PAPER • OPEN ACCESS

Comparative evaluations of sustainability, durability and resilience of external envelopes for environmentally efficient buildings

To cite this article: M Nicolella *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **296** 012023

Comparative evaluations of sustainability, durability and resilience of external envelopes for environmentally efficient buildings

M Nicolella[1], R Landolfi[1], A Pino[1] and C Scognamillo[1,*]

[1]University of Naples Federico II, Department of Civil, Architectural and Environmental Engineering, Via Claudio 21, Napoli, 80125, Italy

*claudio.scognamillo@unina.it

Abstract. The building sector is affected by a significant confusion between the concepts of sustainability and energetic efficiency: indeed, both the paradigms have the aim of safeguarding the planet, but the strategies to enact them certainly follow two different paths, often in contrast between them. The design of building envelopes has definite performance requirements, according to the current framework, but in any case the technological choices to fulfil them are not univocally determined. As an example, the objective of obtaining building envelopes with low transmittance can be reached by a huge number of typologies of solutions and materials, but of course the possible evaluations in terms of sustainability may in some cases show results that overturn the energetic assessment.
Also, considering the strict relation that exists between durability (also in terms of resilience) and sustainability, it can be concluded that the most correct tendency for materials and products can be – more in general – defined as environmental efficiency, the so-called eco-compatibility. Taking moves from the scientific literature on products and materials, both from the point of view of sustainability, and from that of durability and resilience, this work proposes a number of comparative evaluations that analyse the main systems and components of the external envelopes: built-up roofs and roof systems, opaque and transparent walls, ground floor slabs, doors and windows.
LCA analyses, durability assessments and considerations on resilience carried out on the abovementioned systems and components provide very interesting results to guide designers towards more conscious choices, aimed to integrate the different (and sometimes contradictory) aspects that allow to realize energetically and environmentally efficient buildings.

1. Introduction

Technological, operative, legislative innovations in the field of building constructions are nowadays linked by an almost single, common aim: reducing environmental impacts, without limiting the performance of buildings. The recent legislation definitely confirms this tendency: both for new constructions and for existing buildings, there has been a focus in setting limits to the energetic consumption related to heating and cooling by establishing maximum values for the transmittance of the envelope. In correspondence to the necessity of respecting these boundaries, on one side the building market frequently hosts the introduction of materials with lower conductivity, which are more and more widely used in the common practice. On the other side, often the use of materials of synthetic origin is being considered negatively, especially taking account that their choice is led by the will of enhancing the sustainability of constructions. So, there is also a wide research on the possibility to use natural materials that can allow to reach low values of transmittance without involving chemical production.

This kind of global evaluations benefits from the use of Life Cycle Assessment methodologies, in order to consider all the elements that involve an environmental load during the life cycle of a building or of its parts. A building is indeed a dynamic system, and its life is indeed a series of consumptions, which do not limit to those constituted by the materials used for its construction. This also means that this ‘dynamism’ has to be taken into consideration, thinking of the life cycle as a network of scenarios, rather than a single stream of stages. Resilience is a central topic of this reasoning, as it reflects the need to project design in a multi-directional dimension, taking into account the possible variations a building may be related to, and how their probability can be seen as a consequence of design choices.

This paper discusses these items by comparing three sets of solutions for:

- the renovation of existing masonry walls;
- external walls in new constructions;
- roof coverings.

2. State of the art and methodology

The necessity of global valuations to determine the actual environmental weight of designers’ choices on buildings is becoming a frequent topic in research. In the most recent years, sometime later than the standardization of the LCA methodology with ISO 14040-42 code [1], many researchers have pursued the aim of implementing detailed sustainability analyses of various building techniques, often drawing inspiration from the building heritage of their countries, in order to provide designers the acknowledgment of the sustainability of their choices.

In Portugal, there has been the project of developing an LCA database for the *Portuguese Building Technologies*, which initially comprehended 50 building solutions for floors and exterior walls, 40 building materials and the impacts related to the use of 12 systems for acclimatization and hot water [2]; other more specific studies involved the evaluation of the environmental footprint of prefabricated modular building solutions [3] and modular green roofs [4]. It was progressively understood that comparative valuations through LCA could be a significant decisional tool to choose materials and solutions also according to their environmental impact [5], and a particular focus was given to insulation materials [6]. In France, their decisive importance was particularly emphasized, proposing it as a criterion of comparison for single-family houses [7] [8].

Other researchers [9] have at the same time pointed out that sustainability is a multi-criterial aspect, and so it should be examined with tools that allow to consider all its elements. Some combinations between LCA analyses and multi-criteria methodologies have been experimented, such as COPRAS [10] and AHP [11]. On the other side, it became more and more important to research valid criteria with influence on life cycle assessment, among which durability has been examined [12]. This leads to consequences in the field of maintenance as well, of course, as it has been identified by some authors [13].

Resilience has become the object of more and more scientific discussions and research in the last two decades with a relatively rapid generation of the concept of *resilience engineering* [14]. A significant item is its relationship with sustainability [15], a topic which was rapidly applied to buildings, both in contrast [16] and as a mutual integration [17]. Also in relation to design, resilience is now a recurring criterion [18] in the form of resilient design [19]. Possibilities of a consideration of resilience into an LCA have also been realized [20].

Regarding the methodology of this paper, the use of a MCDM was excluded: the critical point of these methods is constituted by the weights that are attributed to the criteria: grouping different aspects into a single value is an operation which requires the decision of a set of arbitrary weights; these weights, of course, influence the entity of the comparison. For this reason, the comparison proposed here is not in the form of a multi-criteria methodology, but it was chosen to adopt an evaluation method to assemble all the environmental impacts into a single indicator, that is to say the *ecoindicator*. This was calculated by the method *Ecoindicator99 H* (hierarchical) through the software *SimaPro*, dividing the impact in the categories of *Human Health*, *Ecosystem Quality* and *Resources* and then grouping them.

Considering that the elements under comparison are mainly solutions for covering layers, rather than load-bearing structures or whole building systems, taking into account resilience requires the research of different approaches than in the usual cases, which tend to refer to the whole construction. In fact, the starting point is the determination of the risks that can generate a disturbance to which these kind of solutions can be subjected; once this is individuated, following some suggestions from the scientific literature, a resilience-integrated LCA has this form:

$$EI = a \cdot (1 - r) + b \cdot r \quad (1)$$

This equation means that the total environmental impact of a system (*EI*) is equal to the summation of the environmental impact of a scenario without disturbances (a) and that of a scenario where a disturbance takes place (b), multiplying them for the complement to 1 of the disturbance probability (r), and for the probability itself, respectively.

The answer cannot be unrelated to durability: the highest risk that these elements can be subjected to does not origin from an external cause, but from their own performance decay. In fact, durability is tied to reliability; hence, the capacity of an element to provide a function for a given duration is a probabilistic matter. For these reasons, since maintenance interventions have, in terms of reliability, the effect of reducing the probability of failure of a system, it can be seen as the key of this problem: regarding solutions of this type, planning a frequent maintenance activity which aims to nullify r means to satisfice resilience requirements in a *robust* way: anomalies are eliminated before they can give place to a problem for the element, which would lead to a diseconomy of corrective maintenance – which can be seen as the term b of equation (1), therefore making the second term negligible. For this reason, for each solutions maintenance programs for a period of 50 years will be detailed in the various comparisons, and their environmental impact will be considered in the LCA.

3. Renovation of existing masonry walls

In the Mediterranean area, and specifically in Naples, a frequent case of requalification involves the old tuff masonry buildings, for which the value of transmittance is higher than the limit imposed by DM 26/06/2015 [21]. In order to fulfil this condition, the ETICS is often a valid choice, but in some cases the buildings have important historical and/or artistic value, and the range of interventions that can be performed on them is limited; in those conditions, it becomes necessary to intervene with thermal insulating plasters, as they are much less invasive.

This study analyses an exemplificative situation where both interventions are possible, so on a building with no artistic or historical constraints, in order to evaluate the sole difference in the eco-compatibility of the two solutions, rather than in the feasibility.

In this case, the transmittance of the two solutions will be equaled by calculating:

- for the ETICS, the width of the insulating material, the polyurethane (TM1);
- for the thermal insulating plaster, the width of the plaster itself (TM2).

The element on which they are considered to be applied is a frequent existing solution in the city of Naples, that is to say a tuff wall with a width of 60 cm. The lateral surface of the building considered is 1000 m^2. According to UNI/TS 11300 code [22], tuff walls with a width of 60 cm have a transmittance of 0.90 W/m^2K and, therefore, a conductivity of 0.54 W/mK. Since this is a requalification and not a new construction, the D.M. 26/06/2015 displays for the climatic zone C, to which Naples belong, a current limit of 0.40 W/m^2K, which will decrease to 0.36 W/m^2K in 2021. The limit considered in this evaluation will prospectively be set to 0.36 W/m^2K, and in order to reach it:

- the minimum width for the polyurethane within the ETICS is 35 mm;
- the minimum width of thermal plaster (considering a high-performance thermal plaster, with a conductivity of 0.042 W/mK and a maximum applicable width of 8 cm) is 65 mm.

The stratigraphy of the solution TM1 and TM2 is reported in Figure 1.

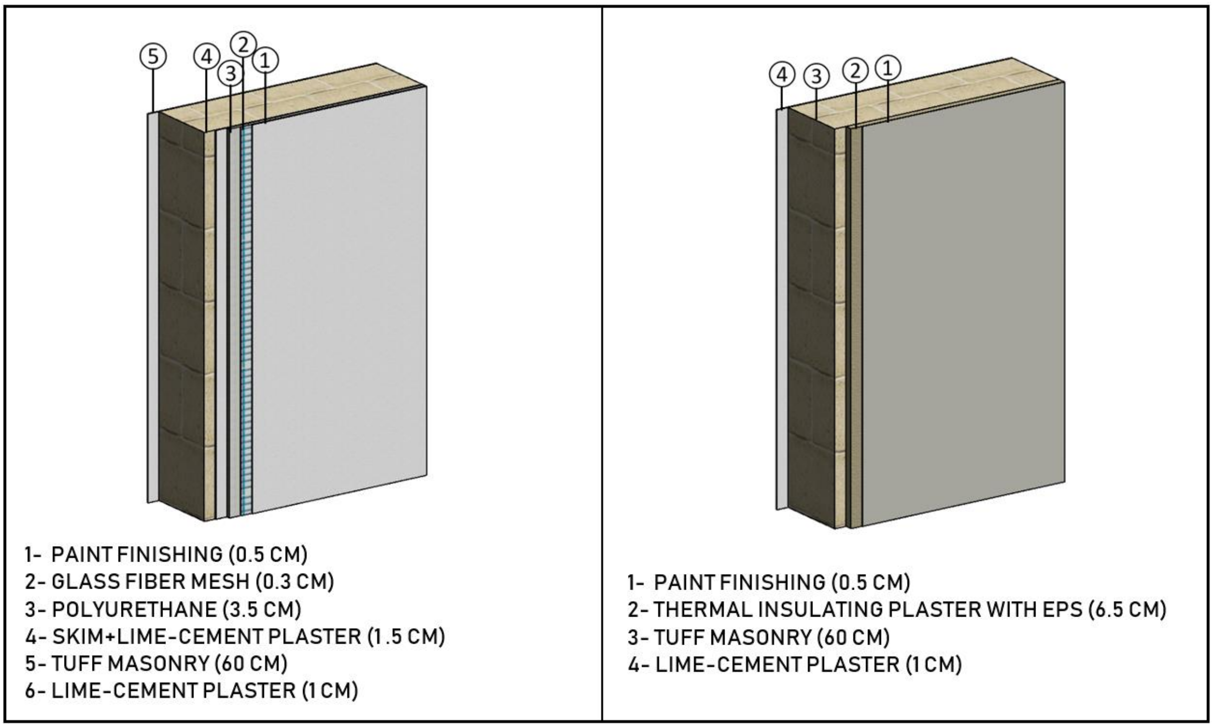

Figure 1. Stratigraphy of a tuff masonry with ETICS (TM1, on the left) and of a tuff masonry with thermal insulating plaster (TM2, on the right)

For TM1, interventions of painting and substitution of the skim are executed with a frequency of 15 years; for TM2, interventions of painting and substitution of the plaster are executed every 15 years.

3.1. Insulating materials in ETICS

The choice of polyurethane as an insulating material in ETICS could be seen as arguable, as it is a synthetic materials, then presumably it might cause an unmotivated increase in the environmental weight of ETICS as calculated with the LCA, with the risk of mistakenly making it more disadvantageous than thermal insulating plaster. For this reason, a preliminary study was carried out on the insulating materials in ETICS – polyurethane, EPS, rock wool, glass wool and cork - taking moves from a previous research and keeping its context and collocation [23]:

- polyurethane;
- EPS;
- glass wool;
- rock wool;
- cork.

In this case, the hypothesized intervention is on a building collocated in Milan, with a lateral surface of 1000 m^2 and the following stratigraphy:

- internal lime-cement plaster, 1 cm;
- hollow bricks, 12 cm;
- air chamber, 1 cm;
- cement mortar, 1 cm;
- hollow bricks, 14 cm;
- external lime-cement plaster, 1.5 cm.

By applying the inverse formula of transmittance and adopting the same structure defined for ETICS in the previous paragraph, the minimum width of the materials which allows to reach the maximum value of transmittance – 0.28 W/m^2K for renovations in the city of Milan, which is in the climatic zone

E – has been calculated, and is reported together with other information, including the distance of the closest establishment where they are produced, in Table 1.

Table 1. Synthetic table of the properties, the quantities and the distances of acquisition of the materials

Material	Conductivity λ (W/mK)	Density ρ (kg/m^3)	Width s (mm)	Weight W (kg/m^3)	Distance d (km)
Polyurethane	0,023	35	60	2160	240
EPS	0,031	30	81	2430	160
Glass wool	0,038	150	86	12900	55
Rock wool	0,032	75	84	6300	55
Cork	0,042	130	110	14300	550

The establishments were individuated through a market analysis, considering that the most realistic choice would be that of the best reseller. At the same time, since the establishments of the best reseller of glass wool, rock wool and cork are located in foreign countries, it was preferred to choose locations in Italy in order to avoid an unmotivated increase of the environmental impact. The results of the LCA analysis for the materials are reported in Figure 2.

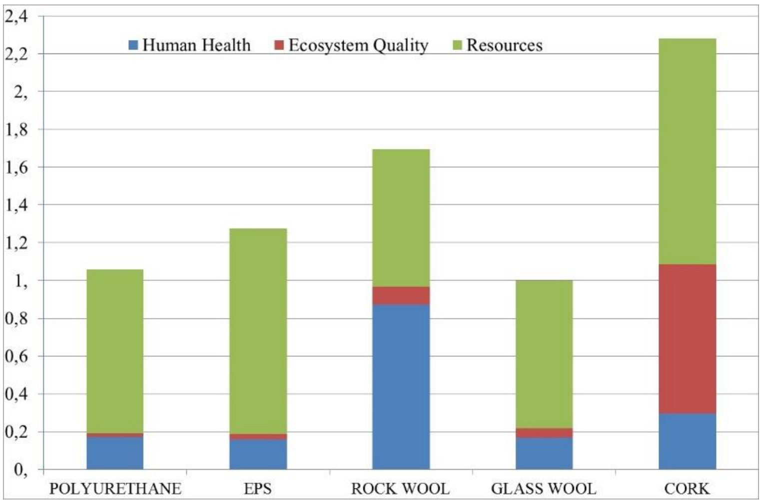

Figure 2. Diagram of the environmental impact of polyurethane, EPS, rock wool, glass wool and cork, evaluated in thousands of ecopoints (kPt) and divided in the categories of *Human Health*, *Ecosystem Quality* and *Resources*

Despite the natural origin of cork, both the higher quantity required to reach the maximum value of transmittance and the longer distance for transportation led it to be the least sustainable material among the five. This result probably overturns many designers' predictions, showing that the impacts related to the production of a material are not the determinant factor in its sustainability. Almost coming joint first, polyurethane and glass wool result to be the most sustainable choice for the insulating material in ETICS and, recalling the logic of resilience that is being followed, the higher durability of polyurethane is a sufficient motivation to justify its use in the examined case of interventions on a wall in tuff masonry.

3.2. Results of the LCA of the renovation of existing masonry walls

The results of the analysis are reported in Figure 3.

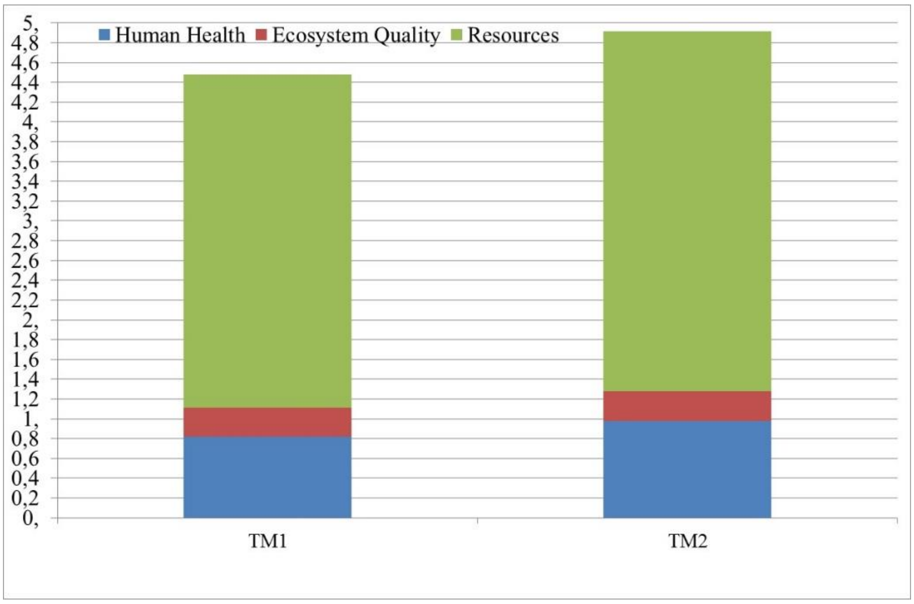

Figure 3. Diagram of the environmental impact of ETICS and thermal insulating plaster, evaluated in thousands of ecopoints (kPt) and divided in the categories of *Human Health*, *Ecosystem Quality* and *Resources.*

The LCA proves that the use of a thermal insulating plaster for the insulation of a tuff masonry wall of 60 cm leads to a higher environmental impact, compared to ETICS. Even if the ETICS, by itself, requires a less sustainable production than a thermal insulating plaster, this difference is reversed when considering a period of 50 years, as maintenance on the plaster involves the replacement of the whole material, while maintenance on the ETICS only affects the external layers of the system.

The small difference between the two – around 500 Pt – constitutes the proof that, without considering resilience and therefore maintenance activity, the result would have been in favor of thermal insulating plaster; in fact, the intense maintenance activity on the second solution certainly has a much higher impact than that on the first one, and despite that the final result is not characterized by a huge discrepancy. So, this means that the impacts related to maintenance can equal the ones from production, showing a strong need for its correct assumption.

4. Multilayer blocks with and without a ventilated façade

The ventilated façade has been codified for the first time by UNI 11018 code [24], consisting in the realization of a ventilated air chamber between wall and cladding, with the effect of reducing the thermal load in the summer period, thanks to chimney effect. What is often overlooked, though, is another characteristic of the ventilated façade, that is to say its protective effect on the internal surface of the enclosure: its panels absorb almost every typology of environmental and atmospheric stress, allowing a huge reduction of the interventions on the 'actual' wall. At the same time, aside from its benefit in the summer period, which cannot be easily quantified, it provides no contribution to transmittance, according to EN ISO 6946:1996 code. So, it will be paired with a multilayer block constituted by a lightweight concrete brick with expanded clay (11.2 cm), a polystyrene panel with graphite additive (7.5 cm) and another lightweight concrete brick with expanded clay (11.2 cm), with a total transmittance of 0.29 W/m^{2}K, which satisfies by itself the limit of 0.34 W/ m^{2}K imposed by D.M. 26/06/2015 for the climatic zone C of Naples.

The two solutions under comparison will be:

- multilayer block with plaster on both sides (MB), in Figure 4;

- multilayer block with internal plaster and ventilated façade (MB+VF), in Figure 5.

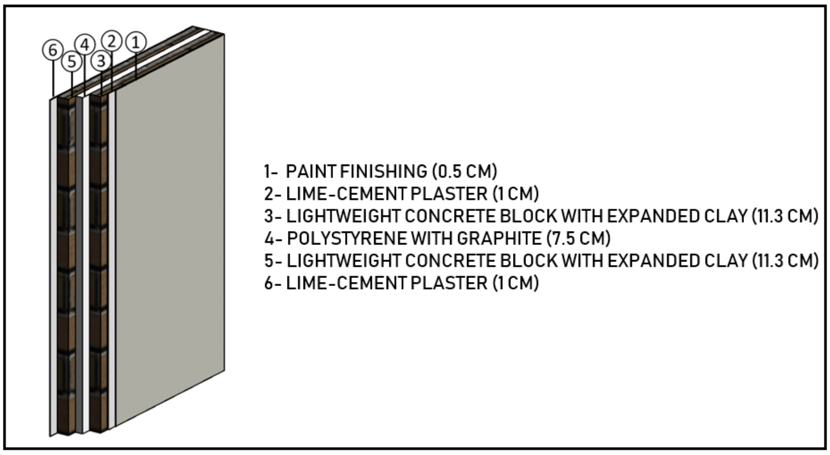

Figure 4. Stratigraphy of a multilayer block constituted of hollow bricks and polystyrene with graphite (MB).

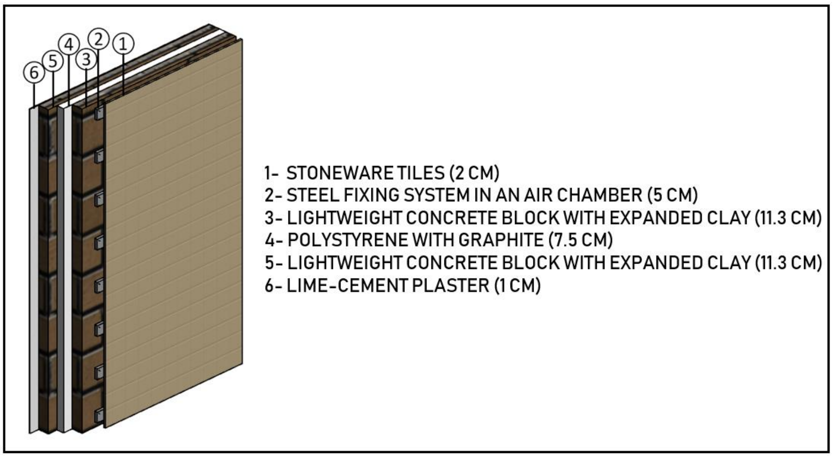

Figure 5. Stratigraphy of a multilayer block constituted of hollow bricks and polystyrene with graphite, and a ventilated façade (MB+VF), with measures in centimeters.

The maintenance activity for the two solutions consists in:

- painting interventions every 15 years and substitution of the plaster every 30 years for the wall without ventilated façade;
- no interventions for the wall with ventilated façade.

The absence of interventions is related to the strong protective effect of the ventilated façade, and the durability of this solution is enhanced by the multilayer block as well: while more common solutions with a ventilated façade usually place the insulating material in direct contact with the air chamber, exposing it to several stress agents, in this case it is collocated between two layers of bricks, and so does not require any maintenance interventions in the considered period.

4.1. LCA results
The results of the LCA are reported in Figure 6.

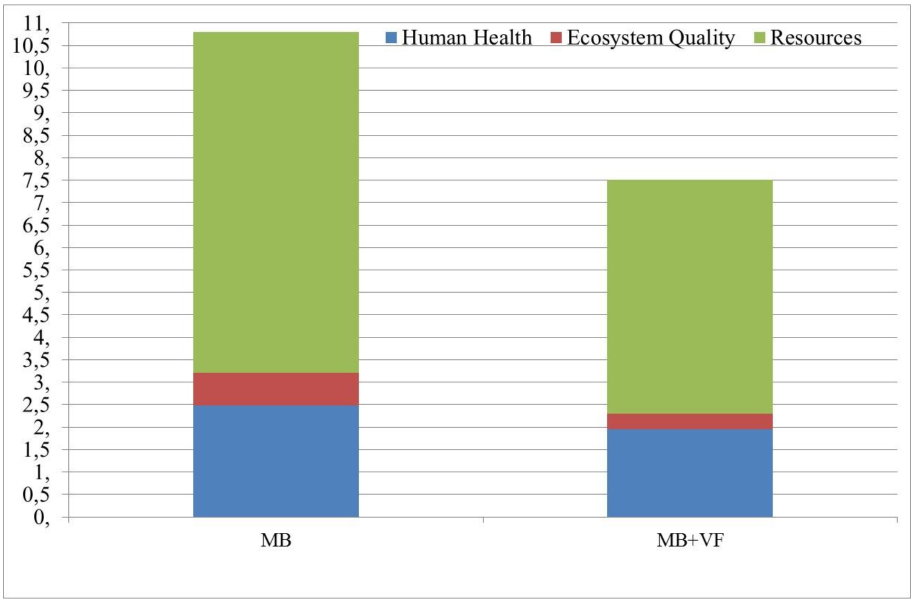

Figure 6. Diagram of the environmental impact of a multilayer block with and without a ventilated façade, evaluated in thousands of ecopoints (kPt) and divided in the categories of *Human Health*, *Ecosystem Quality* and *Resources.*

This comparison shows that a ventilated façade, already in a period of 50 years, produces a lower environmental impact than a lime-cement plaster, which requires substitutions every 30 years, providing the same performance in the protection of walls with no structural function. Often, the difficulty to give a quantitative measure of its contribution to the reduction of the energy required for cooling systems tends to discourage its use considering the impact related to its initial production, without giving the correct importance to its capability to avoid interventions, and the energetic – and economic, as well – saving that derives from that.

5. Solutions for roof coverings in the Mediterranean area

For this comparison, the LCA on the solutions are only executed on the floor coverings, and so will not consider anything under the gradient screed. These solutions differ according to the typology (warm roof and inverted roof) and the finishing layer. The 7 solutions can be identified as:

- warm roof with thermo-reflective paint finishing (WR1);
- warm roof with gravel covering (WR2);
- warm roof with ceramic floor (WR3);
- warm roof with floating floor (WR4);
- warm roof with synthetic covering (WR5);
- inverted roof with gravel covering (IR1);
- inverted roof with floating floor (IR2).

The difference between a warm roof and an inverted roof consists in the inversion between the waterproofing layer and the insulating layer: in the former, the waterproofing layer is more external, while in the latter it is displaced under the insulating material; the aim of this inversion is to have the insulating material dissipate more thermal energy before it reaches the waterproofing membrane, in order to keep it more protected from thermal variations, and therefore thermal stress. The purpose is, then, to increase its durability, in exchange for performing a higher number of maintenance interventions on the insulating materials over time. So, the evaluation will show whether this choice benefits or not the global sustainability. The stratigraphy of the solutions is reported in Figure 7.

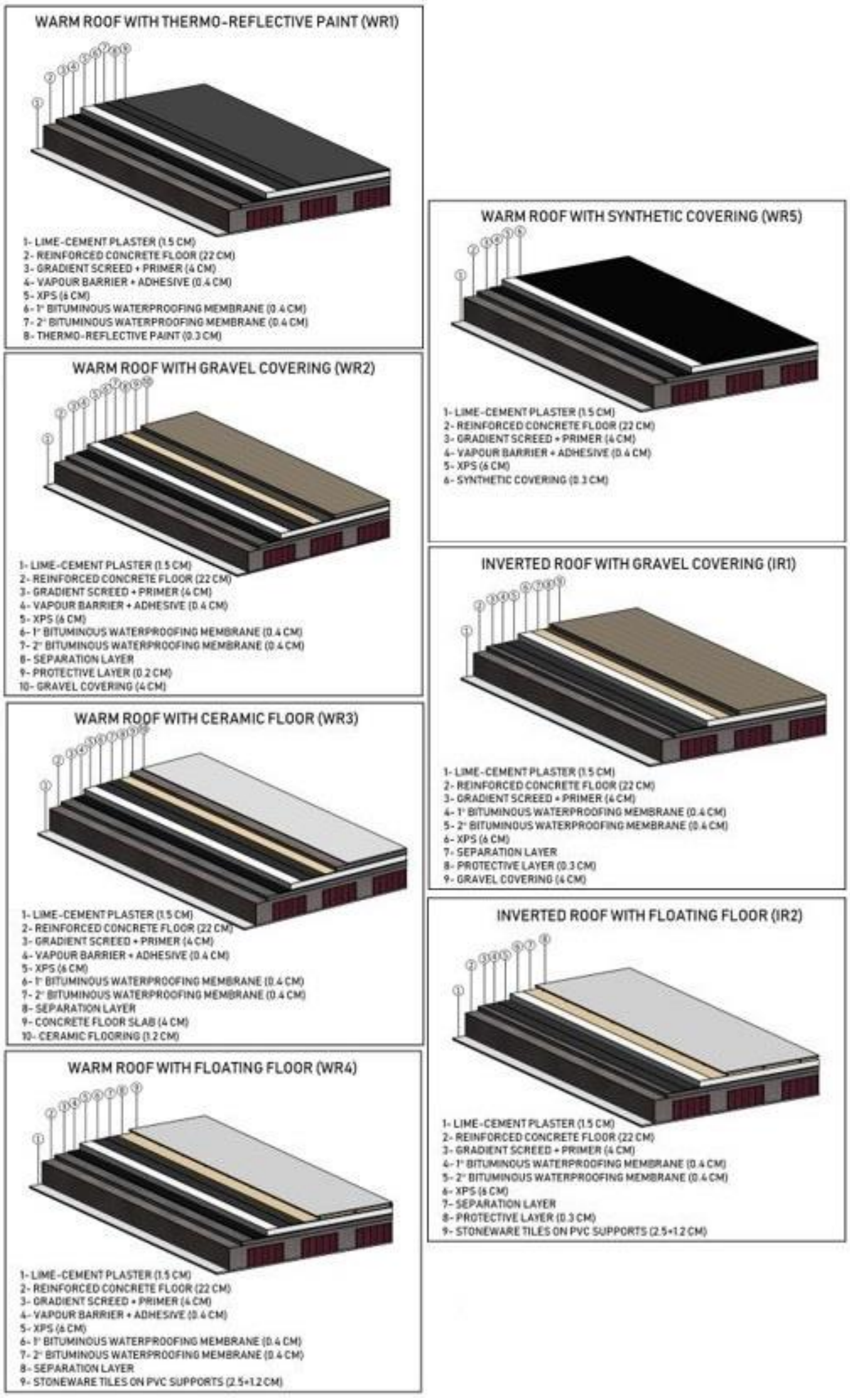

Figure 7. Stratigraphy of the 7 solutions for roof coverings

The maintenance activity on the seven solutions in the following:

- on WR1, painting interventions every 3 years, addition of a new waterproofing membranes on the existing ones on the 15th and 35th year, then substitution of all the waterproofing membranes and the insulating panel every 25th years;
- on WR2 and WR4, addition of a new waterproofing membranes on the existing ones on the 15th and 35th year, then substitution of all the waterproofing membranes and the insulating panel every 25th years;

- on WR3, substitution of the waterproofing membranes, of the ceramic floor, the concrete floor slab and the insulating panel every 25 years;
- on WR5, substitution of the synthetic covering every 30 years;
- on IR1 and IR2, substitution of the waterproofing membrane every 25 years.

5.1. LCA Results
The results of the LCA analysis on the 7 solutions are reported in Figure 8.

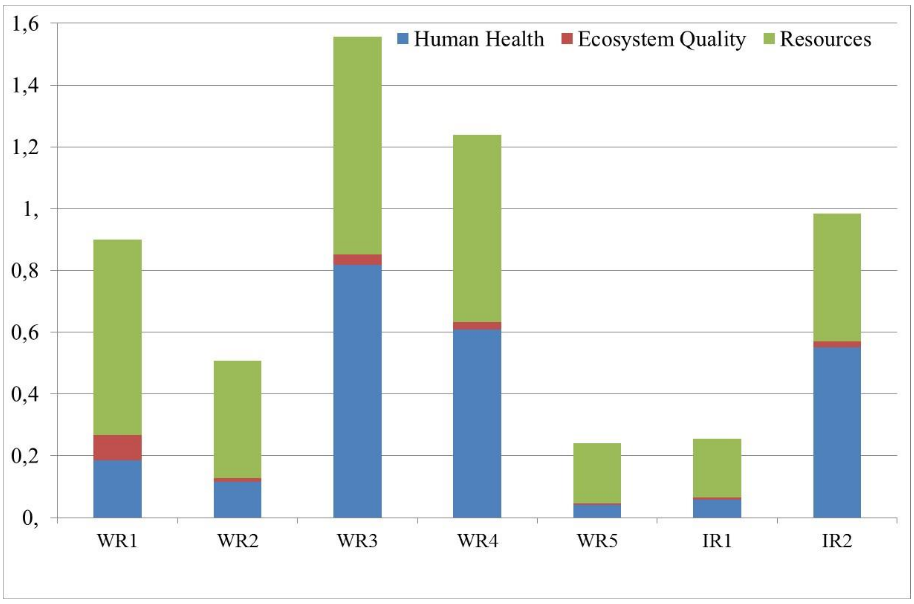

Figure 8. Diagram and table of the environmental impact of 7 typologies of roof covering, measured in thousands of ecopoints (kPt) and divided in the macro-categories of Human Health, Ecosystem Quality and Resources

Since a surface of 100 m^2 was considered, the entity of the values is of course lower than in the other comparisons. Apart from that, the results show quite heterogeneous environmental impacts: the ecopoints of the warm roof with ceramic floor (WR3) are around seven times those of the warm roof with synthetic covering (WR5). Firstly, there is a significant difference between the roofs which use ceramic tiles, both in floating and traditional floors, and those who do not, as they lead to notable impacts both in terms of *Resources* and *Human Health*, for their production. The warm roof with thermo-reflective paint covering has a not negligible impact as well, and in this case the reason can be tied to maintenance. In fact, while thermo-reflective covering protects the membrane from thermal stress, at the same time it requires a very frequent maintenance; moreover, gravel coverings produce the same effect but needs no interventions.

The topic of maintenance can be evidently noticed by examining almost every pairwise comparison:

- the only difference between WR3 and WR4 is in the typology of floor (traditional floor in the former and floating floor in the latter), so as the floating floor allows to avoid the demolition of the ceramic tiles during maintenance activity on the inner layers, its impact is lower;
- IR1 and IR2 are inverted roofs with the same materials as the warm roofs WR2 and WR3, but their impact is always lower than their respective warm roof. This decrease is certainly related to the reduction of interventions allowed by the structure of the inverted roof.

Finally, the warm roof with synthetic covering (WR5) provides the best performance, and this can be related to the absence of gas usage in its application and for its lower frequency of interventions needed to ensure its durability.

6. Conclusions

Incorporating resilience into Life Cycle Assessments requires an acknowledgement of the probabilistic bonds that tie the various scenarios and stages of a building component, and their constitution is linked to durability. Considering maintenance activity as the element that increases the resilience of a component is indeed the tool to draw a connection between the research in the field of durability and its environmental benefits, as it can determine in a more accurate way the minimum energy consumption related to maintenance, needed to ensure the resilience of a system.

The comparisons in this paper lead to several interesting deductions, such as the variety and the variability of the factors that contribute to define the judgements of sustainability. In the case of the comparison of the insulating materials in ETICS, both quantity and transport, which were the most relevant factors, deeply depend on the context: of course transportation would have had a totally different influence if the building site were in Sardinia – or in Portugal, where cork production is much wider – but the quantity as well varies according to the place, or rather to the climatic zone, according to which the values of maximum transmittance are set.

In all the other comparisons, the limelight undoubtedly belongs to the aspect of maintenance, and how it influences the environmental impact of a building solution in a drastic way. The major consequence that can be drawn from this resides in the concept that, in order to perform truly eco-compatible design choices, maintenance should not be considered as a consequence of the choices of materials and solutions, but rather has to embodied in the early phases of the designing process, in order to constitute a criterion to guide designers to find optimal solutions in this sense as well.

References

[1] ISO – International Organization for Standardization 2006 ISO 14040-42:2006 Environmental management - Life cycle assessment - Principles and framework

[2] Bragança L and Mateus R 2010 LCA Database for Portuguese Building Technologies *Proceedings of the International Initative for a Sustainable Built Environment* (Villamoura, Portugal)

[3] Faludi J, Lepech MD and Loisos G 2012 Using Life Cycle Assessment Methods To Guide Architectural Decision Making for Sustainable Prefrabricated Modual Buildings. *Journal of Green Building* **7** 151-70

[4] Perira de Oliveira LA and Cortez Alves SC 2015 Life Cyle Assessment of modular green roof architectural solutions. *Proceedings of International Conference on Engineering ICEUBI 2015* (Cavilha, Portugal)

[5] Zabalza Bribián I, Capilla AV and Aranda Usón A 2011 Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. *Building and Environment* **46** 1133-40

[6] Pargana N, Duarte Pinheiro M, Dinis Silvestre J and De Brito J 2014 Comparative environmental life cycle assessment of thermal insulation materials of buildings. *Energy and Buildings* **82** 466-81

[7] Colli C, Bataille A, Antczak E and Buyle-Bodin F 2018 Life-Cycle Assessment of a French Single-Family House Refurbishment: The "Bat-Eco2" Case Study. *Procedia CIRP* **69** 160-5

[8] Peuportier BLP 2001 Life cycle assessment applied to the comparative evaluation of single family houses in the French context. *Energy and Buildings* **33** 443-50

[9] Drejeris R, Kavolynas A 2014 Multi-criteria Evaluation of Building Sustainability Behavior. *Procedia – Social and Behavioral Sciences* **110** 502-11

[10] Medineckiene M, Turksis Z and Zavadskas EK 2011 Life-cycle analysis of a sustainable building, aplying multi-criteria decision making methods. *Proceedings of the 8th International Conference on Environmental Engineering* (Vilnius, Belarus)

[11] Asha Kiran B and Nageswara Rao P 2013 Life Cycle Assessment (LCA) and Multi-Criteria Decision Making (MCDM) for Planning, Designing and Commissioning of Green Buildings. *International Journal of Advanced Trends in Computer Science and Engineering* **2** 476-9

[12] Iraldo F, Facheris C and Nucci B 2016 Is product durability better for environment and economic

efficiency? A comparative assessment applying LCA and LCC to two energy-intensive products. *Journal of Cleaner Production* **140**

[13] Khamidi MF, Lateef OA and Idrus A 2010 Building Maintenance: A Path Towards Sustainability. *Malaysian Construction Research Journal* **7**

[14] Wears RL 2006 Resilience Engineering: Concepts and Precepts. *Quality and Safety in Health Care* **15** 447-8

[15] Marchese D, Reynolds E, Bates M, Morgan H, Clark S and Linkov I 2017 Resilience and sustainability: Similarities and differences in environmental management applications. *Science of the total environment* **613-4** 1275-83

[16] Phillips R, Troup L, Fannon D, Eckelman MJ 2017 Do resilient and sustainable design strategies conflict in commercial buildings? A critical analysis of resilient building frameworks and their sustainability implications. *Energy and Buildings* **146** 295-311

[17] Achour N, Pantzartzis E, Pascale F and Price ADF 2015 Integration of resilience and sustainability: from theory to application. *International Journal of Disaster Resilience in the Built Environment* **6** 347-62

[18] Matthews E, Friedland CJ and Orooji F 2016 Optimization of Sustainability and Flood Hazard Resilience for Home Designs. *Procedia Engineerging* **145** 525-31

[19] Scott J 2016 Principles for Resilient Design – A Guide for Understanding and Implementation *IRGC Resource Guide on Resilience* ed I Linkov

[20] Pizzol M 2015 Life Cycle Assessment and the Resilience of Product Systems. *Journal of Industrial Ecology* **19**

[21] D.M. 26/06/2015 Decreto interministeriale 26 giugno 2015 – Adeguamento linee nazionali per la certificazione energetica degli edifici (Italy)

[22] UNI – Ente Italiano di Normazione 2014 UNI/TS 11300-1:2014 Prestazioni energetiche degli edifici - Parte 1: Determinazione del fabbisogno di energia termica dell'edificio per la climatizzazione estiva ed invernale

[23] Landolfi R 2018 Valutazioni Life Cycle Assessment per l'isolamento a cappotto di pareti: confronto fra diversi materiali. *Ingenio-web*

[24] UNI – Ente Italiano di Normazion 2003 UNI 11018:2003 Rivestimenti e sistemi di ancoraggio per facciate ventilate a montaggio meccanico - Istruzioni per la progettazione, l'esecuzione e la manutenzione - Rivestimenti lapidei e ceramici