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Design of Sustainable Agricultural Buildings. A Case Study of a Wine Cellar in Tuscany, Italy

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Academic Editor: Adrian Pitts
Received: 18 February 2016; Accepted: 8 April 2016; Published: 13 April 2016

Abstract: This research concerns the design of an agricultural building with a high degree of sustainability, located in a farm in the south of the Tuscany region, Italy. The building, intended mainly as a wine cellar, offers innovative construction solutions of high deconstructability and has features of low environmental impact, economic competitiveness and constructive simplicity. In particular, the design of the basement cellar involves the use of gabions and stones for the realization of the foundations, the ground retaining walls and all other bearing walls. A different solution is adopted for the external wall which remains entirely above ground. It is also made by gabions, but it is externally covered with a coat of straw bales and is plastered with clay or lime. The roof-bearing structure is made of steel beams and galvanized steel sheets. A layer of fertile soil is arranged on the roof to form a green roof system. This research aims to spread the design criteria of deconstructable buildings, based on the use of natural materials with low environmental and economic impact. Where it is not possible to employ natural materials, reusable or recyclable materials are used.

Keywords: sustainable-building design; gabion-walls; land-consumption; design-for-deconstruction

1. Introduction

Construction activities contribute significantly to pollution and to the degradation of the ecosystem, accelerating the depletion of fossil fuels and resources [1]. Furthermore, 40% of the total global annual energy consumption and 16% of the total water consumption are related to the activities of the construction sector [2,3]. Buildings and construction materials are evaluated under the framework of sustainability [4], and an attempt has been made to promote resource efficiency and the use of sustainable materials [5,6].

These topics are a priority for the research group of Rural Buildings of the Department of Agricultural, Food and Forestry Systems (GESAAF), which over the years has developed several projects addressing the sustainable development of farm buildings [7]. These aims have to be achieved through the adoption of consistent choices in the implementation process, in terms of design, choice of natural and locally available materials and construction methods, costs and criteria for the potential removal of the building and restoration of original conditions [8].

The deconstructable anthropizations should be arranged for temporary changes of the locations, in order to allow the fulfillment of business farming [9,10].

These principles seem to find practical applications in Bill No. 2039/2014 [11] of the Italian government on the "Reduction of the land-consumption and reuse of the built land", which, after months of discussions in various parliamentary committees, appears close to being endorsed. The main purpose of the rule is identified in the containment of land consumption, as a common good and a not-renewable resource, and secondly and consequently, in the protection of agriculture areas, natural areas and landscape.

These objectives have a dual purpose, because they allow both to pursue the aim of conservation of the agricultural vocation of the soils and to effectively protect the landscape, as a fundamental component of the morphological Italian territory.

A progressive overbuilding of the national agricultural surface is still in progress. The data provided by the ISPRA Report 2015 [12] on land consumption show that every day in Italy over 100 ha of free surface are overbuilt. The data of 2014 show that 200 km^2 of land have been overbuilt, which means 55 ha/day and 6–7 m^2/s were taken away from the agriculture.

In order to effectively contain the current drain on agro-forestry soil, which is fertile and rich in biodiversity, we need government policies of territory addressing sustainable land planning.

This research aims to develop design criteria for an agricultural sustainable building that combines environmental and economic sustainability, the reduction of land consumption and deconstructability.

This goal can be reached by using natural building materials such as stone, straw, clay, lime, non-treated wood, cork, and colored earths. These ancient building techniques are updated on technical and scientific bases [13]. Several experimental applications in the field of the traditional building have been realized. Some prototypes using the gabion system have been realized since the early 1990s of the last century (*i.e.*, Archery Center in Barcelona, 1989–1992; Terrasson Cultural Greenhouse, 1994; Dominus Wine Cellar in California, 1995–1997; residential accommodations in Montpellier, 1997–2000). However, natural materials cannot be used to perform all the functions. Materials that are advantageously recyclable, such as galvanized steel, or easily removable and optionally reusable, such as ethylene-propylene diene monomer (EPDM) sealing sleeves, can be employed when natural materials are not usable.

By using these materials by means of advanced techniques, and by applying an accurate and careful design, any construction can be realized.

2. Results

The project involves the design of a multi-purpose agricultural basement building with the dimensions 18 m × 10 m, which will be divided internally into three distinct functional areas: an area devoted to a wine cellar (18 m × 5 m), a laboratory for the finishing of farm products (12.20 m × 4.80 m) and a tasting area (5.30 m × 5.50 m). The bearing walls and foundations are entirely built with a wire mesh gabion system and loose stones (Figures 1 and 2).

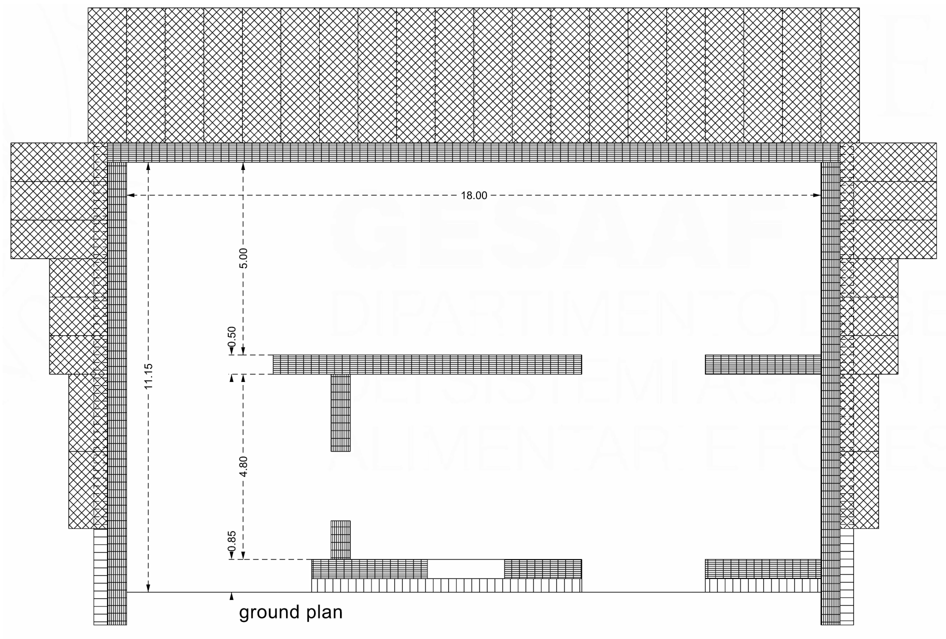


Figure 1. The building's ground plan.

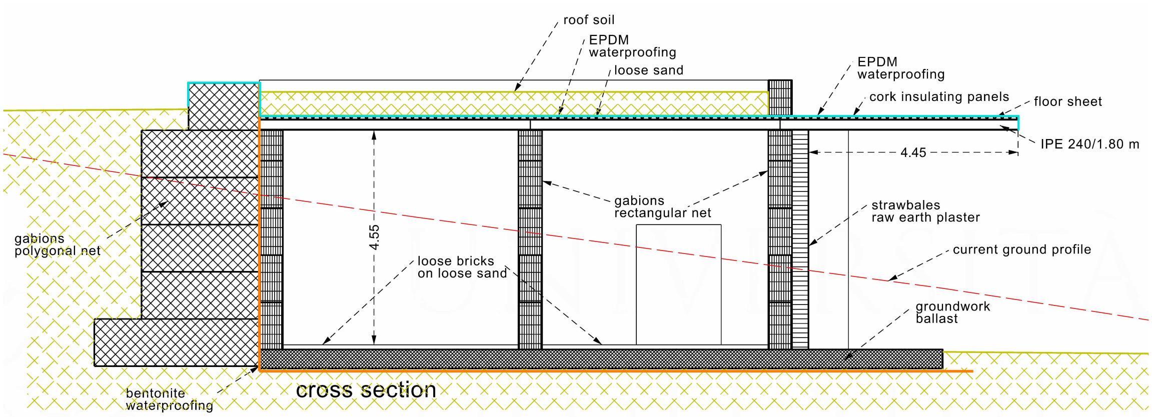
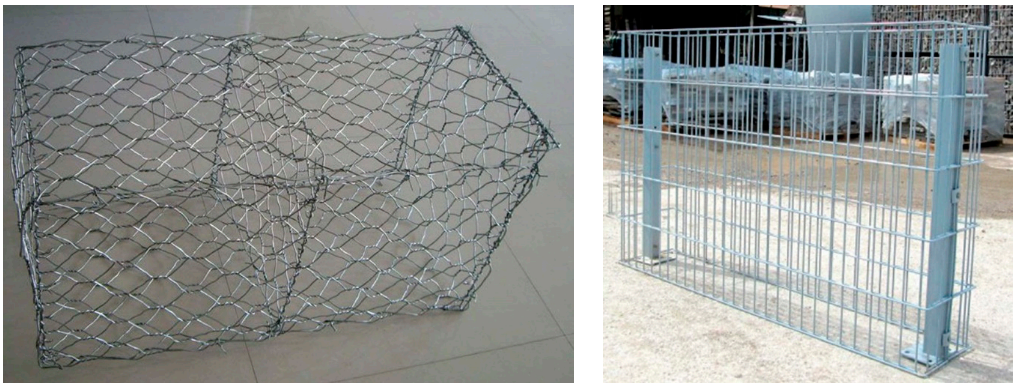


Figure 2. The building's cross-section.

The ground retaining walls involve the use of modular gabions with a polygonal net with the dimensions of 1 m × 1 m × 4 m, 1 m × 1 m × 3 m, 1 m × 1 m × 2 m (Figure 3a).



(**a**) (**b**)

Figure 3. (**a**) Gabion with polygonal net; (**b**) Gabion with rectangular net.

The bearing walls, both external and internal, are made of modular gabions with a rectangular net, and they have a thickness of 0.5 m (Figure 3b).

The foundations are made of a compressed gravel ballast, on which the bearing walls directly rest.

The stacked gabion baskets constitute a loose stone wall with a considerable thickness and mass, which ensures a structural function and helps to regulate the thermal variations of the building.

In order to waterproof the building, bentonite clay sheets are placed both between the ground-retaining gabions and the bearing walls, and between the foundation ballast and the ground.

The inner surfaces of the gabions can be left as they are or coated with plaster of clay or lime.

The indoor flooring will be made of loose bricks arranged on loose sand. Alternative solutions of coatings, imposed by the local health authority to ensure the health and hygiene safety of the processes of transformation and the storage of products, can be evaluated in the working design phase.

The roof-bearing structure is flat, made up of steel beams with a spacing of 1.80 m. The roof beams are cantilevered from the front by approximately 4.00 m, allowing a large deck area overlooking the entrances to manage the items of the farm.

Above the roof-bearing structure, galvanized steel sheets of 1.5 mm thickness can be arranged.

The projecting part of the roof structure, uncovered by the soil, is insulated with cork insulating panels.

The roof waterproofing is made of an ethylene-propylene diene monomer (EPDM) layer, easily removable and optionally reusable at the end-of-life of the building.

A layer of fertile soil (about 0.50 m) is arranged on the galvanized steel sheets to form a green roof system, suitable for horticulture and cultivation of herbaceous species and shrubs, particularly Marruca (*Paliurus spina-christi*), which gave the name to the rural village object of this study.

The doors, the windows and their frames are made of non-treated wood, namely chestnut.

The inner and external plasters are lime-washed with painting colored with red or yellow ochre earth.

Figures 4–6 show the environmental integration of the building into the surrounding rural landscape through smart design.

Figure 4. Rendering of the agricultural sustainable building.

Figure 5. Rendering of the building with particular view of the green roof.

Figure 6. Rendering of the building with side view.

3. Discussion

It is important to highlight that this design has no architectural presumption, but it is only an example of the appropriate use of sustainable materials and construction techniques. All building materials used in the construction have a high degree of sustainability and deconstructability. Other building materials, which are unfortunately commonly used, such as concrete and masonry, are never used in any part of the building. This also results in a very low level of land consumption.

The use of the gabion system in construction is suitable for joining the functional and engineering requirements with a good environmental impact of farm buildings. Moreover, this system has characteristics of remarkable versatility and can be used in other sectors that are less conventional, such as hydraulic engineering.

The simplicity of the dry construction technique, in particular the construction and installation of gabions, is suitable to implement processes of assisted self-construction *in situ*.

From the perspective of sustainable development, it is important to choose basic building materials for each project, taking into consideration their importance in terms of economic, environmental, and social impact. In this way, buildings and construction materials can be evaluated under the framework of sustainability. Currently, in Italy, their use is mainly restricted to rural applications, but the positive qualities showed by the materials and construction techniques could extend their applications for civilian dwellings.

Future challenges could concern the further development of research to maximize the use of sustainable materials in order to design other sustainable buildings following this new approach. For this reason, the authors aim to contribute to policies for the management of the rural territory of the Tuscany region, spreading the design criteria of deconstructable buildings based on the use of recyclable, renewable, locally available and environmentally friendly raw materials, with low environmental and economic impact.

Future research will focus on the characterization of the physical properties, in particular mechanical, thermal, acoustic, and fire resistance, of building elements made of natural materials. In fact, all the European Standards allow the use of certified building materials in constructions exclusively. This research will also define test methods, which are adapted to their simplicity and affordability, ensuring cost-saving features and frequent zero-km (km0) availability of natural materials. From this point of view, research is in progress which is aimed at the development of a simple and economical method for the detection of the thermal conductivity of the rectangular straw bales directly taken from the fields after harvesting.

The achievement of the certification of the investigated materials would allow widespread use of these materials, because the risks and charges both of the planners and the local authorities issuing building permits would be mitigated.

4. Materials and Methods

4.1. Study Area

The design of a multi-purpose agricultural basement building concerns a construction located in the village of Marrucheti, Campagnatico (Grosseto), in the south of the Tuscany region. In particular, the study area is located inside the Farmhouse La Casetta, at about 50 m altitude on the southern slope of the valley of the Ombrone river (Figure 7). The area of the farm is about 60 hectares, cultivated with vineyards, olive trees and grains.

Figure 7. Study area.

4.2. Preliminary Surveys

In order to design a basement building, requiring appropriate construction excavations, a preliminary geological and geotechnical survey to investigate the lithology of the intervention was carried out.

The lithotypes are sandstone, belonging to the formation of Macigno. Surveys have shown the presence of superficial alteration materials comparable to sand thickness not exceeding 1.40 m, with underlying altered sandstone with a medium grain.

From the geomorphological point of view, the project area is stable. There are no instability conditions and therefore the foundations can rest directly on the rock mass.

Even the hydrologic-hydraulic assessments of the study area have allowed the construction of the building in relation to the hazard and feasibility classes identified by the current City Plan and by the Hydrogeological Plan of Campagnatico.

4.3. Building Materials

The materials produced by the construction excavations on the upstream side of the building (height about 5.0–6.0 m), largely rocky, will be reused in the construction site: the earthy portion will be used for the leveling of the area to the boundary of the new building, while the sandstones will be used for the realization of gabions.

Gabions are baskets made of zinc-coated steel wire mesh, filled with stones of a size equal to 1.5–2 times the maximum size of the mesh. The steel wire mesh must observe EN 10223-4 [14]. The durability of gabions is high (over 60 years); they are removable, easily transported and can be stacked on top of each other in order to constitute load-bearing walls suitable for use in structures resistant to lateral pressures and vertical loads [15].

As regards the selection of building materials, it should be clarified how this is made as a function of their suitability for the design of a deconstructable building. Industrial building materials with high features of disposability, reusability or recyclability have been selected.

In detail, the technical features of the materials used for the design of the sustainable agricultural building are reported:

1. Natural stone is one of the oldest building materials and is the natural material par excellence. Natural stone, in the present area available at km0, requires energy efforts concerning its life cycle greater than that of other materials, such as wood and raw earth [16]. However, the stone has no problems for disposal and any store of material gives rise to non-polluting deposits. From a thermodynamic point of view, the high thermal inertia of the stone, which has to, as a consequence, dephase in time and mitigate the peaks of the oscillations of the temperatures, makes it particularly suitable for use in a wine cellar, in which the maintenance of steady temperature is very important.
2. The steel of the gabion baskets and of the load-bearing roof structure is an energetically expensive material both during the production and during the recycling processes. However, it has the feature of being totally recyclable for an unlimited number of times. In the world, over 400 million tons of metal is recycled each year, over 40% of the steel used comes from recycling, and the energy conservation compared to production from raw material is 65%–80% [17]. In the US, the recycling rate of structural steel (recycled steel/scrap steel generated in the same year) is close to 100% [18]. Even zinc used for steel galvanization is totally recyclable.
3. In the present design, the straw constitutes the external cladding of the bearing wall completely off the ground, in substitution of materials in synthetic foam. Straw waste is an inevitable and generally undesirable consequence of the cultivation of cereals. The world cereals production in 2015 is expected to amount to 2.5 Gt, on 700 million hectares [19]. A small amount of straw is used as bedding in livestock, as biomass for energy production, and in other minor ways. However, in most cases, the straw represents a disposal problem and it is left to decompose or be burned on the field. As such, it requires further actions and, therefore, environmental and economic costs [20]. The straw, as well as wood, is a carbon sink, which is an accumulator of carbon dioxide. The CO_2 is trapped in the straw for an indefinite amount of time and it goes back into the atmosphere through combustion or decomposition. When the straw waste is burned or when it decomposes, 1.00 ton of straw produces about 1.35 tons of CO_2 [21]. Therefore, in order to promote the permanent storage of CO_2, one of the best actions for global development is the use of straw waste as a building material in construction. The proposed design provides for straw packaged in rectangular bales [22], and it also comes from field harvesting.
4. Raw earth and lime used for the plastering of walls are materials which have a high degree of sustainability. Lime and red ochre earth are used for coloring plasters.
5. The bentonite clay sheets, used as the waterproofing system of the building, are disposed with a rate of very low or no pollution.
6. The bricks used for flooring are made up of clay. They are removable, transportable and recyclable materials, without significant interventions in terms of energy costs.
7. Cork insulating panels and ethylene-propylene diene monomer (EPDM) sheets are used in the roof, respectively, for insulating and waterproofing. The EPDM layers are simply placed on the structure and therefore they can be removed and possibly reused.

Furthermore, it is important to remember that the agricultural building designed by GESAAF can be realized, for the most part, by zero-km-available raw materials.

Acknowledgments: The authors gratefully acknowledge Luca Manini, owner of the Farmhouse la Casetta, for the financial support of this project.

Author Contributions: Leonardo Conti, Matteo Barbari and Massimo Monti contributed equally to this work. They designed the study and wrote the manuscript until its final version.

Conflicts of Interest: The authors declare no conflict of interest.

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