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Assessing environmental impact of green buildings through LCA methods:acomparison between reinforced concrete and wood structures in the European context

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Abstract

Life Cycle Assessment (LCA) can be used successfully to make decisions in sustainable building design and construction. Nevertheless, the method is rarely utilized for many reasons. First of all,in the common practice the energy consumption during the period of use is considered the main indicator of the environmental impactof buildings. Secondarily, databases relative to products, components and their installation cannot be found soeasily. The goal of this paper is tomake a comparison between two different construction technologies through Life Cycle Assessment methods, trying to understand the potentialities and the limitations of the available LCA tools. Although results may be limited to the specific context of Europe, we try to put in evidence the usefulness of the method in a design perspective, if carefully selected and adapted. The comparison regards two different structural solutions for a mid-sizedgreen building:an innovative wood structureand a reinforced concrete structure, built with a consolidated technology.According to the LCA approach,overall wood structures are environmentally less impactful thanconcrete ones, but different kinds of impact emerge in a wider perspective.

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Keyword: LCA methods; green buildings; wood construction; reinforced concrete construction

1.Introduction

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Although LCA can be used successfully to make decisions in sustainable building design and construction, there are very few studies in Italy that have compared alternatives of the same building typology using this method. An example of an LCA application is asocial housing project in Rome, called Case Rosse[a].

In this paper the environmental sustainability is evaluated through LCA and, particularly, through the comparison between a newly designed building, an innovative wood construction, and areinforced concrete construction. Thiscomparison is particularly significant in southern Europe wheredry solutionshave recently replacedtraditional technologies, not only for small houses, but also formid-sizedbuildings.Forthe reconstruction in the Italian regionof Abruzzo,after the earthquake of 2009,the contractsfor new emergency units required a certain level of sustainability and a significant reduction of construction costs. In many cases dry technologieswere recognized as better solutions[b].

2. Case study

The case study is based on the design of a green residential building, wheregreen means that the building is conceived to meethigh environmental standards and to becertified by an independent third party. The building was designed for an architecture competition in 2009 and wasmeant to be flexible and adaptable todifferent areas in southern Europe. The units are made by the aggregation of two 3,6 x 5,4 metersbasic modules containingthe kitchen, the living-room and the bathroom. Other modulescan be added to the basic elementsaccording to functional needs (Fig. 1).

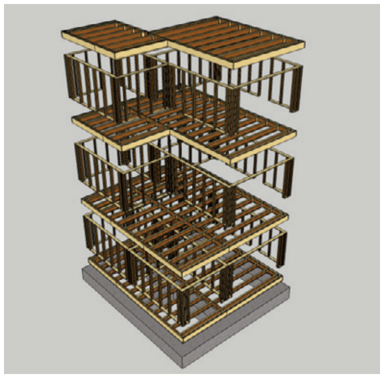

Fig. 1. (a) perspective view of the designed building; (b) structural organization of the building

The wood structure iscomposed by Joist beams. The I-Joists are I shaped wood beams, made by two laminated wood wings glued to a core made of OSB or plywood or high density particles[c]. The beams use the same generating process of IPE sections, optimizing the material for its bending strength. The

[a]See “Approccio life cycle alla progettazione energetica ed ambientale dell'edilizia residenziale. Applicazione sperimentale al P.R.U. Di Case Rosse” and “Impatti ambientali col metodo LCA e risparmi energetici secondo la legge 10/91: strumenti di valutazione per un'edilizia sostenibile”. Both The example are reported in Neri P. (a cura di), *Verso la valutazione ambientale degli edifici – Life Cycle Assessment a supporto della progettazione ecosostenibile*, Alinea, Firenze, 2007.

[b] In the reconstruction plan, named C.A.S.E., 150 residential buildings were rapidly built in the period 2009-2010. Among them, 30 where erected in steel, and 70 embodied wood structures.

[c] In the specific case of STEICO sections, the core is a panel made by high density particles.STEICOjoist are the elements for floor beams and roof beams, with a thicker core (8mm) to increase the shear strength. The section of the wings varies from 45x45mm to 45x90mm, the height from 20cm a 40cm. STEICOwallelements are used as wall studs. The core is thinner(6mm) because shear strenght is less important, but also in order to reduce thermal bridges.

construction technique of the building is the platform frame.The structure isverified with a seismic analysis, that is not reported here.

The wood structure, named Joi, wants to be a ready-to-use, versatile, and flexible solution, thatcan evolve with time according to the user needs. This means being enlargeable, modifiable in terms of internal distribution and services. Internal and external finishescanalso be personalized. In fact, they are not defined in advance, as they depend on the location and the taste of the user.

Thestructure that was selected for the comparison,named StandardED, represents the recurrent standard solution for residential units in Italian areas. The dimensions of the structural elements were taken from some reinforced concrete structures, designed according to thenew european standards (Eurocodes). These standards aremore restrictive than the previous ones. The external walls of the concrete structure are made of clay blocks, according to the normal practice. The solutions for the envelope are made in such a way that energy performances (U-value, thermal inertia) and acoustic performances (phonoinsulating power) of StandardED are the same of Joi.

Due to these preliminary assumptions, the LCA analysis was limitedto the raw buildings, and consisted in comparing the construction phase of the solution in wood with the analogous solutionin concrete. The study will be eventually completed with the other phases of the life cycle, taking into consideration the energy consumption. Thesephases will influenceall the components of the buildings, which are the object of the operations of maintenance, disposal and recycling.

In order to simplify the comparative study, a functional unit was extracted from the buildings.The unit is structured on three levels; the total floor area is 230 m^2, (the ground floor is 95 m^2, the first floor is 77 m^2, andthe second floor 58 m^2) and the total height is9,5 m.

According to EN ISO 14040:2006,LCA is divided into 4 phases: goal definition, inventory, impact assessment and interpretation. For the inventory of the materials and energies only the contribution of the raw construction was taken into account, excluding floor surfaces, wall surfaces, stucco work and roof surfaces. The shared components of the two solutions were not considered, in order to focus on the most relevant differencies (not only structural, but also forced by structural solutions) and on the different environmental charges.

In both solutions the considered elements were:

- foundations,
- structures
- floors, excluding floor surfaces
- cladding walls, excluding finishes
- dividing walls, excluding finishes

Regarding thefoundation excavations, the transportationdistance to an authorized landfillwas supposed to be 50km. For the steel bars of the concrete foundationsan average incidence of 100 kg/$m^3$was considered, and an average incidence of 200 kg/$m^3$for the steel bars embeddedin piers andbeams.

The reuse of scaffolding material before disposal was supposed to be ten times.Polystyrene panels were considered to be placed in theStandardED buildingfor thermal insulation, replacing the cellulose panels of theJoi building.

For the transportation of concrete, low cementconcrete, mortar, clay blocks and steel, all typical of southern Europe, a distance of 100 km was considered. The OSB panels and C24 wood panels were supposed to be foundwithin a radius of 300 km, while the transportation distance was supposed to be 200kmfor coatings and thermo-acoustic insulation, and600 kmfor I-Joist sections[d].

[d] The nearest production of I-Joist from STEICO is placed in southern Germany.

Electric power needed and oil consumption for StandardEDwere real dataderived from the construction site of an Italian residential building of the same size.

Confronting data from the fabrication of similar apartment buildings, the realization periodfor StandardEDwas approximately set to 4 months for the raw structure, including all the elements of the inventory. That allowed to evaluate the costs and the energy consumption of the construction. Confronting other construction sitesofwood buildings, it was established that the realization period for Joiwas less than 50% of the period required for StandardED. Costs and consumption could also be approximated to 50%.If these last considerations seem quite simplistic, it is also true that the environmental impact and the energy consumptionof the constructionphaserepresent only 5% of the impacts and consumptions of the entire construction process, with a small potential error.

3. Selection and adaptation of LCA tools

The open source software openLCA (GreeDeltaTD) was usedfor the inventory phase and Eco-indicator 99 for the following assessment phase.Eco-indicator 99is valid for the european context but needs to be adapted according to the personal experience. Itallows to aggregate the results of an LCA in easily comprehensible and usable parameters, called eco-indicators. These indicators consider three categories of damage: Human Health, Ecosystem Quality and Resources. Each damage category is then subdivided into impact categories. Of course, the effectiveness and the quality of an LCA method depends on the accuracy of the impact assessment.As already evidenced by other authors, Eco-indicator 99has some limitations[e]:

- the CO_2 emissions are considered only in the impact category Climate Change, but it is important to consider them also in the category Ecosystem Quality, because the climatic changes due to the global heating don't produce damages only on humans but also on vegetal and other animal species;
- the characterization of Land Use is very strong compared to the other categories of impact in Ecosystem Quality, penalizing the agriculturaluse of soil, compared to the same use as a consequence of civil and industrial construction;
- the damages due to iron emissions are not consideredin the categories Ecotoxicityand Carcinogens;the emissions due tonitrogen and phosphorus flows are not consideredin Acidification/Eutrophication;the damages due tochemical oxygen demand (COD) andbiologicaloxygen demand (BOD)are not consideredin Carcinogens;
- the evaluation that is given according to different cultural perspectives can be an advantage, but it is based on inquiries that are inevitably influenced by single opinions and personal interests;
- water, gravel, sand, uranium and silver are not considered limited materials;
- themethod does not operate economic evaluations;
- the method is referred only to the european context, which could be a problem for global evaluations;
- a real evaluation of energy consumption, which in some cases it is very representative of the damage, is missing.

The evaluation of the environmental impact with Eco-indicator 99 was performed in the egalitarian version, which outlines a long term vision of the environmental impact. This vision takes into account the category Human Health by 30%,the category Ecosystem Quality by 50% and the category Resources by 20%. In order to face the limitations of Eco-indicator 99, some modifications were introduced, as suggested bysome authors (Neri, 2007). These modifications are reported below.

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[e]Cfr. Neri P. (a cura di), op. cit., par. 6.2.5.2. Obviously, a way to avoid potential mistakes of a certain LCIA methodology is to compare the results with other results from different methods and deriving generalremarks.

Waters have been added to the impact categoryMinerals, excluding superficial waters, to take into account the fact that a biggerconsumption of water (unlimited substance) always requires a bigger quantity of energy for its extraction. As characterization factor it is considered the energy surplus (year 1990) to extract a liter of water caused by groundwater lowering of 60m, as effect of an increase of water consumption by 5 times. For waters with unspecified provenience, the characterization factor has been reduced by 0,4855, because ISTAT data revealed that in Italy, in the year1999, the extracted water from the ground has been 48,55% of the total.

Gravel, sand, uranium and silverwere added in the category Minerals,asfundamental substances for the production of building materials and energy. In order to define these characterization factors, the hypothesis of the consistency of the relations between different substances was made.

The substances nitrogen and phosphorus, COD (Chemical Oxygen Demand –) and BOD (Biochemical Oxygen Demand –) were added tothe impact category Acidification/Eutrophication, because they produce the eutrophication of water. Iron emissionswere added in Carcinogens. The category Costs, which utilizes the emission Costwith characterization factor 1, was added.

Furthermore, the method Cumulative Energy Demand was added to Eco-indicator 99.It is a very simple swiss method that takes into account the global embodied energy of a process, consideringalso the extracted primary maters and the equivalent Mj that they might have produced. In such a way it is possible to correct the fact that in Eco-indicator 99 a real energy balance is not accomplished.

4. Life Cycle Impact Assessment and interpretation

The character of big diversity that the wood structure has in comparison to other materials and techniques utilized not only in Italy, but also in a big part of Europe, and the lack of a national database, as mentioned above, has made necessary to adapt the obtained data the national context.

A confrontation between two similar structures has been conducted by the american consortium CORRIM (Consortium of Research on Renewable Industrial Materials)on two building envelopes in Atlanta, that enclose a single level space of 200 m^2: the first in wood the other in concrete[f]. The confrontation between these data has permitted to refine the production cycles that have a significantinfluence on the structural parts of this case study.

The following databases have been tested and then utilized: Ecoinvent, swiss database, NREL, free USdatabase by NREL, ELCD, databaseof the Joint Research Center of the European community.These databaseswereimported inthe softwareopenLCA.

As long as concerns the data used for the modeling, it is not possible to find an european production process for the I-joist elements. It was necessary to modify the composite wood I-joist processing, at plant, contained inthe NREL database, and transfer it tothe European context. Practically, the sub-processes of I-Joist production were analyzed and, according to the available data, a set of alternatives was evaluated, maintaining the same quantitiesbut making some substitutions.

The use of very different quantities of reinforced concrete and steel is the reason forhaving two solutions with different weights: StandardEDweights about 500.000 kg, whileJoiweights only 160.000 kg.

Talking about the results, Joi generally demonstrates a bigger impact on Ecosystem Quality (only 10%), balanced byconsiderably smaller impacts in the categories Resources and Human Health (fig. 2).

The results of the category Ecosystem Quality are explained by the fact that Eco-indicator 99 tends to give a very strong characterization to Land Use, in respect to other impactsof the same damage category. Given the fact that the wood utilized for the realization of Joi is inevitably extracted from forests and

[f] The institute aims at collect and propose reports on innovative materials, to be inserted into the major american databases (after validation). In this case we refer to module I “Design of residential building shells – Minneapolis and Atlanta”

green areas, sometimes intensively, the Land Use category (land occupation) acquires a big importance in determining the impact on Ecosystem quality. The problem of land occupation for wood production does not concern the building sector , but can be resolved with politics aiming at regenerating woodreserves.

For the other impact categorieswithin Ecosystem Quality Joi is more favorable approximately by 50%.

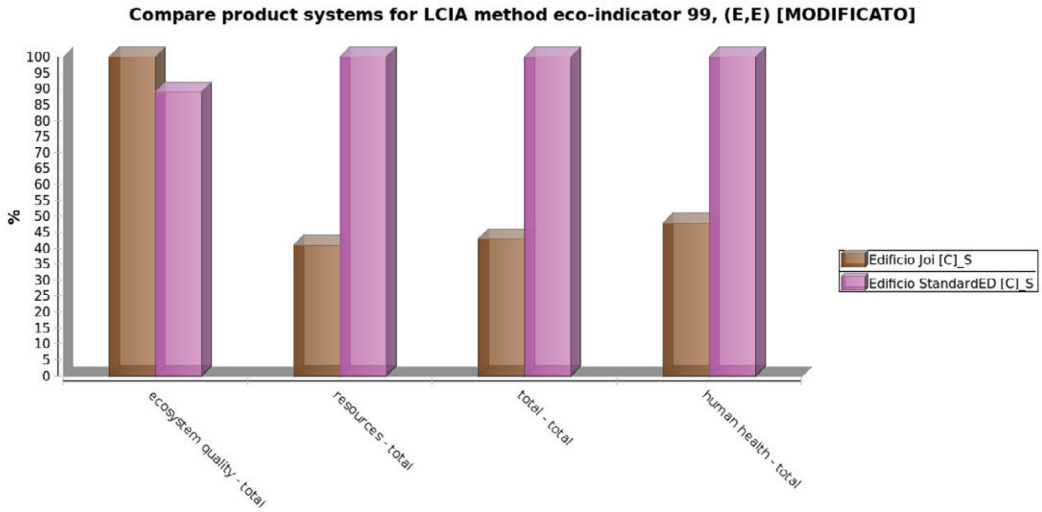

Fig.2. global comparison of the damage categories.

As regards the impact categories contained in Human Health,the same trend of Ecosystem Qualityis confirmed. The only comparable impact is relative to the emission of cancirogens elements.Joigives off cadmium and arsenic, coming from the processes of OSB fabrication, from the resins used to glue the I-shape sections, from the treatment of wood and particulates, and from the sawing processes for the realization of the components. The same elements are present in the exit flows of the industrial processes for the production of concrete.

Operating a first energy balance through the Cumulative Energy Demand method, which considers all the energy contributions and not only the primary energy, the Joibuilding has a more favorable global energy balance than StandardED. Thesecond is more convenient only regarding biomass energy, due to the large use of wood in Joi, and wind energy.

Breaking down the global process of construction in its three main parts of materials production, transportation and construction, it is evident that the biggest contribution to environmental impact isgiven by the production of materials in factories.Transportation weights 60% and 70% of materials production and energy for theconstruction on site only 1-5%.Relatively to every part of the construction process, the previously evaluated trend of 50% is respected:

- the production of materials for StandardEDleads to an index of 17.500 eco-points, while the production of the materials for Joi to an index of 6.700 eco-points;
- transportation for StandardED has been evaluated 10.900 eco-points, transportation for Joi4.800 eco-points;
- the energy demand for the construction site hasan index of 390 eco-points forStandardED, and 195 eco-points for Joi.

Confronting the two transportation processes, although it can be supposed to have long distances from the factory to the building site, wood elements are still more convenient than concretefor distances that are 6 times longer. As mentioned above, the biggest part of environmental charges and energy consumption comes from the production phase in factories.

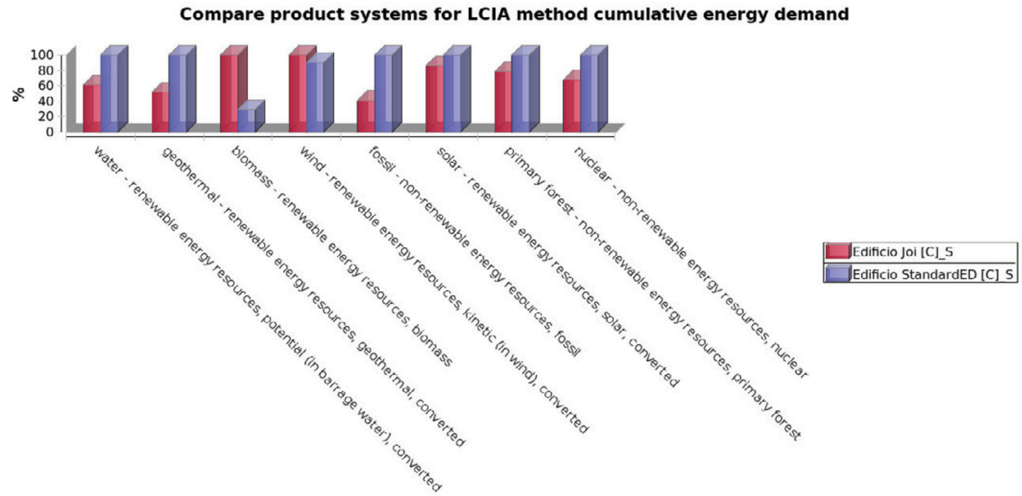

Fig.3. Confrontation between StandardED and Joi energy balance.

After a first comparison, the diagram is very similar to the one for the entire production process. theJoisolutionhas a smaller impactsin Ecosystem Quality by 5%, in Resources by 65% and in Human Health by 70%.

Globally, the production of materials for the platform frame solution are better evaluated by approximately 60%. Resources savings are particularly favorable: in material extraction savings of 35% and fossils 65%. For the subcategories Human Health and Ecosystem Quality impact ad flow profiles are very similar to the ones of the entire realization process, having StandardEDa much bigger impact on the category Land Use than Joi, and a quite similar impact on Carcinogenics.

It is clear that overall Joi consumes less energy and, most of all, uses more renewable energy sources. In particular, the energy consumption of Joi is 45% ofStandardED for hydroelectric energy and 170% for biomass energy. It has already been described that this data come from the massive use of wood and its derivatives, but it is not necessary a weakness. Besides, the use of electric energy is approximately 80%, the use of fossil fuels 45%, the use of solar energy80%, the use of wood from non renewable resources (primary forest) 70%,and the use of nuclear energy50%.

Analyzing the components of the buildings, the wood floor does twice the damage a concrete slab, relatively to Ecosystem Quality. As explained before, Eco-indicator 99 applies a strong characterization to the impact category Land Occupation, whose index is amplified by the big amount of wood used in Joi.

Observing the other sub-categories, relative to Ecotoxicity, Acidification and Eutrophication, the traditional concrete technology is very impactful and not convenient compared to the floor realized with a wood design. Ad adequate management of the wood resources could make very convenient the use of wood floors, balancing the problem related to Land Use.

Analyzing the elements of the wood floor, relativelyto the categoriesEcotoxicity, Acidification/Eutrophication e Stored Ecotoxicity, a big part of the environmental charge come fromthe

OSB panels, introduced in the project because diffused in the commercial market, but containing resins with toxic effects. The substitution of these materials with equally performative but less impactful materials could improve the design of the Joi building. Similar results are obtained also confronting the walls, given the analogies of materials and building techniques.

However, the foundations are the most impactful components on Human Health, for the dust and the carcinogen emissions during the preparation of the concrete.This brings to the conclusion that reduced foundations in size, always give smallerenvironmental impacts.

As regards the impact of the cladding walls, the incidence of Joi is 40% to 50% ofStandardED. For the category Climate Change the charge of the proposed floor is even 80% less.

On the contrary, the emissions of cancerogines elements are comparable, even if they are always smallerfor Joi.In fact, the contributions of arsenic, cadmium and particulate are very similar. Again, considering the contributions of the single materials, the environmental damage is given by the use of OSB.

As regards the category Resources, the Joicladding wall hasan overall charge that is 50% ofStandardED’s. It provokes a smaller damagefor the sub-category Mineral Extraction (20% less) and for Fossil Fuels (50% less). The materials that belong to the wall with a bigger damage for this category arethe STEICOwallsections, SW90 sections and OSB.

5. Conclusions

According to LCA methods, the estimated environmental impact of wood buildingson human health, resources and ecosystem quality is generallysmallerthan a typical concrete structure. However, as evidenced by the methods, the vast use of wood threatens the quality of the ecosystem. Therefore, an intelligent wood resources policyis necessaryto favour the regeneration of the environment compatibly to the requirements of the building industry.

The use of standard OSB panels, like other similar materials, should be limited,as it is the bigger responsible of the damage to human health from cancerogen agents, and to the ecosystem from elements that provoke acidification and eutrophication. From this point of view, in order to optimizewood design, some alternatives could be evaluated like high density panels or other recycled materials.

According tothe cost analysis, wood structures resulted more convenient (17%), and bigger savings could be obtained speeding upthe construction process. The transportation from distant places doesn’t seem to be a major problem, either environmentally or economically.The limitation of wood systems in southern Europe building market isdefinitively derived from the ability of using this technology, but not from environmental issues.

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