Multi-criteria Decision Analysis of a Building Element Integrating Energy Use, Environmental, Economic and Aesthetic Parameters in Its Life Cycle

Giulia Sonetti and Patrizia Lombardi

Abstract With the increasing concern of the building environmental impacts, governmental regulation and people own consciousness have shown rising interest in buildings protocols and methods for sustainability certification. Life cycle assessment (LCA) represents a useful tool for designers, companies and building owners in every phase of the construction process, but its daily use encounters several applicability problems. It is indeed hard to take into account crucial parameters regarding the economic, aesthetic and energetic performances of each alternative in a whole sight. The aim of this paper is to exploit LCA techniques to evaluate the environmental impacts of three different types of roof analysed within the building component scale. A green, reverse, and simply waterproofed roofs have been drawn and split into each component's environmental impacts, whereas a multi-criteria decision analysis (MCDA) tool integrating economic, social and aesthetic parameters. LCA results showed that the reversed roof solution gives out the minimum environmental damage ($-69, 46\%$ compared to the common waterproofed roof). The results from this LCA analysis are included in a more holist MCDA approach which is able to consider different objectives (thermal performance, construction cost, aesthetic performance, social utility, environmental impact). This integrated evaluation is conducted according to different scenarios and points of view (eco-social and business-as-usual) and gave scenarios with a synoptic assessment of each maximized performance. Conclusive remarks show that an MCDA qualitative analysis coupled with the quantitative result from LCA appeared to be very helpful in comparing options in the design phase of a building, and a useful communication tool among all the stakeholder of the construction process. This new approach based on the LCA-AHP analysis can help decision makers to find sustainable alternatives among available options and promises a more sustainable product or process.

G. Sonetti (✉) · P. Lombardi
Interuniversity Department of Regional and Urban Studies and Planning, Politecnico di Torino and Università di Torino, Viale Mattioli, 39 10125 Turin, Italy
e-mail: giulia.sonetti@polito.it

P. Lombardi
e-mail: patrizia.lombardi@polito.it

G. Mondini et al. (eds.), *Values and Functions for Future Cities*, Green Energy and Technology, https://doi.org/10.1007/978-3-030-23786-8_26

Keywords Environmental performance · Building assessment · LCA · MCDA · Decision making

1 Introduction

With the increasing concern of the building environmental impacts amongst public and private companies, governmental regulation and people own consciousness have shown rising aspiration towards sustainable urban development. The building sector is one of the most contributors to global energy consumption and environmental impacts—it is often called "the 40% sector" (CAN Europe 2005; Cabeza et al. 2014; Nejat et al. 2015) because it is responsible for up to 40% of total energy use worldwide (UNEP 2007; WBCSD 2007; De T'Serclaes 2007). What is currently hard to achieve, is not the evaluation of a specific characteristic of a single material, or of the overall building performance, but rather the synoptic assessment of an assembly of elements among the same construction process. The lack of such vision discourages architects and designers to innovate or propose a new agreed solution. Life cycle assessment (LCA) provides a holistic approach to define materials and products environmental impacts along with their use-phase and disposal scenario (Alshamrani et al. 2014; De Felice et al. 2013; Vilches et al. 2017). Several single building materials and products have already been assessed with LCA (De Felice et al. 2013; Guardigli et al. 2011; Jeswani et al. 2010): wood, concrete (Björklund and Tillman 1997), roofs (Berto et al. 2018), insulating stone wool (Schmidt et al. 2004), hard floor coverings (Günther and Langowski 1997), and so on. However, there is still a little number of analyses on medium scale elements (Chau et al. 2015; Vilches et al. 2017).

As highlighted in many different reviews on LCA in the built environment (Anand and Amor 2017; Buyle et al. 2013; Jeswani et al. 2010), there are no solid guidelines on which stream of methods should be applied under specific circumstances. Although they can be applied for comparing different building designs with respect to their environmental impacts, there are still some drawbacks in boundary scoping, methodology framework, data inventory and practices, which impairs their usefulness as a decision making support tool. Conceivably, the usefulness of LCA can be further enhanced in building construction by standardizing the requirements for individual studies on the boundary scoping, methodology choices and data inventories so as to establish benchmarks for different types of buildings. Also, it is important to extend the current scope of LCA to include effects of indoor environmental qualities, building location as well as social considerations. The fundamental LCA concept is useful to formulate the building environmental assessment schemes embracing all these aspects. Of equal importance, is to search for effective policy governance measures to encourage building designers and developers to apply life cycle study in early design stage even though it may slightly prolong the tight building design schedule. The aim of this paper is to exploit LCA methodologies (Sect. 2.1) to evaluate the environmental impacts of three different types of roof analysed within the building component scale (explained in Sect. 2.2). A green, reverse, and simply waterproofed roofs have been drawn and split into each component's environmental impacts, whereas a multi-criteria decision analysis (MCDA) tool integrating economic, social and aesthetic parameters (Sect. 2.3). The results (Sect. 3) from this LCA analysis are included in a more holist MCDA approach which is able to consider different objectives (thermal performance, construction cost, aesthetic performance, social utility, environmental impact). This integrated evaluation is conducted according to different scenarios and points of view (eco-social and business-as-usual) and gave scenarios with a synoptic assessment of each maximized performance.

Conclusive remarks in Sect. 4 show that an MCDA qualitative analysis coupled with the quantitative result from LCA appeared to be very helpful in comparing options in the design phase of a building, and a useful communication tool among all the stakeholder of the construction process.

2 Methods

2.1 LCA Scoping

The aim of the first part of this study is the comparison between the environmental impacts of three different types of roof, in order to identify the solution with the minimum amount of damage points. The functional unit is constituted by one square meter of roof. The system boundaries go from the raw material extraction to the disposal scenario, considering the machines and the energy needed in the production phases, for the transportation from the firm to the site and for the end-life treatment of those materials. Unlike the single material analysis, here the energy consumptions for summer/winter cooling/heating is included.

The method follows the SimaPro function scheme, where data collection for the product and its components are collected, the single framed are for contents of each database and the double framed for the calculation and the evaluation phases. The assumption at the base of the evaluation is the one embedded in the Eco-indicator 99 method, modified with the updated database dedicated to the Italian products and processes presented by Neri (2007). Eco-indicator 99 takes into account three damage categories (Human Health, Ecosystem Quality, Resources) and the following impact categories: Human Health Carcinogenic, Respiratory organics, Respiratory inorganics, Climate change, Radiation and Ozone layer measured in DALY (Disability Adjusted Life Years); Ecosystem Quality Ecotoxicity, Acidification, Eutrophication, and Landuse measured in PDF * m^2y (Potentially Disappeared Fraction of Plants species), Resources, Minerals and Fossil fuels measured in MJ surplus. All the transportations input was considered from the nearest production plant to the building site that has been set in Salerno, Italy. The geographical setting is also crucial for the climatic boundary condition when calculating the thermal load within 1 ms of the practical unit. The amount of Thermal Power (Pti) needed to maintain an internal room temperature of 20 °C in wintertime is given by the (1):

$$Pti = (l/s) * S * DT Þ Pti = ki * Si * Dti \quad (1)$$

where:

l is the thermal conductivity (W/mK), s is the thickness (m), S is the surface area (m^2) (supposed to be orthogonal to the thermal incoming flux. i.e. that the roof is horizontal and *D*T is maximum), and *D*T is the difference between external and internal temperature, and $k = 1/(1/a_i + 1/a_e + \Sigma s_i/l_i)$. The Primary Energy Q_{ti} is obtained by multiplying P_{ti} to hours/day, to days/months, to the months/year and to the supposed life years of the building, only for the supposed operational time frame of heat plant. In order to take into account also another important parameter like diffusivity, increased during summer, for the calculation of the cooling thermal power some adjustment factors by means of experimental data and diurnal variation of temperature and the thermal lag. Obviously, it is assumed that each proposed roof package must respect every law prerequisite in terms of security, safe, maximum U value, sound reduction and humidity control (dlg n° 192, following the 2002/91/CE).

2.2 LCI—Life Cycle Inventory

The roof assembly tagged R1 is a waterproofed concrete roof. It is made up as illustrated in Fig. 1 to calculate its thermal performances. The results (U value = 1.772 W/m^2K, total thickness = 0.32 m, superficial mass = 370 kg/m^2) were input in Simapro for the energy consumption during winter and summer. The process flow was compiled as in Table 1.

With the same structure as the R1, R2 is a typical reversed roof. It has the R1's layers plus an insulation layer of polystyrene (7 cm), a waterproof layer and a gravel bed on the top (8 cm) are illustrated in Fig. 2.

The R3 roof is a typical green roof composed as the R1 plus an insulation layer of expanded polystyrene (8 cm), an air gap between the structure that collect the ground and the above understructure (2 cm), waterproof layer and a ground bed on the top (10 cm) with a certain percentage of humidity to let the plants grow on it. The thermal properties are calculated with the Termus software.

2.3 Multi-criteria Decision Analysis

Multi-criteria decision analysis (MCDA) provides a systematic process for trading off effects of various alternatives, taking into account all the aspects and values involved in the decision and synthesized individual contributions. Originally developed in the field of Operative Research, discrete MCDA is able to determine lists of priorities from a finite series of choice options (alternatives) which are assessed and compared in relation to identified characteristics of the problem (criteria) when it is appropriately broken down into its fundamental elements. In particular, MCDA

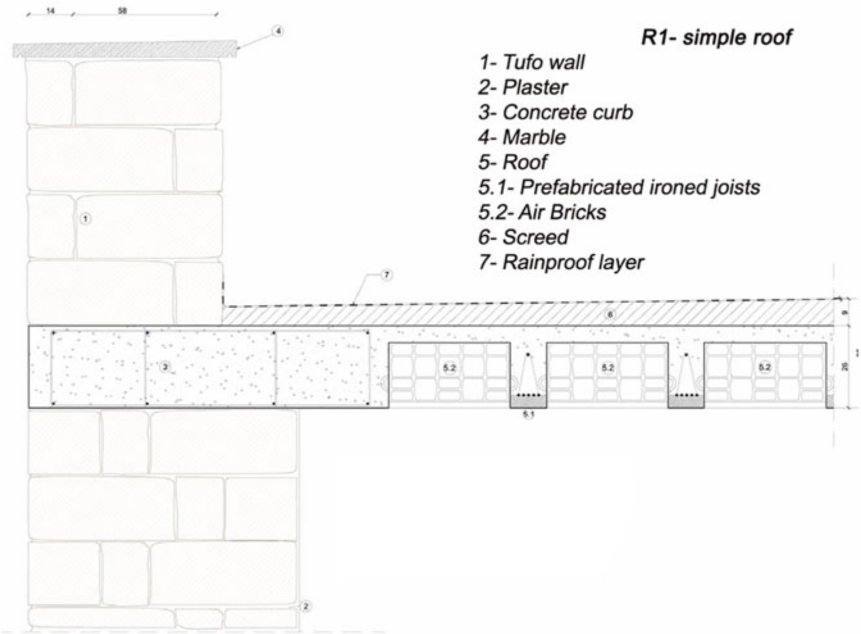

Fig. 1 The roof assembly tagged R1 (waterproofed concrete roof)

provides the following benefits: a clear definition of the criteria used in the selection of an option between alternative solutions; a weighting of the criteria to be used in the evaluation, in accordance with different point of views; a combination of multiple aspects which have a different nature; a comparison between objectives, strategies of the various subjects involved, and available resources; a transparent and explicit evaluation approach.

Literature presents a wide range of MCDA methods which can be grouped in families, as quantitative, qualitative and mixed (Figueira et al. 2005). These differ from each other in the nature of the information they are able to manage, i.e. cardinal (hard), ordinal (soft) or mixed data.

There are two major schools of thought in MCDA that govern the methods proposed in this field: the French school, represented by the ELimination and (Et) Choice Translating REality (ELECTRE) family of outranking methods; and the American school represented by the Analytical Hierarchy Process (AHP), proposed by Saaty in the 80's (Saaty 1990, 1996b). These schools regard both the evaluation of a finite set of alternatives, based on a finite set of conflicting criteria, by a decision making body. However, the French school channels subjective human judgments through partial systems of binary outranking relations between the alternatives and via a total system of outranking relations, while the American school allows to design partial value functions on the set of alternatives (being able to assess a global value function, too). That is why, for the scope of this work, that is encompassing many

Table 1 Example of process flow in the Simapro Software (R1—simple roof)

1 mq rainproof layer in PVC (SARNAFIL G 476-20) (sp = 0.002), 1p; weight = 2.8 kg	Transport, lorry 28t/CH S, 2214.8 kg km From Sarnafil firm plant in Milano to the building site in Salerno = 791 km * 2.8 = 2214.8 kg km
1 mq lightened concrete (10 cm = 0.1 m) 1p; weight: 45 kg	Transport, lorry 28t/CH S, 2240 kg km slab from the firm to the site, supposing a cave near Salerno which can provide all the components: 112 kg * 20 km = 2240 kg km
1 mq airbrick floor with ironed joints (0.22 m) 1p; weight: 117.744 + 114.92 + 88 = 321 kg	ExtTemp, max = 31.2 °C, intT = 26 °C. DifExtTmax-intT = 5.2. DTeqmax = (15.2 − 8.5)/200) * (700370) + 10.5 = 21.555 (h23) Adjusting factor: −0.3/DTeq = 21.255 Pte = 1.772 * 1 * (21.255) = 38 W
1 mq plaster (0.01 m) 0.75 p/0.02 * 0.015 = 0.75p; 28 * 0.75 = 21 kg	Eti = 37.664 W * 4 h/d * 2 * 26d/y * 100y = 783408.288 W = 783.408 kWh (heat)
Heat, natural gas, at boiler condensing modulating <100 kW/RER S 3648.902	Transport, lorry 28t/CH S, 5448.8 kg km air bricks: 272.44 kg * 20 km = 5448.8 kg km
kWh energy consumption during winter: P_{ti} = 1.772 * 1 * (20 − 2) = 31.896 W Eti = 31.896 W * 8 h/g * 26 g/m * 5.5 m/a * 100a = 3648902.4 W = 3648.902 kWh	Transport, lorry 28t/CH S 280 kg km plaster: 14 kg * 20 km = 280 kg km
kWh Heat: energy consumption during summer: superficial mass: 370 kg/m^2	RP_Recycle PVC from the site (with coproduct) Sarnafil membrane: 2.8 kg
ExtTemp, max = 31.2 °C, intT = 26 °C. DifExtTmax-intT = 5.2. DTeqmax = (15.2 − 8.5)/200) * (700370) + 10.5 = 21.555 (h23) Adjusting factor: −0.3/DTeq = 21.255 Pte = 1.772 * 1 * (21.255) = 37.664 W	RP_Recycle concrete screed no steeled (with coproduct): 45 kg
Eti = 37.664 W * 4 h/d * 2 * 26d/y * 100y = 783408.288 W = 783.408 kWh (heat)	RP_Recycle concrete floor (with coproduct): 272.44 kg − 2.112 (steel) * 2 − 1.12 = 267 kg
RP_Recycle steel (with coproduct): kg 2.112 * 2 + 1.12 = 5.3 kg	RP_Recycle plaster (with coproduct): 14 kg

alternatives at the time (making useless the comparison couples to couples of different options), we chose to adopt the Analytic Hierarchy Process (AHP), developed by Saaty (1980, 1992, 1993, 1994, 1995, 1996a) which translates expert judgments in a 9 points-scale, providing cardinal indices for operationalizing. The mathematician Thomas L. Saaty developed the AHP as an aid to managers in making decisions. Subjective assessments and objective facts are incorporated into a logical hierarchical AHP framework to provide decision-makers with an intuitive and common sense approach in quantifying the importance of each decision element through a comparison process. This process enables decision-makers to reduce a complex problem to a hierarchical form with several levels (Saaty and Forman 1993).

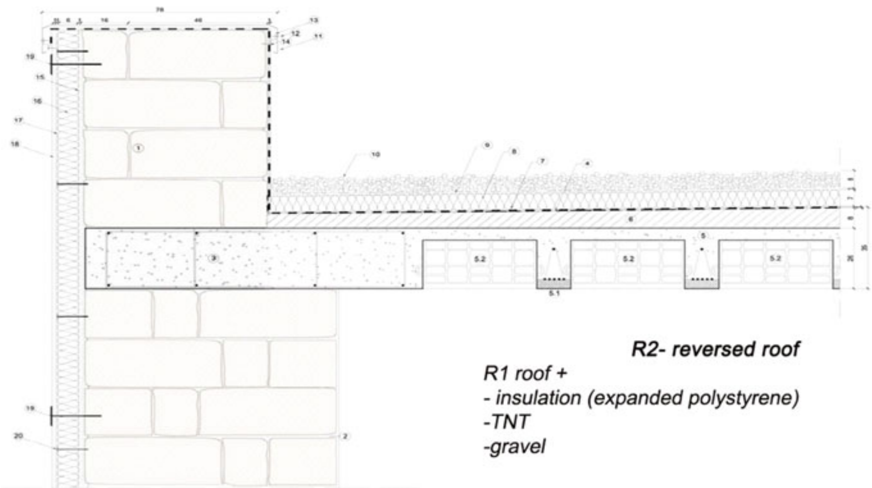

Fig. 2 The roof assembly tagged R2 (reversed roof)

In setting up the decision hierarchy, the number of levels depends on the complexity of the problem and on the degree of detail the analyst requires to solve the problem. Generally, the hierarchy has at least three levels: goal, criteria and alternatives (Saaty 1995). Since each level entails pairwise comparison of its elements, Saaty suggests the number of elements at each level is limited at a maximum of nine (Saaty and Vargas 1991).

The process starts by determining the relative importance of particular alternatives with respect to the criteria and the sub-criteria (Saaty and Kearns 1991). Then the criteria are compared with respect to the goal. Finally, the results of these two analyses are synthesised by calculating the relative importance of the alternatives with respect to achieving the goal.

The process of comparison is represented by forming a comparative matrix. If the analyst has at his disposal n alternatives, or criteria that form the comparative matrix, then he must make $n(n-1)/2$ evaluations. Pairwise comparison data are collected for only half of the matrix elements: diagonal elements always equal one and the lower triangle elements of the matrix are the reciprocal of the upper ones.

Pairwise comparisons give to the user a basis to reveal his/her preference by comparing two elements. Furthermore, the user has the option of expressing preferences between the two as equally preferred, weakly preferred, strongly preferred, or absolutely preferred, which would be translated into pairwise weights of 1, 3, 5, 7 and 9, respectively. The numbers 2, 4, 6 and 8 are used as intermediate values when there is not an agreement between preferences. The reciprocal numbers 1/2, 1/3, …, 1/8, 1/9 complete the matrices. The technique of the AHP takes as input the above comparisons and produces the relative weights of elements at each level as output using the “eigenvalue” method. The eigenvector of each comparative matrix is the priority list, while the eigenvalue gives the measure of consistency in making the assessment or comparison. The synthesised eigenvector is the global sequence of the alternatives with respect to achieving the goal.

The last step of the procedure aggregates relative weights of various levels obtained from the previous step in order to produce a vector of composite weights which serves as ratings of decision alternatives in achieving the most general objective of the problem. The use of AHP is facilitated by the availability of a user-friendly supporting software Expert Choice that we used for the calculation.

3 Results

3.1 Results from LCA

From the analysis of the result of the LCA applied to the three types of roofs (Table 2), it can be inferred that the R2 solution, i.e. the reversed roof, provides the minimum damage (32.621 Pt), with a reduction in comparison to the simple roof (R1) by 69.46% (see Fig. 3). The green roof (R3) produces 33.146 damages points. In *Human Health* the reversed roof produces the minimum damage (9.2596 Pt) with a reduction in comparison to the simple roof by 37.99%, above all for the *Carbon Dioxide, Fossil* contained in the fossil fuels category and most founded in the process for the cooling and heating loads. In *Ecosystem Quality* the green roof produces the minimum damage (0.62078 Pt) with a reduction in comparison to the simple roof by the 47.36% above all due to two components, 1095.5 kg of *Nitrogen oxides* and *Transformation to dump site, benthos*, funded in the process for cooling and heating. The reversed roof damage is 0.67491 Pt. In Resources the reversed roof produces the minimum damage with 22.686 Pt, decreasing the impacts by the 74.96% above all thanks to the minor consumption of *Gas, Natural, in Ground* used for the cooling and heating of the building. The other most affected damage categories are the “respiratory inorganic”, due to the particulate matter emission in transportation and excavation of the material from the cave. The one that is strongly reduced is the “Climate Change” category, thanks to the dramatically reduced energy consumption during the using phase when the roof is in a way or in another well insulated. The disposal scenario of a particular plastic layer in the reversed roof makes the percentage of carcinogens increase in the histogram bars, so a polyolefin or special paper substitute can be suggested in order to avoid that negative impact.

3.2 Results from AHP

The first step in applying the AHP model is dividing the problem into one or more criteria which will be used to weight the alternatives options (Fig. 4). This means

Table 2 Comparison between the three roof total damage points according to eco-indicator 99 assessment method

Comparing 1 p ‘green roof’ (R3), 1 p ‘reversed roof’ (R2) and 1 p ‘simple roof’ (R1)	R3	R2	R1
Total	33.145976	32.620652	106.831487
Carcinogens Pt	0.9084119628	0.9841191168	1.004148323
Respiratory organics Pt	0.00763135484	0.007414438007	0.01503910413
Respiratory inorganics Pt	7.212694771	6.803770798	8.5384135
Climate change Pt	1.324238064	1.457387747	5.459976974
Radiation Pt	0.005789951968	0.006007926603	0.0155119458
Ozone layer Pt	0.0008189146497	0.0008740981077	0.003561682825
Ecotoxicity Pt	0.05274776477	0.1731405503	0.2618430628
Acidification/Eutrophication Pt	0.3194349386	0.2557380259	0.4943969149
Land use Pt	0.2485956065	0.2460343585	0.4233034532
Minerals Pt	0.3015665528	0.2722716805	0.6319686174
Fossil fuels Pt	22.76404612	22.41392649	89.98332425

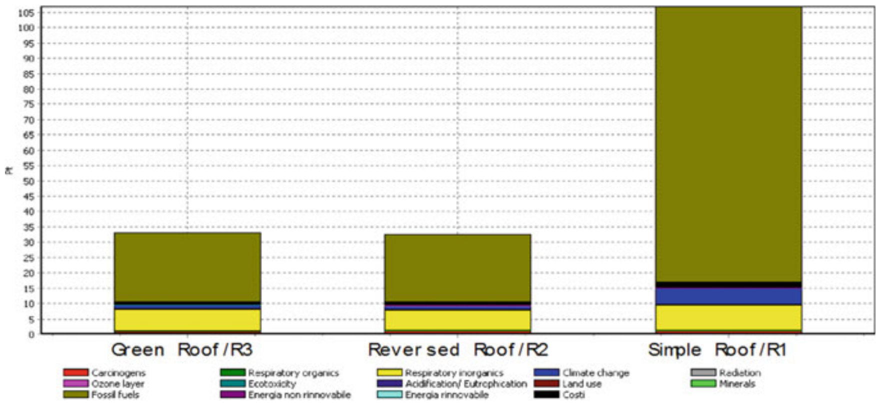

Fig. 3 Comparison between the three roof total damage points according to the eco-indicator assessment method

that it is necessary to define the hierarchical levels: goal, criteria, sub-criteria and alternatives.

In our case, the goal is to assess the different type of roofs according to their performances on the aesthetic, economic, and social point of views. The final set criteria are as follows:

1. Thermal resistance
2. Construction costs
3. Aesthetics

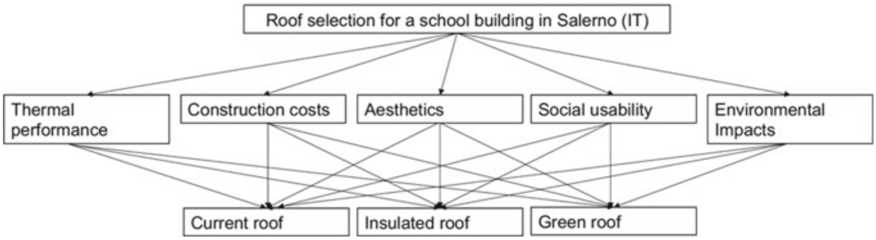

Fig. 4 The decision hierarchy. At the top level is the main goal of the decision making. The second level consists of the criteria that contributes to the overall goal. The third level is comprised of the different alternatives

4. Social usability
5. Environmental impacts.

Both the first and last criteria are derived from the previous LCA application. Additional quantitative data are related to the costs of each option. These are obtained summing up materials and site assembly as found in the regional built environment costs of unit list: the gravel roof (R2) turned out to cost 176.26 €/ms, the green one (R3) 195 €/ms, while the simply waterproof roof (R1) costs 125.69 €/ms.

The performance evaluation of the aesthetical and social issues has been conducted by the authors in consultation with designers, by adopting the pair comparison approach suggested by Saaty (2005).

The results from the overall performance evaluation of the three roofs are illustrated in Fig. 5, which reflects the neutral scenario (all criteria weights are equal to 1). As one can notice, the overall performances of the green roof are higher than the others. Specifically, this roof shows very high performance for the aesthetics (see photo) and social issues (gardening, etc.). On the contrary, the insulated roof is performing better in the thermal and environmental aspects while the current one (R1) only in relation to the construction cost criterion.

Two additional extreme evaluation scenarios have been considered in this application in order to reflect the major viewpoints of the built environment stakeholders involved, and specifically:

- an ‘eco-social’ scenario, where the aesthetic, social and context criteria are the only weighted criteria (Fig. 6);
- an opposite ‘efficient’ technical viewpoint (‘business as usual’) scenario where only the thermal performances and building costs are considered (Fig. 7).

In the first case, it is again the green roof to achieve higher performances, followed by the insulated and the current one. On the contrary, in the second case, it is the insulated roof to be ranked first.

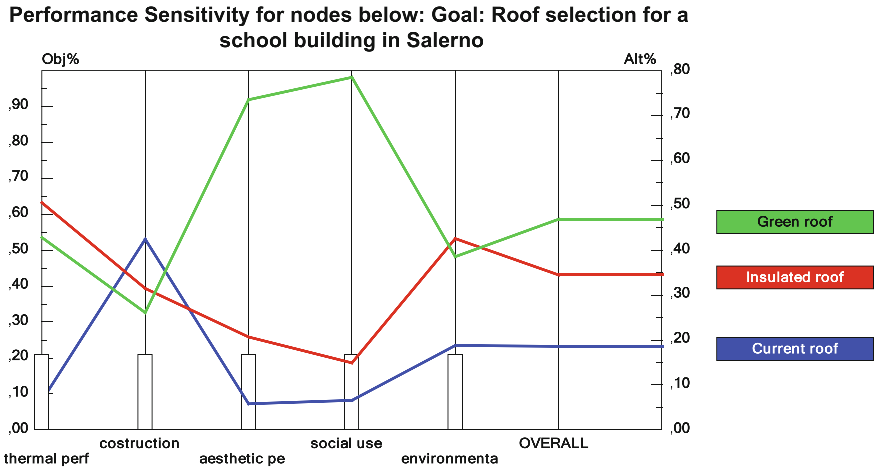

Fig. 5 The overall performance evaluation of the three roofs with the AHP method

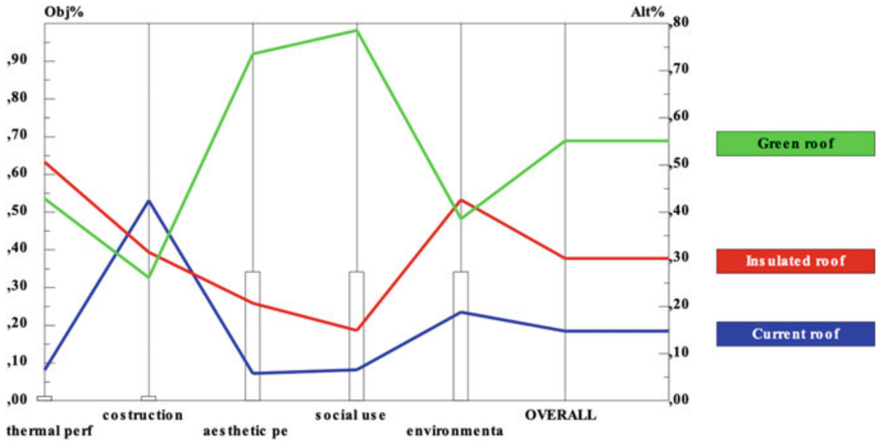

Fig. 6 The performance evaluation of the three roofs with the AHP method second an 'eco-social' scenario, the only weighted criteria are the aesthetic, social and context ones

4 Discussions and Conclusions

Regarding the first LCA comparison discussed in this paper, it is plain that the major source of environmental damage comes from the energy consumption in the use phase. This means that, in order to reduce this and consequently the overall impact, not only is necessary count on renewable energy sources to avoid fossil fuels and gas consumption, but it will be also crucial to beat on the energy performance of

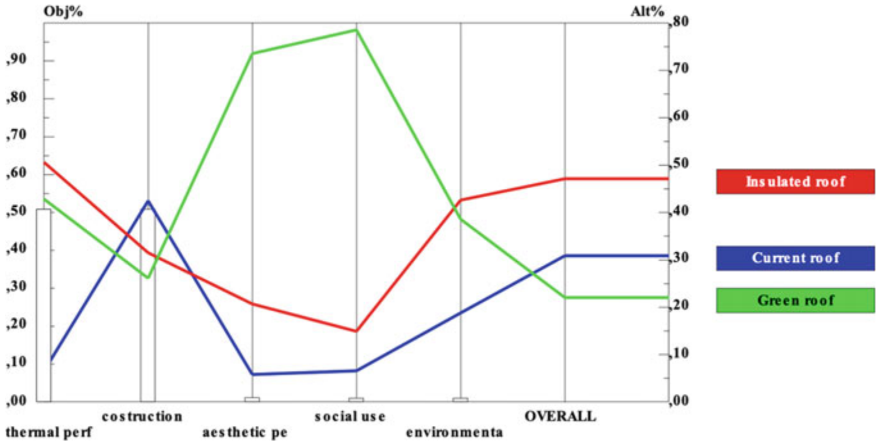

Fig. 7 The performance evaluation of the three roofs with the AHP method second an "efficientist" scenario where only the thermal performances and building costs are considered

the single component. If a layer of insulation, at first step analysis, would present a major embodied energy or higher pollutants index in the production phase, those effects could be overcome by less energy required for cooling and heating. In other words, apparently more polluting insulation would be more desirable than a natural, non-treated layer. The latest could be less impacting in the production or disposal phase but making the cooling and heating loads rise up for a longer period of time. For the peculiarity of the building sector, long-term performance is essential to do a correct evaluation. Regarding the methodology used to compare the alternatives, a strong accent must be put on the essential availability of a local database and different assessment methods that involve local material, transportation, resources and pollutant potentially dangerous, and any other local special boundary. It could have been useful to have compared, starting from the same database set, the result with other assessment methods to compare also different weight factor for the three ranking perspectives (Hierarchist, Individualist, Egalitarian). In the end, the work showed that the relationship between design, energy consumption and disposal scenario is very, very complex (Sonetti 2011), yet the implementation toward integrated ICT for regenerative sustainability design can be further developed (Sonetti et al. 2018, 2019). Experimental use of MCDA and LCA by individuals as an architectural design tool and integrated with existing decision-making software for energy planning can also be further envisaged as a useful step toward practical implication of this study (Abastante et al. 2017; Tavella and Lami 2018; Todella et al. 2018).

Although with its limitation, the LCA methodology seems to be the only one that can provide scientific data to make:

– the designer aware of the sustainability of the building since the earlier sketches
– the producer pushed to avoid pollutants emission during the production process of the material and to forecast a sustainable disposal scenario (the more the renewable energies will be part of the energy sources, the more a material environmental impact will fall not in the use phase but in its manufacturing and disposal phases)
– the public administration promoter of good practice and awarded green behaviour by buildings, constructors and designers
– the user aware of the added value of the building and conscious of the footprint left on the Earth.

To let in that virtuous circle a big effort is required from every single actor of the building process, but, as researchers, huge preliminary works will be needed to provide a social standard to which compare the results at the small, medium and large scale. Above all in Italy, on side of the energy performance declaration now mandatory for all the new construction, it could be useful one contemporary, mandatory Ecolabel criteria for the building material, package or whole construction, in order to force the research and the market in this direction. However, MCDA brought new perspective into traditional LCA. Conceptually, the use of qualitative, participative and prospective elements of MCDA procedural framework are complementing LCA. MCDA can provide information on site-specific aspects that cope well with the local constraint about social and economic issues, even when acquired by expert panels in a qualitative way, but risks are around the corner: LCA reliability can be stretched out beyond comparability if different scales and level of deepness are included all together on the results. This might lead to a trade-off between broadening and deepening the approach, with the result of making LCA even more complex and time-consuming for everyday use (if economic and social aspect are quantified as the environmental impact) or too analytical know-how and resources while trying to involve many stakeholders and criteria. One of the major advantages of our methodology is that it: breaks down a problem into elementary aspects; collects basic input data for all criteria of LCA Analysis and AHP Model; classifies the various environmental impacts; aggregate weights and scores to establish the final ranking in order to define the optimum solution. We believe that our new approach based on the LCA-AHP analysis helps decision makers to find sustainable alternatives among available options and promises a more sustainable product or process.

References

Abastante F, Lami IM, Lombardi P (2017) An integrated participative spatial decision support system for smart energy urban scenarios: a financial and economic approach. Buildings 7:103

Alshamrani OS, Galal K, Alkass S (2014) Integrated LCA-LEED sustainability assessment model for structure and envelope systems of school buildings. Build Environ 80:61–70. https://doi.org/10.1016/j.buildenv.2014.05.021

Anand CK, Amor B (2017) Recent developments, future challenges and new research directions in LCA of buildings: a critical review. Renew Sustain Energy Rev 67:408–416. https://doi.org/10.1016/j.rser.2016.09.058

Berto R, Stival CA, Rosato P (2018) Enhancing the environmental performance of industrial settlements: an economic evaluation of extensive green roof competitiveness. Build Environ 127:58–68

Björklund T, Tillman A-M (1997). LCA of building frame structures environmental impact over the life cycle of wooden and concrete Frames. Technical Environmental Planning Report 1997:2 Chalmers University of Technology, Uppsala

Buyle M, Braet J, Audenaert A (2013) Life cycle assessment in the construction sector: a review. Renew Sustain Energy Rev 26:379–388. https://doi.org/10.1016/j.rser.2013.05.001

Cabeza LF, Rincón L, Vilariño V, Pérez G, Castell A (2014) Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: a review. Renew Sustain Energy Rev 29:394–416. https://doi.org/10.1016/j.rser.2013.08.037

CAN Europe (2005) Input from environmental NGOs at the start of next round of the European Climate Change Program (ECCP). Climate Action Network Brussels, 24th October 2005

Chau CK, Leung TM, Ng WY (2015) A review on life cycle assessment, life cycle energy assessment and life cycle carbon emissions assessment on buildings. Appl Energy 143:395–413. https://doi.org/10.1016/j.apenergy.2015.01.023

De Felice F, Campagiorni F, Petrillo A (2013) Economic and environmental evaluation via an integrated method based on LCA and MCDA. Procedia—Soc Behav Sci 99:1–10. https://doi.org/10.1016/j.sbspro.2013.10.465

De T'Serclaes P (2007) Financing energy efficient homes, existing policy responses to financial barriers: IEA information paper. International Energy Agency (IEA), OECD/IEA, Paris, France, p 2007

Figueira J, Greco S, Ehrgott M (eds) (2005) Multiple criteria decision analysis: state of the art surveys, vol 78. Springer Science & Business Media

Guardigli L, Monari F, Bragadin MA (2011) Assessing environmental impact of green buildings through LCA methods: a comparison between reinforced concrete and wood structures in the European context. Procedia Eng. 21:1199–1206. https://doi.org/10.1016/j.proeng.2011.11.2131

Günther A, Langowski H-C (1997) Life cycle assessment study on resilient floor coverings. Int J LCA 2(2):73–80

Jeswani HK, Azapagic A, Schepelmann P, Ritthoff M (2010) Options for broadening and deepening the LCA approaches. J Clean Prod 18:120–127. https://doi.org/10.1016/j.jclepro.2009.09.023

L.D. 152 (2006). Decreto Legislativo 3 aprile 2006, n. 152, Norme in materia ambientale. Italian law 152 of the 3rd April 2006 on the environmental field edited in Gazzetta Ufficiale n. 88 of 14 April 2006—Supplemento Ordinario n. 96

Nejat P, Jomehzadeh F, Taheri MM, Gohari M, Majid MZA (2015) A global review of energy consumption, CO_2 emissions and policy in the residential sector (with an overview of the top ten CO_2 emitting countries). Renew Sustain Energy Rev 43:843–862

Neri P (2007) Verso la Valutazione Ambientale degli Edifici—life cycle assessment a supporto della progettazione eco-sostenibile. Edited by Alinea Editrice, ISBN 9878860551740. http://www.alinea.it

Saaty TL (1980) The analytic hierarchy process. McGraw Hill, New York

Saaty TA (1990) Decision-making for Leaders, RWS Publications, 4922 Ellsworth Ave., Pittsburgh, PA

Saaty TL (1992) Multicriteria decision making—the analytic hierarchy process, vol I. RWS Publications, 4922 Ellsworth Ave., Pittsburgh, PA 15213, AHP Series

Saaty TL (1993) What is a relative measurement? The Ratio scale phantom. Mathemat Comput Modell 17(4-5):1–12

Saaty TL (1994) Fundamentals of decision making and priority theory with the analytic hierarchy process, vol. VI. RWS Publications, 4922 Ellsworth Ave., Pittsburgh, PA 15213, AHP Series

Saaty TL (1995) Decision making for leaders, vol. II. RWS Publications, 4922 Ellsworth Ave., Pittsburgh, PA 15213, AHP Series

Saaty TL (1996a) Decision-making with dependence and feed-back—the analytic hierarchy process. RWS Publications, Pittsburg

Saaty TL (1996b) The analytic network process. RWS publications, Pittsburgh, USA (completed revision 2001)

Saaty TL (2005) Theory and applications of the analytic network process: decision making with benefits, opportunities, costs, and risks. RWS Publications, Pittsburgh

Saaty TL, Forman E (1993) The hierarchon, vol. V. RWS Publications, 4922 Ellsworth Ave., Pittsburgh, PA, 15213. AHP Series

Saaty TL, Kearns K (1991) Analytical planning, vol IV. RWS Publications, 4922 Ellsworth Ave., Pittsburgh, PA 15213. AHP Series

Saaty TL, Vargas LG (1991) Prediction, projection and forecasting. Kluwer Accademic, Boston

Schmidt AC, Jensen AA, Clausen AU, Kamstrup O, Postlethwaite D (2004) A comparative life cycle assessment of building insulation products made of stones wool, paper wool and flax. Int J Life Cycle Assess 9:53–56, 122–129

Sonetti G (2011) Environmental convenience of a building retrofit. In Proceedings of conference: people and buildings held at the offices of Arup UK. Network for Comfort and Energy Use in Buildings, London

Sonetti G, Naboni E, Brown M (2018) Exploring the potentials of ICT tools for human-centric regenerative design. Sustainability 10(4):1217

Sonetti G, Brown M, Naboni E (2019) About the triggering of UN sustainable development goals and regenerative sustainability in higher education. Sustainability 11(1):254

Tavella E, Lami I (2018) Negotiating perspectives and values through soft OR in the context of urban renewal. J Oper Res Soc 70:1–26

Todella E, Lami IM, Armando A (2018) Experimental use of strategic choice approach (SCA) by individuals as an architectural design tool. Gr Decis Negot 8:1–16

UNEP (2007) Buildings and climate change: status. Challenges and Opportunities, UNEP, p 2007

Vilches A, Garcia-Martinez A, Sanchez-Montañes B (2017) Life cycle assessment (LCA) of building refurbishment: a literature review. Energy Build 135:286–301. https://doi.org/10.1016/j.enbuild.2016.11.042

World Business Council for Sustainable Development (2007) Energy efficiency in buildings: business realities and opportunities. WBCSD