embodied in a building is the total energy consumed in extracting the raw materials, manufacturing the components and constructing the building on site. It includes the energy consumed for transportation within and between each of the stages leading to the completed building. Calculated in this way embodied energy figures are clearly site specific. They are related to the specific materials, suppliers and efficiency of distribution and delivery route. There is however generally no need for such a precise figure to be determined in order to provide useful data for building designers. It is common practice to consider 'Factory Gate' figures for embodied energy. These represent the energy embodied in the extraction and manufacturing processes and exclude the final delivery to construction site. However there can be significant differences for similar materials produced through different supply chains. The UK Code for Sustainable Homes and USA LEED Leadership in Energy and Environmental Design are standards in which the embodied energy of a product or material is rated, along with other factors, to assess a building's environmental impact.

Embodied energy figures published for common building materials vary enormously and there is often little indication of how they have been obtained 12. Furthermore, embodied energy data refers to the mass or volume unit of materials (Joule/kg or J/m³), and does not take into account the different performance as far as thermal or sound insulation.

5. THERMAL INSULATING MATERIALS
In order to give a more precise evaluation of the Embodied Energy of thermal insulating materials, a comparison was carried out taking into account the different thermal conductivities of the various materials. The Functional Unit (FU) was defined as the quantity of material necessary to guarantee a thermal resistance of 1 m²K/W for 1 m² of wall. According to the different thermal conductivities and densities, the thickness and the weight of each material necessary to guarantee such a performance was evaluated, and the corresponding Embodied Energy calculated. Results, expressed in MJ/FU, are reported in Fig. 2. It is evident that some natural materials, such as cellulose flocks or cotton, show very low values of Embodied Energy, while expanded polyethylene or polyurethane exhibit the highest values 2. There are also some natural materials (wood fibres) whose embodied energy is as high as that of synthesised materials. Such results are confirmed by the application of the Cumulative Energy Demand method to the entire Life Cycle of some of the materials in Fig. 2; the results are reported in Fig. 3. If we consider the whole life cycle, cellulose flocks is the material with the lowest energy demand, while expanded polyethylene the one with the highest.
**Figure 2**: Embodied Energy of various thermal insulating materials per Function Unit (MJ/FU)

**Figure 3**: Comparison of the entire Life Cycle Impact of various thermal insulating materials (Cumulative Energy Demand Method), for a given value of thermal resistance
6. ACOUSTIC MATERIALS

It is more difficult to describe the performance of acoustic materials with a single index as it has been done with thermal insulating materials, since there are at least three acoustic properties which are of interest for building designers: airborne sound reduction index $R_w$, impact sound reduction index $\Delta L_{W}$ and sound absorption coefficient $\alpha_s$. Airborne sound reduction index $R_w$ is often available for wall packages including bricks and plasters, so it is difficult to obtain the data for a single material. Some data concerning the absorption coefficient and the impact sound reduction index of traditional and sustainable materials is reported in Table 1, along with their Embodied Energy per mass unit. When not specified, absorption coefficient refers to 4 cm thick panels while the index of reduction of impact noise refers to 2 cm thick panels.

It is confirmed that Expanded Polystyrene has a very high value of embodied energy per mass unit, glass and rock wool intermediate values, while coconut or cellulose very low values.13

<table>
<thead>
<tr>
<th>Material</th>
<th>Absorption coefficient $\alpha_s$ at 500 Hz (-)</th>
<th>Index of reduction of impact noise $\Delta L_{W}$ (dB)</th>
<th>Embodied energy (MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hemp</td>
<td>0.6 (30 cm)</td>
<td>-</td>
<td>15</td>
</tr>
<tr>
<td>Kenaf</td>
<td>0.74 (5 cm)</td>
<td>-</td>
<td>15</td>
</tr>
<tr>
<td>Coco fiber</td>
<td>0.42</td>
<td>23</td>
<td>4.90</td>
</tr>
<tr>
<td>Sheep wool</td>
<td>0.38 (6 cm)</td>
<td>18</td>
<td>12.60</td>
</tr>
<tr>
<td>Cork</td>
<td>0.39</td>
<td>17</td>
<td>7.05</td>
</tr>
<tr>
<td>Cellulose</td>
<td>1 (6 cm)</td>
<td>22</td>
<td>4.24</td>
</tr>
<tr>
<td>Flax</td>
<td>-</td>
<td>-</td>
<td>33.12</td>
</tr>
<tr>
<td>Glass wool</td>
<td>1 (5 cm)</td>
<td>-</td>
<td>34.60</td>
</tr>
<tr>
<td>Rock wool</td>
<td>0.9 (5 cm)</td>
<td>-</td>
<td>22.12</td>
</tr>
<tr>
<td>Expanded polystyrene</td>
<td>0.5</td>
<td>30</td>
<td>99.20</td>
</tr>
</tbody>
</table>

7. CASE STUDIES

In order to implement LCA methodologies and verify the influence of material choice on the entire life cycle of a building, several simulations were carried out on buildings typical of Italian architecture (an independent house, an office building, a block of flats), whose energy and environmental performance was optimised also thanks to the LCA approach. Particular attention was paid to the choice of materials and to the exploitation of renewable energies within the building (photovoltaic modules, passive solar systems).14

For the sake of brevity only a few results are reported here. The Eco Indicator method, applied to the entire life cycle of the three buildings, shows that the relative impact of the construction phase is not negligible, varying from 13% of the office building up to 25% of the independent house. The impact due to the operation of the building (whose life was estimated at 50 years) was of course the highest contribution to the overall impact (up to 86%), but this will decrease due to the new regulations on energy savings in buildings.15 For this reason, especially in future scenarios, the choice of environmentally-friendly materials, with a reduced embodied energy and which are recyclable at the end of life of the building, will become more and more important.

To evaluate the impact of the choice of natural thermal and sound insulating materials, various optimisations of the three buildings were carried out. For the sake of brevity, the results of the block of flats (building c) are reported here. The initial design of the building included conventional insulating materials, such as glass wool and expanded polystyrene. All the insulating materials were substituted with thicker panels of recycled cellulose flocks (commercial name ISOCELL). The results of the LCA simulations, with regard to the three methods, are
reported in Table 2. The benefits are evident in all life cycle phases and with regard to all the evaluation methods. The reduction of Cumulative Energy Demand is equal to 3.7% during construction and to 3.5% during operation of the building. The emissions of CO2eq during operation are reduced from 74,922 kg per year to 72,444 kg per year; considering a lifespan of the building of 50 years, the total reduction is approximately 125 tons of CO2eq. There is also a significant reduction of the impact at the end of life of the building, due to the recyclability of the insulating material (-18.4%).

Figure 4: Views of the three buildings chosen as case study for LCA analysis a) independent house; b) office building, c) block of flats

Figure 5: Eco Indicator methodology. Overall impact and relative contribution of the building phases for the independent house
**Figure 6:** Eco Indicator methodology. Overall impact and relative contribution of the building phases for the office building.

**Figure 7:** Eco Indicator methodology. Overall impact and relative contribution of the building phases for the block of flats.
Table 2: Block of flats - results of LCA simulations with regard to the initial design and the optimization of thermal and sound insulating materials.

<table>
<thead>
<tr>
<th>Life cycle phase</th>
<th>Cumulative Energy Demand</th>
<th>IPCC GWP 100a</th>
<th>Eco Indicator 99</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MJ-Eq Variation (%)</td>
<td>kg CO2-Eq. Variation (%)</td>
<td>Pt Variation (%)</td>
</tr>
<tr>
<td>Construction - initial design</td>
<td>14132193 - 3.7</td>
<td>1048201 - 0.3</td>
<td>84602 -2.3</td>
</tr>
<tr>
<td>Construction - optimization</td>
<td>13616005 - 3.5</td>
<td>1044752 - 3.3</td>
<td>6144,79 -3.5</td>
</tr>
<tr>
<td>Operation - initial design</td>
<td>1196691 - 3.5</td>
<td>74922 - 3.3</td>
<td>5929,07 -3.5</td>
</tr>
<tr>
<td>Operation - optimization</td>
<td>1154311 - 5.3</td>
<td>72444 - 14,9</td>
<td>1131,49 -18,4</td>
</tr>
<tr>
<td>End of life – initial design</td>
<td>-1895570 - 5.3</td>
<td>-73043 -14,9</td>
<td>-83926 -14,9</td>
</tr>
<tr>
<td>End of life – optimization</td>
<td>-1996229 - 5.3</td>
<td>-83926 -14,9</td>
<td>-1131,49 -18,4</td>
</tr>
<tr>
<td>Entire LCA - initial design</td>
<td>1453020 - 3.4</td>
<td>95109 - 2.4</td>
<td>7748,92 -2.8</td>
</tr>
<tr>
<td>Entire LCA - optimization</td>
<td>1403402 - 3.4</td>
<td>92827 - 2.4</td>
<td>7748,92 -2.8</td>
</tr>
</tbody>
</table>

8. CONCLUSIONS
Life Cycle Assessment procedures can be a powerful tool to evaluate the real sustainability of a building or of a building material over its entire life. The paper presents the procedures of LCA studies, discusses the concept of embodied energy of thermal and sound insulating materials and provides some related data. The paper presents also the results of some simulations carried out on some typical buildings (an independent house, an office building, a block of flats), whose energy and environmental performance was optimised also thanks to a LCA approach. The results show that the substitution of conventional thermal and sound insulating materials with sustainable ones (i.e. recycled materials) has significant effects on the impact of all the various phases of the life of the building (construction, operation, end of life).

ACKNOWLEDGMENTS
The research was made possible thanks to the National Project FISR “Genius Loci - Il ruolo del settore edilizio sul cambiamento climatico”, funded by the Italian Ministry for University and Scientific Research.

REFERENCES