Life Cycle Assessment Impact Indicators for Simulation-Based Optimization of Buildings

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***Abstract*—The themes related to the enhancement of sustainability in the built environment have been gaining increasing concerns by the scientific community, other than by governments. Accordingly, there is a need for the availability of tools that can help scientists and policy makers in choosing the most appropriate intervention measures that simultaneously take into account environmental as well as energy and economic aspects.**

To this purpose a literature review of scientific articles dealing with the optimization of the energy and environmental performance of buildings, making use of LCA and economic analyses was conducted. The results of this earlier step of research (which would serve as the basis for future developments) are aimed at singling out a small set of indicators to be used in a multi-objective optimization methodology for the improvement of buildings sustainability.

***Index Terms*—buildings, LCA, optimization, review, sustainability**

I. Introduction

In recent decades there has been an increasing focus on environmental concerns, particularly in relation to the assessment and mitigation of the impacts of processes and products, concerning various sectors (UN, 2015; IEA, 2019; Vocciante et al., 2021; Capitano et al., 2022) . Evidence of this are some relevant policies and initiatives such as the UN Sustainable Development Goals – SDGs "11 – Make cities and human settlements inclusive, safe, resilient and sustainable" and "Goal 12 – Responsible consumption and production" (SDGs), the EU climate-energy frameworks long-term strategies (EU, 2014 ;EU, 2018), Green Deal (EU, 2019) and recovery plan Next Generation EU (EU, 2020) ; this latter imported nationally by most countries, such as the Italian Recovery Plan – PNRR (MISE, 2022) .

The life cycle-oriented methodology has gained prominence in this regard (UNFCCC 2021) . The philosophy behind the application of the life cycle approach is known as Life Cycle Thinking. Namely, three main "dimensions" of the Life Cycle Thinking have been developed, according to the three aspects of the sustainable development. That is, Life Cycle Assessment – LCA for the environmental dimension, Life Cycle Costing – LCC for the economic dimension and Social Life Cycle Assessment – SLCA for the social dimension (ISO, 2006) .

Regarding the built environment as well, the design of a Nearly Zero Energy Buildings – NZEBs, and in general of a low-energy buildings and/or districts, involves different aspects like the economic cost, the comfort indoor, the energy consumption, other than the life cycle environmental impacts, also considering the different points of view of policy makers, investors and inhabitants (EPBD, 2010; EPBD, 2012; UNEP, 2020; Cirrincione et al., 2021) .

Within this context, LCA allows to evaluate the environmental impacts of products and processes (including those concerning the built environment) across their entire life cycle, including raw material acquisition, production, use, and end-of-life (Peri et al., 2022; Rizzo et al., 2023; Llorach-Massana et al.; 2023) . LCA popularity stems from its rigorousness, based on mass and energy balances, and its flexibility in analyzing processes at varying levels of detail depending on data availability and scope of the study. In fact, LCA helps identify key sub-processes for improvement to reduce environmental impacts (ISO, 2006; Cirrincione et al., 2020) .

The methodology and procedure to properly perform an LCA study is standardized by the ISO 14000 regulation family (ISO, 2006; ISO, 2017a) and their subsequent updates and integrations. Accordingly, an LCA study is composed of four stages, each one interacting with the others (depending on the aim and the intended use of the study):

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- (I) goal and scope definition;
- (II) inventory analysis;
- (III) impact assessment;
- (IV) results interpretation.

Although the deepness and the amplitude of the included details may vary from one LCA to another, the generic framework to be used is the same. Specifically, in the first stage the functional unit should be defined, indicating precisely the product and/or process under study. Then, all the input and output process flows are referred to the functional unit, necessary to compare many studies on the same basis (Rebitzer et al, 2004) .

The level of accuracy of an LCA study depends on which method is chosen. In detail, three families of impact assessment methods can be listed: process-based analysis, input-output analysis, and hybrid analysis (Stephan et al, 2012) . Process-based analysis involves bottom-up analysis of energy and mass flows, but it has limitations due to system boundary incompleteness, neglecting many input flows. Input-output analysis provides a higher level of detail, using statistical techniques based on financial transactions and considering the entire economic system. Hybrid analysis methods combine process data with input-output methods to assess the entire supply chain of a product, aiming to fill gaps and provide a comprehensive evaluation.

The widespread adoption of the LCA method in both research and industrial sectors, serving as a scientific foundation for assessing environmental impacts, has garnered significant international attention due to its strategic importance. For instance, LCA is proposed as a support decisions tool in many EU calls for research funding, and it is a mandatory assessment method to adopt when applying for the EU Ecolabel (EU, 2017) Environmental certification.

However, as every other analysis technique, LCA is also characterized by some limitation to be taken into account in its use. One of such limitation is linked to the subjectivity of the analyst (introducing some effect related to his beliefs or bias). Moreover, the accuracy of the analysis is limited by the availability of high-quality information and data, other than by the assumption made to simplify and model the representation of the reality (during the inventory phase some aspects might be over- and/or under- estimated). Additionally, it should be noted that results deriving from a specific study should not be extended to a wider and/or narrower framework (*e.g.*, results related to a region cannot be extended to a whole country).

Thus, the adoption of a multi-criteria approach is required to manage some potential conflicting domains. In detail, one of the most suitable approaches is to integrate the preliminary building design and/or renovation phase in a multi-objective optimization problem, allowing to rapidly compare many alternatives and to identify the most adapt interventions. Such an approach would allow to single out the optimal combinations of parameters (*e.g.*, thickness of energy insulating material, type of insulating material, type of glazing surfaces, technology for environmental climate control) through an optimization technique taking into account economic, energy and environmental aspects through the LCA approach.

This paper focuses particularly on the latter aspect, namely in defining the role of the LCA in the building environmental sustainability enhancement multi-objective optimization problem. To this aim, literature research has been conducted in order to single out the most relevant LCA-based indicators, specifically related to passive energy retrofit of buildings envelopes at district/urban level.

II. Materials and Methods

According to the latest version of the Environmental Product Declaration – EPD (CEN, 2021) , the following impact categories have to be generally considered when performing a LCA (ISO, 2021) study:

- Climate Change – CC, not including biogenic carbon (kg CO2 eq.), often referred to as Global Warming Potential - GWP;;
- Ozone Depletion – OD (kg CFC-11 eq.), often referred to as Ozone Depletion Potential – ODP and/or Photochemical Ozone Creation Potential– POCP;
- Terrestrial Acidification – TA (kg SO2 eq.), often referred to as Acidification Potential - AP;
- Freshwater Eutrophication – FWE (kg P eq.), often referred to as Eutrophication Potential - EP;
- Marine Eutrophication – ME (kg N eq.);
- Photochemical Oxidation Formation – POF (kg NMVOC), ;
- Water Depletion – WD (m3);
- Metal Depletion – MD (kg Sb-eq.), often referred to as Abiotic Depletion Potential – ADP;
- Fossil Depletion – FD (kg oil eq.);
- Embodied Energy – EE (MJ).

Focusing on buildings, a specific LCA methodology framework for the evaluation of energy and environmental performance is given by the EN 15978:2011 European standard (CEN, 2011) . This standard specifies the method to assess the environmental performance of a building according to the LCA approach and provides the correct means for the reporting and the communication of the outcomes. Moreover, the standard specifies the life cycle stages and boundaries of the study, dividing them in product fabrication and construction (A modules), use (B modules), end of life (C modules) and benefits (D modules). While regarding the impacts, these may be split in embodied (*i.e.*, those related to the fabrication of the materials, the building construction and the end of life) and operating (*i.e.*, those related to the use phase of the building) terms (Schwartz et al, 2016; Tumminia et al, 2018) . Furthermore, the most important indicators to be used in the building sector are also given by the standard, as follows:

- the Global Warming Potential (GWP) measures the heat retained by a greenhouse gas in the lower atmosphere and is typically calculated over defined time frames, such as 20, 100, or 500 years. Common gases contributing to this phenomenon include carbon dioxide, methane, and nitrous oxide. GWP is expressed as the equivalent mass of carbon dioxide required to produce a similar effect (IPCC, 2001) ;

- the Ozone Depletion Potential (ODP) quantifies the extent to which emissions of a substance reduce the ozone layer in the stratosphere, leading to an increase in ultraviolet radiation in the atmosphere. Chlorofluorocarbons are primarily responsible for this phenomenon. ODP is expressed as the equivalent mass of trichlorofluoromethane needed to induce a similar effect;
- the Acidification Potential (AP) denotes the capacity to generate acid emissions or to acidify land and water, leading to phenomena like acid rain and a decrease in the pH of atmospheric water by introducing H+ ions. Common contributors to this phenomenon include sulphur and nitrogen oxides, as well as ammonia. AP is quantified as the equivalent mass of sulphur dioxide required to induce a similar effect;
- the Photochemical Ozone Creation Potential (POCP) quantifies the ability of airborne substances to generate atmospheric oxidants such as ozone at ground level, primarily driven by volatile organic compounds. POCP is measured in terms of the equivalent mass of ethene needed to produce a similar effect;
- The Eutrophication Potential (EP) signifies the decrease in water oxygen levels resulting from heightened nutrient levels, leading to an overgrowth of algae and plants, and disrupting the ecological balance among species. EP is measured in terms of the equivalent mass of phosphorus tetroxide required to induce a comparable effect;
- The Abiotic Depletion Potential (ADP) quantifies the utilization of finite, non-renewable mineral resources, measured in terms of the equivalent mass of antimony needed to cause a similar impact;
- The evaluation of primary energy demand can be conducted using either Cumulative Energy Demand (CED) or Global Energy Requirement (GER), terms that are typically interchangeable.

As for the LCA impact factors, these are usually drawn from international databases as Ecoinvent (Recht etal., 2016; Kiss et al., 2020), KBOB (Hollberg et al., 2013; Klüber et al., 2014), Ökobau (Hollberg et al., 2014; Hollberg et al., 2016; Montana et al., 2020) , or from the Environmental Product Declarations - EPDs. In the same way, costs data are collected from such available databases or market surveys (Cellura et al., 2019) . Using reliable and representative data is, in fact, a very important issue in LCA studies, since the results may be influenced by site-specific conditions. Indeed, in line with the philosophy that optimisation studies are usually employed to obtain generic indications on the problem to be further investigated with more detailed simulations, the majority of research studies employ secondary data (namely average values from the literature), in order to get generic and simplified results to be subsequently deepened according to specific needs. In addition to environmental issues, another important aspect to consider - especially when dealing with optimization concerns - is the economic one. This latter, as previously mentioned, via the life cycle approach is expressed in terms of Life Cycle Costing – LCC. This is a cost accounting method that considers all costs and cash flows associated with the entire life of a product or service. This includes relevant costs from acquisition to disposal, as well as any income and externalities within the agreed scope. LCC analysis involves comparing alternatives or estimating future costs (hence, it is also subject to a certain level of uncertainty due to predicting average interest and inflation rates over the analysis period). The LCC is standardized at international level by the ISO 15686-5:2017 (ISO, 2017b) . and at European level by the EN 15459 (CEN, 2017) , and can be expressed as global cost of a building - CG() - as shown in Eq. (1): (1) where CG() is defined as the sum of the following terms:

- The initial investment cost (CI);
- The annual cost at the year i due to the j-th component (Ca,i (j)), given by the sum of energy supply, running and replacement costs, actualized with the discount rate Rd (i);
- the final value of the component (Vf, (j)), if the expected lifetime of the building is longer than the reference period considered in the analysis.

Based on these assumptions, for the purpose of this work a number of 30 papers were identified and analyzed. In fact, as a first criterion for skimming the total articles found, it was chosen to consider recent papers (*i.e.*, published in the last eight years). Then, to further refine the literature on which to base the choice of indicators to be included in the building resilience enhancement multi-objective optimization problem, papers dealing specifically with integration between environmental, energy and economic aspects using up to date optimization techniques were selected. Results of such selection are shown in the following Table I, where the references, prevalent scope and used environmental, energy and economic indicators/parameters are briefly summarized.

TABLE I
MOST COMMON TOOLS FOR THE SIMULATION-BASED BUILDING OPTIMISATION

Software Tools	
Building Performance Simulation	***Building Performance Optimisation***
DOE-2 [1]	BEopt [2]
EnergyPlus [3]	GenOpt [4]
ESP-r [5]	MATLAB Optimisation Toolbox [6]
IDA-ICE [7]	modeFRONTIER [8]
TRNSYS [9]	Opt-E-Plus [10]

III. RESULTS AND DISCUSSION

The performed analysis, object of this paper, highlights the early stage of research in sustainable building practices applied to buildings envelopes at urban/district level in terms of LCA indicators, noting limited studies but diverse approaches. Most studies explore optimal strategies related to energy consumption and carbon emissions, often favouring sustainable solutions and natural materials (over non-sustainable options and synthetic materials) despite costs. The LCA impact assessment indicators employed in the reviewed studies are among the most commonly used in LCA studies on buildings. Most of the studies optimised the use phase of the building employing the GWP as an objective function, indicating a greater attention to the environmental issues rather than to the primary energy. Apart from the GWP, the use phase energy demand of the building was assessed through the CED. Other indicators identified in these works are EE, OD, TA, FEW and less commonly POF. The variables assessed in the reviewed studies are various, although they are mainly related to the envelope. Nevertheless, the following groups may be identified:

- Early design parameters, as the number of floors or the building orientation;
- Opaque envelope components, namely the materials and thicknesses of each layer;
- Transparent envelope components, as windows glazing or surface;
- HVAC equipment features, as the inclusion or the rated size of a specific technology;
- features, as the inclusion or the rated size of a specific technology.

Concerning passive interventions, the opaque envelope components are the most common category, assessed through the optimal thickness or material (at least for one of the envelope components). More in detail, the insulation-related variables (thickness or material) are the most popular variables, but massive materials as concrete and bricks were optimised as well. As for the active solutions, the assessment of the best HVAC was also quite common, although it was changed out of the optimisation process parametrically in some cases. Specifically, the heating system is the predominant topic since most of the studies were developed in cold climates, while space cooling or ventilation technologies were hardly included. However, the embodied impacts of the equipment were often neglected. Early design parameters (such as, optimal number of floors or orientation) were included in only few studies. This is probably due to the fact that the renovation of existing buildings is more common than the design of new ones. Based on the analysis of the collected and reviewed indicators, the most relevant ones for the purpose of this work were selected. Specifically, the indicators of greatest relevance appear to be the following: • as environmental indicator, the Global Warming Potential (GWP), LCA climate change impact category; • as energy indicator, the Cumulative Energy Demand (CED) or the Global Energy Requirement (GER), which are usually synonyms that express primary energy consumption; • as economic indicator, the Life Cycle Cost (LCC). Hence, at least such indicators per category should be used as a starting point for further development of this research, which would include the implementation and development of a software tool able to analyse and optimize the best stock of measures of passive energy retrofit of buildings envelopes at district/urban level.

IV. Conclusions and Further Developments

A. *Figures and Tables*

a) Positioning Figures and Tables: Place figures and tables at the top and bottom of columns. Avoid placing them in the middle of columns. Large figures and tables may span across both columns. Figure captions should be below the figures; table heads should appear above the tables. Insert figures and tables after they are cited in the text. Use the abbreviation “Fig. 1”, even at the beginning of a sentence.

TABLE II
TABLE TYPE STYLES

Table Head	**Table Column Head**		
	Table column subhead	***Subhead***	***Subhead***
copy	More table copy[a]		

[a]Sample of a Table footnote.

Fig. 1. Example of a figure caption.

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