Layered dry envelope components in the Mediterranean areas.
A field evaluation of a sheep wool-lime mix.

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ABSTRACT

This paper describes the results of a research aimed to design and assess a new layered envelope component that might be implemented on buildings of the Mediterranean area, in order to improve the energy efficiency and the environmental sustainability. These goals have been achieved by means of the use of local and natural building materials or arising from renewable resources. In particular, thermal insulating has been realize utilizing a mix of natural and mineral materials, obtaining a biocomposite with comparable building physics and mechanical properties to commonly used building materials. Among natural materials, the sheep wool was chosen since it is, on the hand, a waste to exploit and, on the other hand, it has a good behavior towards heat, moisture and indoor air pollution. Several sample have been realized mixing sheep wool, at different granulometry, with lime in different weight percentages. For each sample, thermal tests have been performed by means of a heat flow meter. The U value, Yie, mass and time lag have been evaluated for the whole designed system according to the Italian standards. In order to compare the environmental impact of the designed system with a similar commercial product, a Life Cycle Assessment has been carried out. Finally, thermal performance of the envelope system was evaluated by simulating its use in the retrofit of the old structure of a factory both in wall and in floor elements. The results was good in terms of energy balances of the building, while LCA results are contradictory, being one of the main issue the lack of data for local materials not directly investigated by authors.

KEYWORDS

Natural materials, sheep wool, dry-built envelope, life cycle analysis, thermal performance.

INTRODUCTION

Energy efficiency in buildings is one of the main strategies to reduce environmental impact of the building sector. This goal can be obtained not only reducing energy demand for heating and cooling, but also, for example, improving envelope performances. On the other hand, the new approaches to energy efficient design are not only moving in the direction of lower and

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lower U-values to achieve lower energy consumption, but also including development and use of natural and local building materials reducing the global impact of the building in a life cycle perspective. The development of natural construction materials represents an increasingly highlighted issue in order to reduce thermal losses and greenhouse emissions during the building life.

Many researchers have approached the study of natural materials, especially investigating their thermal insulating properties. The most studied materials are hemp [1,2], jute [3, 4], cork [5], hay [6], flax [7, 8], coconut [9]. Beyond high environmental performances, a good natural material should also respect traditional quality criteria, like transpirability, hygroscopicity, fire resistance, molds and fungi resistance, odorless, lack of radioactivity and dangerous substances, electrical neutrality and recyclability [10,11]. Sheep wool, hemp and flax, for instance, are characterized by a low thermal conductivity value and by a good ability to regulate the moisture content. However, many natural materials are affected by the risk of flammability [12]. Differently, sheep wool is also self-extinguishing and acoustically absorbent [13]. Another aspect that has to be taken into account about the utilization of natural materials in buildings is the change of some of their properties, according to the considered material [14], depending on the zone of provenience, harvest time, extraction methods, attacks from alkaline and biological substances, deterioration due to high temperatures or humidity (natural fibers are generally hydrophilic) [2].

In this work, a first analysis of the thermal behavior of a biocomposite concrete, constituted by a mineral matrix (lime) with the addition of sheep wool, has been carried out, with particular attention to the amount of fibers and its granulometry in the mixture. Moreover, a new layered envelope component that might be implemented on buildings of the Mediterranean area in order to improve the energy efficiency and the environmental sustainability, has been designed and assessed. The designed layered envelope system is composed by a layered core panel and two dry claddings. Two Oriented Strand Board panels, a waterproof sheet of Kraft Paper and a thermal insulating panel, in turn, compose the layered core panel, which could be used as a partition wall as well as a component of envelope walls, floors and roofs.

Enhancing the physical properties of a natural material by introducing and testing biocomposite represents an opportunity in order to carry out better performances of buildings. A recent research of the University of Catania compared four layered envelope systems by assessing physical properties, both thermal and mechanic, and the environmental impact of the construction stage [15]. In the work of Kozlowski *et al.* [16] a flexible upholstery barrier non-woven based on natural raw materials such as mats made with flax and wool has been studied. In this paper, authors have investigated the thermal performances of several samples realized mixing sheep wool, at different granulometry, with lime in different weight percentages. The experimental phase has adopted dosages and methods already utilized in a previous research conducted on hemp biocomposite at the Laboratory of Natural Materials for Building Construction at University of Palermo [1]. The choice to test a crop fiber in a mineral matrix was driven by the need to reach a higher mechanical resistance. Expected and achieved results of the present research are coherent with the previous studies and show that biocomposite based on natural material have a more variable and less controllable behavior than synthetic and widespread solutions but drastically decrease the environmental impact. In this framework a good tool account for this impact is represented by the LCA [17]. In order to compare the environmental impact of the designed system with a similar traditional product, a Life Cycle Assessment has been carried out. Finally, the thermal performance of the whole designed envelope system was evaluated by simulating its use in the retrofit of the old structure of a factory either in wall and in roofing elements. The results was good in terms of energy balances of the building, while LCA results are contradictory because of the lack of data for local materials not directly investigated by authors.

The aim of research The final goal of the research was to design a multipurpose envelope system that would be naturally insulated, locally produced, built with low embodied energy materials and easy to install. An important feature was the multi-disciplinary approach at different scales that has allowed us to integrate knowledge and approaches from different scientific fields as building technology and building physics.

METHODOLOGY

Several objectives have been pursued, reporting in the following.

- Testing a biocomposite to realize an insulation panel that could associate a low conductivity and a high thermal inertia to satisfy thermal requirements of a warm climate.
- Designing an envelope solution that would be insulated with the tested insulation panel and easy installed as facade, roof, floor and partition wall.
- Evaluating the environmental impact of the facade construction.
- Simulating either the energy need of an existing building that would have been refurbished by replacing the envelope with the designed one and the on-site energy production thanks to photovoltaic panels.

In order to satisfy these aims the research and the present paper have been composed in the following sections: “construction technologies research”, “experimentation on sheep wool insulation”, “design”, “environmental performances evaluation” and “energy performances evaluation”.

CONSTRUCTION TECHNOLOGIES RESEARCH

Traditional construction technologies

The development of construction techniques is based on a complex system of human habits, climatic conditions, availability of material and general resources. The observation of the historical framework allows to enhance the current ones focusing on social needs. Since an issue written by Kenneth Frampton [18], two approaches could have been recognized in the whole construction history. In one hand, massive and wet building have been realized ensuring a good thermal behavior being the most common technique used in earthen wall, fortifications and buildings. The “stereothomy”, which is the name of this approach, is based on the overlap of single bound with mortar elements. In the other hand, the "tectonic approach" is recognizable for linear and modular structures that define a spatial matrix. Usually, it brings dry structure and flexible assembly systems. From the 11st century BC in Sicily, construction techniques have been evolved basing on high value of mass to release the heat absorbed during the day. Nowadays, energy efficiency represents one of the major strategies to reduce the environmental impact of buildings and it can be obtained increasing the energy saving of the building with better envelope solutions. Building in a warm climate requires to ensure the thermal inertia because increasing the thickness of the insulation could not be always satisfying. Thermal inertia includes attenuation and time lag and is related to the material mass, all physical parameters that play a main role in the Mediterranean buildings [19].

Available commercial products

To compare industrial products currently on the marketplace gives the opportunity to highlight many strength and weakness factors related to specific performances and cost aspects. Twenty-eight existing products have been assessed in order to evaluate the advantages and disadvantages in terms of ease of installation, energy performances, embodied energy by the incidence of transports. As expected, panels using a complex layering made of different material allows to satisfy increasingly requirements. The comprehension of the analysis is facilitated by a well structured cataloging distinguishing among constructive techniques, materials and thermal properties, that origins from the existing classification reported in Italian standard UNI 8290/81 [20]. The additional classes are:

- Composition: compound layered panels / to be composed layered panels.
- Insulation material: vegetable / animal / mineral / mixed / synthetic.
- Cladding material: several solutions.
- Insulation position: internal / in a cavity / external.
- Constructive technology: bounded / dry built / mixed.

The scope of this study was to extract some topic requirements to be applied in the design objectives. The product will be an insulation panel made with natural materials, characterized by high density and heat capacity, to be produced on-site.

LAB TEST OF SHEEP WOOL INSULATION

Methodology

The testing phase was conducted at the Laboratory of Natural Materials for Building Construction at University of Palermo, in 2013 within three months. The choice to use sheep wool was raised by the opportunity to valorize a waste into a building material, recycling a lost resource insofar sheared wool not used for the textile trade must be disposed in Sicily. One of the priority was the exploitment of its good thermal and hygroscopic behavior. Sheep wool comprises an excellent hygroscopicity adsorbing above 30% of condensed water. In addition, it is capable to reduce indoor pollution, attracting noxious substances such as formaldehyde. The main purpose of the experiment was to use natural and local materials in order to produce an insulating panel that would also involve a good thermal behavior in terms of dynamic state of heat flow. To achieve a high mass and density with a low thickness a biocomposite made of sheep wool and lime has been realized. The whole production process was realized at the lab, starting from the preparation of material, mixing of the biocomposite, realizing the samples of the insulating panel, evaluating the thermal conductivity.

Preparation of the biocomposite. The first stage consisted in storing and preparing raw materials (Figure 1). Sheep wool flakes, coming from local flocks, have been cleaned only with water in order to separate wastes from fibers without changing the chemical properties. After drying, lime and sheep wool have been grinded. A knife milling machine has been used to reduced the dimension of sheep wool fiber to 6 mm and 4 mm. This phase would facilitate the amalgamation of raw materials. Consequently, the biocomposite has been realized with a matrix of lime (density equal to 564 kg/m^2) and hydraulic lime (density equal to 1012 kg/m^2), water and sheep wool (density equal to 50 kg/m^2). Data on density of lime and hydraulic lime have been declared by the real data sheets, while data on density of sheep wool was derived from literature. In order to test several mixtures, different percentages of sheep wool (respectively equal to 20%, 30% and 40%) and different fiber dimensions have been assumed.

Figure 1. Preparation of the biocomposite.

Measurements. The mixtures have been poured into 300 x 300 mm wooden mold with a thickness equal to 30 mm according to standard UNI EN 12667:2002 [21], which for example recommends to make accuracy in respecting the parallelism of samples. For each mixture, two molds have been realized. The nomenclature assumed was made of three digits that referred to the percentage of sheep wool (L00%) and to the dimension of sheep wool fibers (F0 mm), the last capitalized alphabetic letter allowed to identify the single sample. The molds dried in two phases: first with a natural drying process for fifteen days and then, in a climate chamber for four days. Thermal conditions were set with a temperature equal to 30°C and a forced ventilation. During the whole natural drying period the samples have been weighed every day to control the reduction of water content. Approximately, the decrease of weight varied between 6% and 9%, except for the L30-F6-A specimen for which changed almost to 20%. An evaluation of the conductivity of the samples was made using a heat flow meter. The calculation has been conducted setting the upper temperature equal to 25°C and the lower to 15°C. The generated heat flow varied between 38 W/m^2 and 43 W/m^2.

Results

Table 1 reports the properties of the most representative samples. It is worth noting that the obtained values of conductivity are quite satisfying. Conductivity values are not properly comparable with the one of insulating materials but, on the other hand, they are quite good for material which can provide quite high mass to the structure. Nevertheless, it is important to highlight that further analyses should be carried out on configuration of sheep wool natural biocomposite and on the drying process of the material, as it can greatly influences thermal and mechanical properties.

Table 1. Properties of the samples.

Sample code	Dosage				Density [kg/m^3]	Conductivity [W/mK]
	Sheep wool percentage	Lime	Hydraulic lime	Water		
L20-F4-A	20 %	16 %	64 %	3583 g	747,9	0,15
L20-F6-A	20 %	16 %	64 %	3583 g	747,9	0,14
L30-F6-A	30 %	14 %	56 %	5323 g	660,7	0,13
L40-F6-A	40 %	12 %	48 %	5664 g	573,4	0,11

DESIGN OF A LAYERED PANEL

The second purpose of the research was to design a layered panel that would have the function of a building envelope in accordance with product standards [22]. Dry construction ensures an ease installation which carries out flexibility, versatility and more precision. For instance, it is relatively simple to being removed and replaced if not working. Another interesting aspect refers to the possibility of taking the same product to different parts of the building by changing just a few elements. However, it is a common knowledge that a weakness of layered and dry-built system consists in a low durability [23] that is inversely proportional to greenhouse emissions [24]. The basic version of the envelope system has the following dimensions: mm 2400/1400/160 and the layers are connected with steel profiles. This core is made of two external (2 cm) Oriented Strand Boards, a waterproofing Kraft paper sheet and three (4 cm) insulating panels as tested. The layering of the material was provided by a comparison among some existing and sold solution that have been analyzed during the first part of the research.

Applications

As said before, the system is changeable into other three versions whose installation has been supposed for an existing building. It is important to notice that the following solutions are considerable just a proposal because several alternatives could be designed.

The facade module would enclose the core panel with a covering. Outside a cm 2 not ventilated air cavity and an external cladding with brick slabs while inside another not ventilated air cavity and a plasterboard cladding are added to the core panel. Regarding the roof, the inner side is similar to the facade, while outside a tile cladding is added. The floor consists in a core directly overlapped on the existing floor while the cladding is made with a floating floor that makes possible to integrate radiant panels for a heating supply.

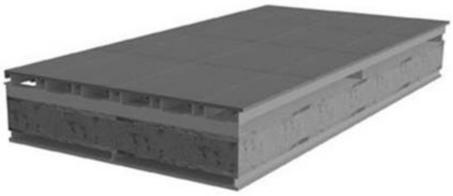

Figure 2. Model of the facade solution.

Thermal properties

The present layered solutions would assure a good thermal insulation and a good heat flow attenuation and time lag too. Table 2 shows the main properties for the four elements. In addition, the vapor condensation check has been performed for different climates with good results.

Table 2. Properties of the envelope solutions.

Components	Thickness (cm)	U value (W/m^2K)	Yie (W/m^2K)	Ms (kg/m^2)	Time lag (h)
Partition	17	0,35	0,089	122	11
Facade	23	0,43	0,098	167	12
Floor	42	0,46	0,054	717	16
Roof	24	0,35	0,056	166	14

Integration with RES

The envelope can be integrated with the plant system, i.e. radiant panels on the floor for heating supply and PV on the roof for energy production. This can be easily allowed by its layered and dry system construction. The advantage is to have a system that does work as structure and systems, making them as efficient. In this way, the PV module is not concerned as a plant simply overlaid on the roof.

ENVIRONMENTAL PERFORMANCES EVALUATION

Method and sources

In order to verify the environmental impact of the production process of the designed system, a life cycle assessment was carried out by using the SimaPro7.1 tool and in accordance with the UNI EN ISO 14040:2006 [25].

Goal definition and scoping. A comparative assessment has been carried out between the designed solution and a similar commercial product. The designed system is a core panel made with a natural biocomposite insulating (sheep wool and lime) and other recycled materials, as Kraft Paper and OSB panels. The reference system, instead, is a core panel sold by an Italian company, which is composed of two external plywood panels, a waterproofing sheet of polyethylene and a rock wool insulating. For the analysis, it is supposed to cover outside both the cores with the same claddings as brick slabs, a layer of plasterboard and two small air cavities. It is important to notice that, both envelope solutions are considerable sustainable and with low embodied energy. This choice is driven by the wish to minimize the use of materials arising from the synthesis of oil. The main goal of this analysis was to demonstrate how a building solution could be maximized if constructed with local and natural materials for the same thermal performances [26].

However, the main weakness of the LCA method is the lack of reliable data regarding local materials. With the exception of data related to the thermal insulation realized (raw material and energy consumption), data from literature, database or from official Environmental Product Declarations (EPD) issued by some companies, have been utilized for the other materials of the analyzed system.

Functional unit. The choice of the functional unit is a fundamental phase of the LCA method because of the opportunity to compare several studies. In this case, one square meter of facade (made of external cladding + cavity air + core + cavity air + internal cladding) providing an U value equal to 0,43 W/m^2K has been assumed for both facade systems.

System boundary. Regarding the assumed boundary conditions, the study focused on the production stage and the transports incidence, not considering the environmental impact related to the use phase and the allocation process of the system and of the provision of capital goods. Data on production have been related to the consumption of materials, including quantities of raw materials and depending wastes and the consumption of not renewable energy. Additionally, distances of transportation of the produced elements to the site of the building have been gathered. In this way, the Life Cycle Inventory (see Table 3 and 4) has been compiled, and the impact assessment was evaluated by using the software database. Particularly, the "Ecoinvent" database referring to European statistics was chosen [27].

Table 3. Life Cycle Inventory of one square meter of the designed facade.

Element	Transportation	Production	
		Raw material consumption	Not renewable energy consumption
	km	kg	MJ
Brick slabs	212	21	0,68
OSB panels	2487	91	5370
Kraft Paper	1576	0,009	1,4
Biocomposite	114	132	1333
Plasterboard	2366	24	133
Metal profiles	60	50	919,0
TOTAL		**319**	**7757**

Table 4. Life Cycle Inventory of one square meter of the reference facade.

Element	Transportation	Production	
		Raw material consumption	Not renewable energy

			consumption
	km	kg	MJ
Brick slabs	212	21	0,68
Plywood	1531	22	9031
Kraft Paper	1576	0,000045	0,70
Rockwool	1531	16	164,5
Polyethylene	1531	170	236
Plasterboard	2366	24	133
Metal profiles	60	50	919,0
TOTAL		**304**	**10486**

Results

Except for the Not Renewable Energy consumption value of the design product that is lower than the one of the reference system, similar results have been achieved for both systems concerning the other ambits of impact, as shown in Figure 3. In particular, the production of the reference envelope mainly affects the ozone layer, abiotic depletion and marine aquatic eco-toxicity categories, while the production of the designed envelope deals with higher global warming potential, eutrophication and acidification ones (see also Table 5).

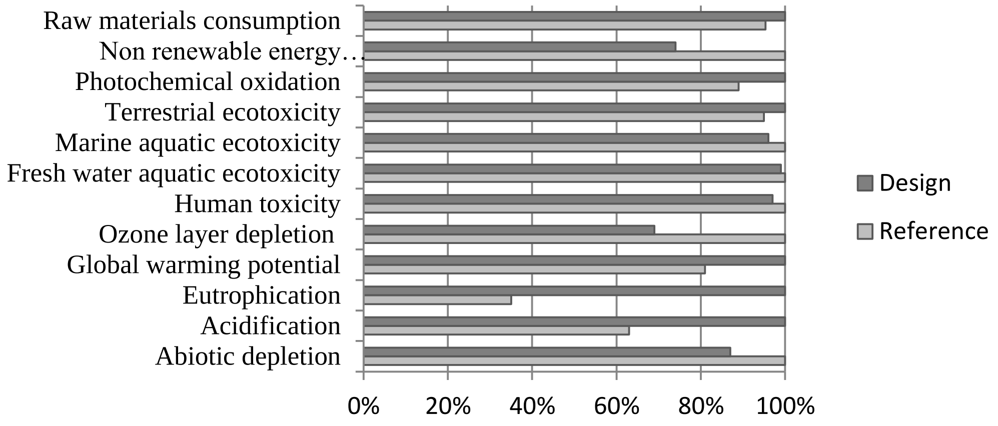

Figure 3. Environmental impact assessment

Table 5. Environmental impact Assessment

Impact category	**Unit**	**Reference**	**Designed**
Abiotic depletion	kg Sb eq	9,7	8,4
Acidification	kg SO2 eq	12,6	20,0
Eutrophication	kg PO4--- eq	1,7	4,9
Global warming potential	kg CO2 eq	1295,9	1599,9
Ozone layer depletion	kg CFC-11 eq	0,000055	0,000038
Human toxicity	kg 1,4-DB eq	4482,6	4348,1
Fresh water aquatic ecotoxicity	kg 1,4-DB eq	962,5	952,9
Marine aquatic ecotoxicity	kg 1,4-DB eq	1282788,9	1231477,4
Terrestrial ecotoxicity	kg 1,4-DB eq	5,9	6,2
Photochemical oxidation	kg C2H4 eq	0,6	0,6
Raw material consumption	kg	304	319
Not renewable energy consumption	MJ	10486	7757

An improvement of the environmental performances of the design product may arise from the possibility of increasing the provision of local materials and elements. For sure, the production of metal profiles is the most polluting process and the chart below confirms this (Figure 4).

However, it is noticeable that also the production both OSB panels and biocomposite, negatively affects the environment.

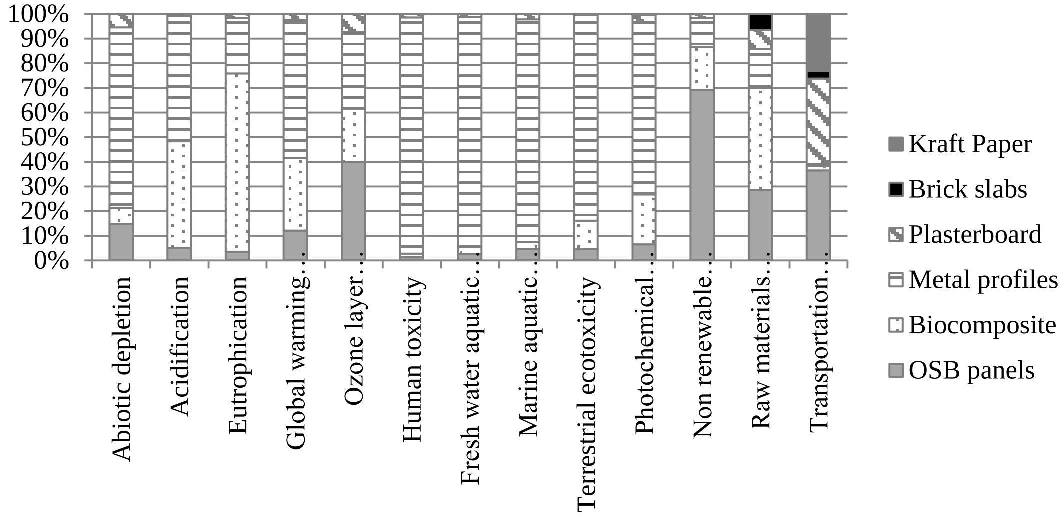

Figure 4. Relative environmental impact assessment of each material of the designed envelope.

It is also worth noting that, the biocomposite production strongly affects the category of eutrophication due to the addition of nutritive substances during the sheep farming. This is explainable noticing that the sheep wool supply represents the most polluting process because of the influence of data on pastoralism and land management, which were not similarly included in the other processes.

Although materials from recycled sources such as Kraft paper and OSB panels have been chosen in order to reduce dissipation of the raw materials, this has caused a high impact of transports since they come from Germany. Hence, a more detailed study of local supply chains and its potential should have been done.

The amount of heterogeneous data adopted clearly represents a weakness of the LCA, which gives some incoherent conclusions. More reasonably, a possible improvement of the methodology should concern a better gathering and definition of real data.

On the other hand, if we consider that the sheep wool which is utilized for the construction of the panel is basically a waste, a specific LCI should be performed not considering the impact of farming activities but only the ones related to the processes realized “outside the farm gates” which are related to its use as raw material for the panel construction (washing, refining, cutting, handing, transport, assembly of the biocomposite). In this case, we can expect very different results in terms of sustainability of the product.

ENERGY PERFORMANCES EVALUATION IN A RETROFIT CASE STUDY

Methodology

The quality of a building depends on many factors such as location (microclimate integration), envelope (shape, materials, orientation), energy consumption (efficiency of each subsystem, appliances, lighting, heating and cooling), occupants habits [26,28].

In order to assess the possible use and efficacy of the product in the scale of building projects, a case study has been chosen in order to perform an energy simulation. The main goal of this stage was to calculate how the energy demand for building climatisation can be reduced as a result of the envelope refurbishment. Consequently, an assessment of the architectural integration between building and plants was conducted. An interior design was prepared supposing a renovation of an old textile farm in Palermo (ITA) and a conversion of the building to a cultural center. Spaces for temporary and permanent exhibit, logistics and catering, workshops for craftsmen, bookshops were provided. The design regarded also technological aspects because of the need to integrate the existing structure with the envelope solution as already described. Except for the floor on which the designed system would have been overlapped, the other parts of envelope would have been replaced (Figure 5).

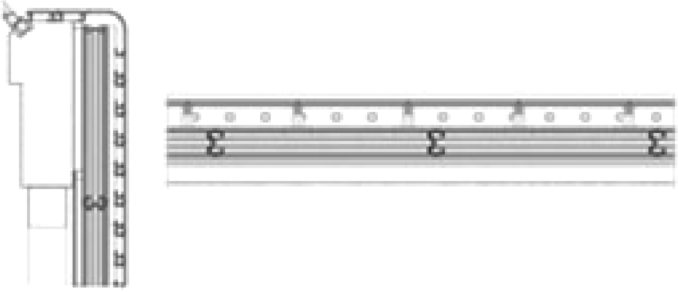

Figure 5. Sections of facade and floor solutions.

Simulation. According to this perspective, the entire building was modeled with the Ecotect tool [29], assigning materials and layers to the envelope as designed and ten thermal zones to the building.

For each thermal zone, six different use profiles were set concerning respectively occupancy, activity, equipment, ventilation, heating, cooling systems.

Finally, exploiting the south-facing of shed roof the installation of above 1800 m^2 of photovoltaic panels with a 12% efficiency has been designed (Figure 6).

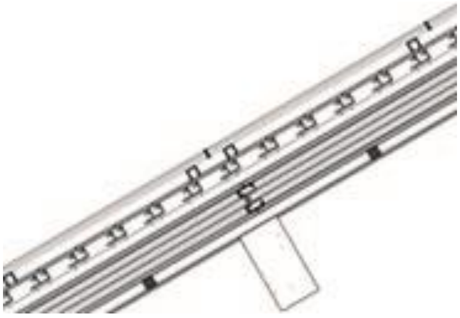

Figure 6. Sections of roof solution.

Good results have been achieved thanks to the more efficient envelope that has optimized an existing good orientation of the building decreasing thermal losses (Table 6). Heating need widely complies with national limits in force which correspond to 6,4 kWh/m$^3_{\text{year}}$ for an exhibit building having a shape factor equal to 0,59 and located in the B climate zone. As an additional proof of the existing favorable orientation of the building, the installation of PV over the roof gained a high efficiency supplying almost 80% electric energy of the overall need.

Table 6. Energy balance.

	Benchmark (kWh/m^3)	Total demand (kWh)	Specific demand (kWh/m^3)	Solar energy production (kWh/m^3)
Heating	6,4	46160	3,6	2,9

CONCLUSIONS

The assumed methodology has allowed to define a well design process by defining goals and prior knowledge. The subsequent analysis made possible to identify the strengths (versatility, low environmental impact, high thermal inertia, almost local production) and weaknesses (conductivity, data availability, raw material availability) of the project in such a way to provide a list of possible improvements.

Since an energy perspective, this research has endorsed that energy efficiency is an important and real purpose to reduce the environment responsibilities of the building sector. This comes from an integration between passive and active measures. On the other hand, more and more local materials should have been adopted to achieve satisfying results in terms of environmental impact and thermal performances. However, it could be argued that standard data are not ever trusted and this rises the need of gathering objective and specific data for each research without which incoherent results are driven. Particularly, material belonging to a crop or animal farming can not be used for feedback on buildings if not previously have been corrected the data. Moreover its necessary to highlight that different and for sure more sustainable results could be achieved when considering only the processes actuated to the sheep wool "outside the farm gates" (washing, refining, cutting, handing, transport, assembly of the biocomposite).

Notwithstanding the foregoing, the research confirms the advantages taken by using natural and local materials because of the lower environmental impact provided. Additionally, it may represent an opportunity to develop the local resources that the global trade has weakened.

REFERENCES

1. Benfratello, S., Capitano, C., Peri, G., Rizzo, G., Scaccianoce, G., Sorrentino, G., Thermal and structural properties of a hemp–lime biocomposite, *Construction and Building Materials*, Vol.48, pp 745–754, 2013.
2. Korjenic, A., Petránek ,V., Zach ,J., Hroudová, J., Development and performance evaluation of natural thermal-insulation materials composed of renewable resources. *Energy and Buildings*, Vol.43, No.9, pp- 2518-23, 2011.
3. Asprone, D., Durante, M., Prota, A., Manfredi, G., Potential of structural pozzolanic matrix-hemp fiber grid composites. *Construction and Building Materials*, Vo.25, No.6, pp.2867-74, 2011.
4. Singh, B., Gupta, M., Tarannum, H., Jute sandwich composite panels for building applications, *Biobased Mater Bio,* Vol4., No.4, pp. 397-407, 2010.
5. Silva, S.P., Sabino, M.A., Fernandas, E.M., Correlo, V.M., Boesel, L.F., Reis, R.L., Cork: Properties, capabilities and applications. *International Material Review*,Vol.50, No.6, pp. 345-65, 2005.
6. Kodah, Z.H., Jarrah, M.A., Shanshal, N.S., Thermal characterization of foam-cane (Quseab) as an insulant material. *Energy Conversion Management*, Vol.40, No.4, pp.349-67, 1999.
7. Lazko, J., Dupré, B., Dheilly, R.M., Quéneudec, M., Biocomposites based on flax short fibres and linseed oil, *Industrial Crops and Products*, Vol.33, No.2, pp.317-24, 2011.
8. Kymäläinen, H.R., Sjöberg, A.M., Flax and hemp fibres as raw materials for thermal insulations. Building Environment, Vol.43, No.7, pp.1261-9, 2008.
9. Rizzo, G., Federico, G,. I materiali fibrosi naturali – Legno, paglia, cotone e altri materiali per un'edilizia sostenibile, *Geoinforma*, Vol. 2, pp.7-10, 2008 (in Italian).
10. Kochhar, G.S., Manohar, K., Use of coconut fiber as a low-cost thermal insulator. In: Graves, R., et al., *Insulation Materials: Testing and Applications*, Vol.3, p. 283-91,1997

11. Kozlowski, R., Mieleniak, B., Muzyczek, M., Mańkowski, J., Development of Insulation Composite Based on FR Bast Fibers and Wool, *Proceedings of International Conference on Flax and Other Bast Plants*, pp 353-363, 2008.
12. Rizzo, G., Federico, G., Le caratteristiche termofisiche dei materiali bioedili – Alcuni dati preliminari di laboratorio. *L'Edilizia - Building and Construction for Engineers*, Vol.154, pp 38-41, 2008 (in Italian).
13. Zach, J., Korjenic, A., Petranek, V., Hroudova, J., Bednar, T., Performance evaluation and research of alternative thermal insulations based on sheep wool, *Energy and Buildings*, Vol.49, pp 246-253, 2012.
14. Bozza, A., Analisi sperimentale su tessuti in canapa per rinforzo strutturale. *Master Thesis*, Università degli Studi di Napoli Federico II, Italy, 2009 (in Italian).
15. La Rosa, A. D., Recca, A., Gagliano, A., Summerscales, J., Latteri, A., Cozzo, G., Cicala, G., Environmental impacts and thermal insulation performance of innovative composite solutions for building applications, *Construction and Building Materials*, Vol.55, pp 406–414, 2014.
16. Kozlowski, R., Malgorzata, M., Bozena, M., Comfortable, flexible upholstery fire barriers on base of bast, wool and thermostable fibres, *Polymer Degradation and Stability*, Vol.96, No.3, pp 396–398, 2011.
17. Ardente, F., Beccali, M., Cellura, M., Mistretta, M., Building energy performance: A LCA case study of kenaf-fibres insulation board. *Energy and Buildings*, Vol.40, No.1, pp 1–10, 2008.
18. Frampton, K., Tettonica *e architettura. Poetica della forma architettonica nel XIX e XX secolo*, Skira editore, Milano,1999.
19. Germanà, M. Luisa, Earth as a building material between past and future - Terra cruda nelle costruzioni fra passato e futuro, in Mecca, S., et al., Earth/Lands. Earthen Architecture in Southern Italy - Terra/Terre. Architetture in terra dell'Italia del Sud, ETS Pisa, pp 37-39, 2011.
20. UNI 8290-1 Edilizia residenziale. Sistema tecnologico. Classificazione e terminologia.
21. UNI EN 12667:2002 Prestazione termica dei materiali e dei prodotti per edilizia. Determinazione della resistenza termica con il metodo della piastra calda con anello di guardia e con il metodo del termoflussimetro. Prodotti con alta e media resistenza termica.
22. Regolamento UE n. 305/2011 del parlamento europeo e del consiglio del 9 marzo 2011 che fissa condizioni armonizzate per la commercializzazione dei prodotti da costruzione e che abroga la direttiva 89/106/CEE del consiglio.
23. Boganini, L., Costruire in area mediterranea. Uno strumento per la comparazione prestazionale delle soluzioni di involucro opaco, *PhD. Thesys*, Università degli Studi di Firenze, Italy, 2013.
24. Mequignon, M., Adolphe, L., Thellier, F., Ait Haddou, H., Impact of the lifespan of building external walls on greenhouse gas index. *Building and Environment*, Vol.59, pp 654–661, 2013.
25. UNI EN ISO 14040:2006 Gestione ambientale - Valutazione del ciclo di vita - Principi e quadro di riferimento.
26. Ardente, F., Beccali, M., Cellura, M., Mistretta, M., Energy and environmental benefits in public buildings as a result of retrofit actions. *Renewable and Sustainable Energy Reviews*, Vol.15, No.1, pp 460–470, 2011.
27. Ecoinvent database v2.0
28. Chidiac, S. E., Catania, E.J.C., Morofsky, E., Foo, S., Effectiveness of single and multiple energy retrofit measures on the energy consumption of office buildings. Energy, Vol.36, No.8, pp 5037-5052, 2011.
29. Autodesk Ecotect Analysis.