Chapter

Life Cycle Assessment in Architecture as Decisional Tool in the Design Stage

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Abstract

The horizon of sustainability calls into question extremely complex phenomena, both in terms of social, economic, and cultural transformations, and in terms of the ecological implications of building activity in its wide territorial and temporal extension, and in terms of and the techniques to refer to. On this last aspect, in particular, today it is necessary to counteract the tendency toward an inconsiderate simplification of the aforementioned complex phenomena, because this simplistic approach is precisely the cause of the often trivialized and sometimes radically wrong interpretations. The chapter develops the theme of environmental sustainability precisely in this complex perspective, assuming the consideration of the entire life cycle of building products, whether they are materials, components, or buildings, as an inescapable reference horizon and the measurement of energy and resource consumption and of the impacts that are determined along the life cycle (Life Cycle Assessment—LCA) as the main tool for assessing the concrete sustainability of design choices with rigor and scientific basis.

Keywords: life cycle assessment, built environment, architecture, buildings, life cycle thinking, design process, regenerative development

1. Introduction

The shift of attention in the design choices derives from the interpretative evolution of the environmental problem and from the new intervention approach: from an *ex post* impact assessment, with the aim of limiting the damage and environmental risks of already existing works and processes, to an *ex ante*, through prevention and research of concepts and strategies aimed at analyzing a building and its parts upstream of the construction process, with the aim of designing an eco-efficient or low environmental impact system. This is a different approach from the practice that has characterized the building industry in recent decades, particularly attentive to a complex and at the same time delicate "environmental system," often exploited to the limit and erroneously considered unalterable: the changes undergone by the ecosystem are known, as a result of human actions, and the visible repercussions caused by these transformations, such as global warming, climate change, soil acidification, water eutrophication, and depletion of the ozone layer. Architecture does not remain extraneous to this framework of problems: it is a manifestation of human activities. Therefore, designing and building according to the criteria of sustainability essentially means dealing with the principles that make the balance between use of resources and environmental impact feasible.

Ecologically responsible design has been acquired in many scientific-disciplinary sectors of architecture and is currently the subject of studies and research by the scientific sector of architectural technology and the building production sector. In these areas, two distinct aspects of the problem are considered in particular: on the one hand, the definition of environmental design strategies for buildings and settlements, and on the other hand, the environmental impacts of building products and of buildings as a whole in order to guide the strategies design them. There is therefore a change of hierarchy between the paradigms of the project, which must be rethought and calibrated on new bases and scenarios of a vision over time of the life of the built artifact. The theme is not only the design of the building, but also of the life of a building, in which the temporal and spatial dimensions are fundamental and must be declined on the different scales of the built environment. The role of duration and maintenance scheduling in buildings is decisive on the life cycle from the early stages of the project; they are aspects closely linked to the technologies used, which in turn are consequences of the environmental context: which technology for which duration? Which technology for which context?

To support the ongoing renewal of the design process, Life Cycle Thinking (LCT) is a criterion through which it is possible to carry out actions or make decisions with awareness of the entire life cycle of the building, the process, and the product in question. It can be defined as a current of thought that compares a product or a process to a living organism, which is born, grows, dies [1]. Through this similarity, the life of a building and its process can be considered as a sequence of phases: that of design, that of extraction and processing of raw materials, that of packaging and distribution to final uses, that of construction and system of individual components, that of use and management and, last but not least, the end-of-life phase, which can be transformed into the first phase of new forms of life, through reuse and recycling. The life cycle of an organism or a process interacts with the surrounding environment, and the interaction with adjacent systems can be assimilated to a chain of flows with inputs (substances for processing, energy, human work, technology, money, etc.) and output (waste substances from processing, energy from network losses, waste materials, etc.), in close contact and exchange with the environmental, social, and economic spheres.

For the construction sector, this approach takes root and is accepted with the delay in the implementation of innovation typical of the sector. The need to evaluate the characteristics of building materials first emerges, then the LCT is implemented by the production chain, and slowly and, often, with actions that are not yet well defined methodologically, the approach to analyzing the life cycle of systems is recognized constructive and buildings as the only viable way to understand the wealth of problems that pervade the design of the eco-efficient building. We can state that many companies, in particular those aware of their harmful load on the environment, are moving (since the seventies), also under the obligation of international agreements on the reduction of environmental impacts, to pursue objectives of a more controlled production; others are moving toward the proposal of more or less "green" products and components, whose effective eco-efficiency must in any case be verified beyond the production phase, once inserted in a building context. But this is not enough, clear guidelines toward higher environmental goals and techniques for the prevention of environmental pollution are still faltering, many attitudes are only palliatives, with an unconscious still destructive and short-term perspective. Efforts in developing eco-efficiency assessment methods for buildings are appreciable, but still too fragmented and ineffective.

The analysis of the life cycle of an entire building presupposes the decomposition into underestimations of the components that constitute it. This operation may appear simple, but it must be recognized that on an operational level it becomes a very complex practice, due to the innumerable amount of information that the many actors involved in the project must provide simultaneously. A possible approach consists in assimilating building components as industrial products, since they are made in manufacturing industries and, only later, delivered to the construction site and assembled as pieces of an industrial product [2]. This affirmation presupposes a way of building with dry assembly technologies, therefore of combining industrial products, but it could also be traced back to traditional shipyards. A building, built with traditional or advanced technologies, is in any case a complex system, whose variables are not always predictable and controllable like an industrial product; it is a system that must also include esthetic, functional, and social aspects. The environmental assessment of a building must not be reduced to the sum of the environmental impacts of the individual components, since a building is not a car which, once built, can be delivered anywhere in the world and works; the building is built in a precise context and the technical and construction choices determine its duration (prolonged over time compared to other everyday objects we have), which also varies according to the user and the weather conditions with which it lives.

Among the many methods of analyzing environmental quality at different scales of the built environment, the Life Cycle Assessment (LCA) environmental assessment methodology is the reference for the detailed and objective quantification of the environmental impacts of a product and of the building along the entire cycle of life, through the quantification of incoming material and energy flows and outgoing polluting emissions in the phases of extraction of raw materials, transport, production, installation, use and management, decommissioning and end of life. The LCA methodology takes into consideration all types of impact in a complete framework of indicators and all phases of the life cycle, up to closing the cycle in the case of recycling at the end of its life, with the balance of the advantages of avoiding further consumption of materials and energy. The LCA assessment, structured in phases, in addition to the definition of the objectives of its application and of the object to be analyzed, provides for an accurate inventory of all the processes of the life cycle of the analyzed product, which translates into a flow diagram with the quantification of matter, water, incoming energy and outgoing emissions of substances into the air, water, and soil. The latter are translated, through a characterization, into environmental impacts (greenhouse effect, thinning of the ozone layer, etc.) and subsequently evaluated, with a score that indicates the severity of the damage, in order to contextualize the environmental damage to a specific reality territorial.

It is therefore necessary that, in addition to understanding the environmental problem, metabolizing the principles of design aimed at the life cycle, strategies and methods are structured aimed at optimizing the sustainable project first and then the eco-efficient architectural product.

2. New approaches for environmentally responsible architectural design

In order to easily understand how it can be designed to protect the environment, a building must be thought of as an ecosystem through which natural resources and semifinished products, components and systems coexist in a continuous cycle of flows (of matter and energy), within which a series of subsystems regulate the flow of one or more types of resources. It is important to understand that the presence of a building in the environment has a large impact both upstream of the construction, before the operational phase, and downstream, at the end of its life span. Focusing on a building and its potential impacts on the environment, it is necessary to consider the two streams of resource flows: those *upstream*, as inputs for the building ecosystem, and those *downstream*, as those that flow out as output from the ecosystem from it. The flow of resources begins upstream (input) with the entire construction and manufacturing industry sector, with the production of building materials, and continues throughout the life span of the building, in which the objective is to create an environment sustainable and healthy for human well-being and related activities. At the end of its useful life, the building must be considered, right from the design and the choices of construction technologies, as a "mine" of components (output flow), to be modified or transformed, for other new buildings or uses. The law of conservation of the mass of Antoine Lavoisier [3] also applies to the building ecosystem, according to which, over a long period, the resources that have entered will eventually come out, presumably transformed. This transformation from entrance to exit is caused by many mechanical processes or human interventions during the use phase of buildings.

It is therefore essential to know and quantify the flows in order to pursue an economy of resources, materials and energy, through the reduction, reuse, and recycling of input flows for a building. Paying attention to the economy of resources, the designer must know how to choose materials and components, knowing the energy content (nonrenewable or renewable) and the environmental impacts as well as evaluating the application context. It must contemplate the containment of nonrenewable resources in the construction and management of buildings, in which a continuous flow of resources, natural and man-made, is generated in and out of the building itself. The concept of Triple Zero, for example, promotes a "concentrate" of sustainability to be considered in the design of a building or a product: production and materials at 0 km, 0 CO_2 emissions, reduction to 0 of waste products, and closure of cycles.

The three strategies contemplated by the principle of resource economy are energy saving, water saving, and material conservation; each focuses on a particular resource needed for building construction and management (**Figures 1**–**3**).

In order to optimize the flows in the various phases of the building process in the design phase, Life Cycle Design (LCD) suggests a methodology for analyzing the construction process and its environmental impact, phase by phase. The same sequence is necessary to operate the inventory of the substances involved (input and output) in the production processes involved in each phase of the life cycle, the initial investigation level of the Life Cycle Assessment methodology, a fundamental part of the LCD thanks to which it is possible to extrapolate the data and information on which to base the environmental impact assessment methods, to be used in the architectural design phase.

The preconstruction phase includes the choice of the site, the design phase, the production processes of materials, and components for the building system up to the delivery on site, excluding the installation. According to the strategy of sustainable design, the environmental consequences generated by the architectural project, the orientation, and the impact on the landscape and that of the materials used are examined. The procurement of building materials also generates an impact on the environment: the harvesting of trees could generate deforestation; the extraction of mineral

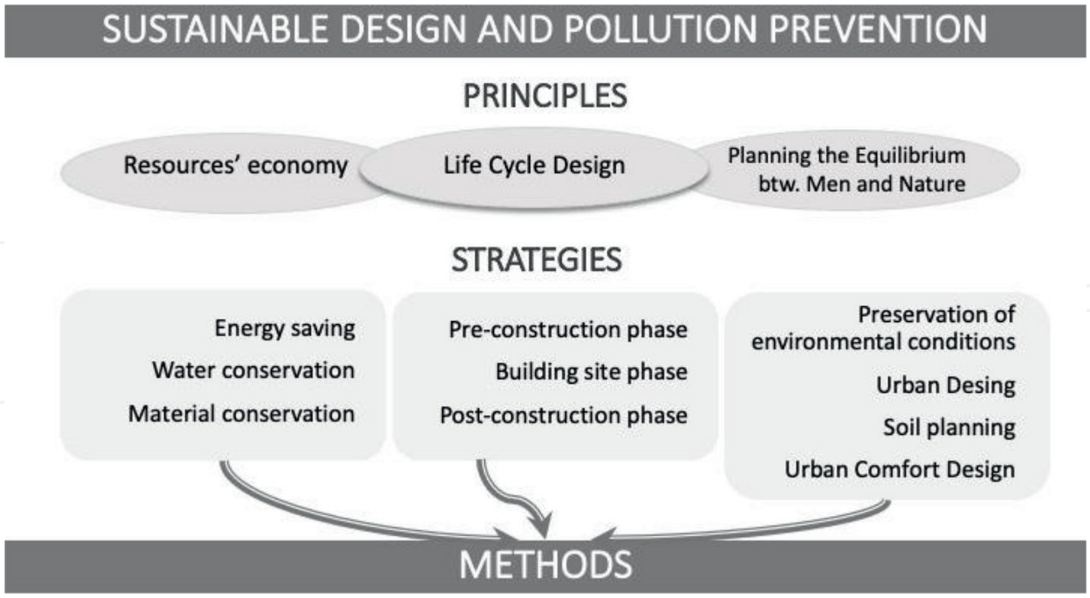

Figure 1.
Conceptual scheme for a life cycle design (LCD) and for the prevention of environmental pollution in architecture.

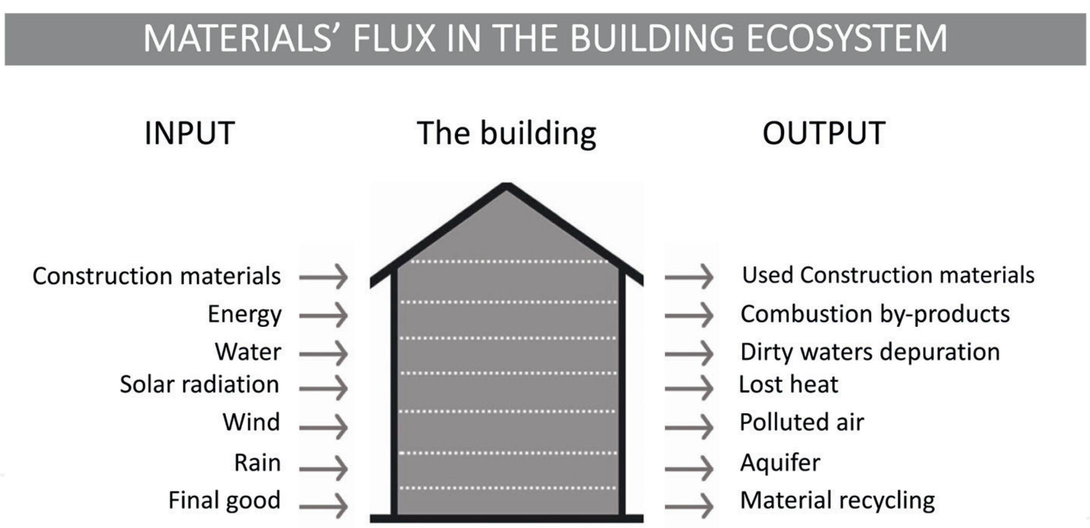

Figure 2.
The flows of substances in input and output in the "ecosystem" of the building.

resources (iron for steel, bauxite for aluminum, sand, gravel, and limestone for cement) cause, in addition to a great visual impact, the erosion of entire mountains or chasms and disturb stability soils, as well as generating acoustic and atmospheric pollution (e.g. fine dust); even the transport of these materials can be a highly polluting activity, depending on the weight and distance from the site. The manufacturing phase of construction products requires large quantities of energy, so much so that in many situations it is highly energy consuming and polluting compared to the energy required by buildings for their air conditioning during use: for example, the steel production chains and aluminum require a high level of energy, for smelting at high temperatures.

The construction phase and the operational phase refer to the phase of the life cycle, in which the building has been physically built and is in use and management.

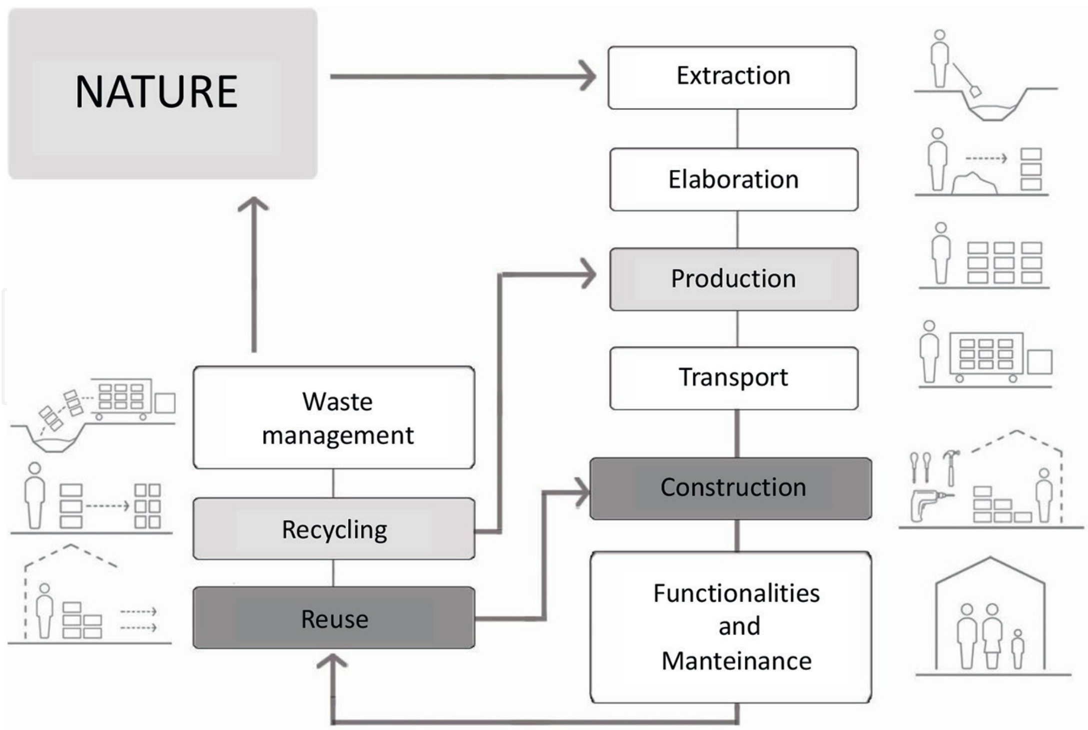

Figure 3.
A sustainable building life cycle.

In the eco-efficient design strategy, the operating methods of the construction and management processes must be investigated in the design phase in order to identify technical, plant, and operational solutions aimed at reducing the consumption of resources. In the investigation of this phase, the possible long-term effects of the built environment on the health of its users are also considered. Works that could significantly contribute to the reduction of the energy demand in this phase are the rehabilitation of the existing envelopes, a more adequate design of the envelopes in new buildings, a regulation of the summer air conditioning, the introduction of automated management systems and a use, where possible of renewable energies. The restoration of the envelopes allows the reduction of consumption for heating and is a binding condition for the installation of summer air conditioning. The post-consumer, or end-of-life, phase begins when a building's useful life has ended. In this phase, the building materials, demolished or preferably disassembled, are transformed into resources for other buildings or waste to be returned to nature. The eco-efficient design strategy focuses on reducing construction waste (which currently includes 60% of solid waste in landfills), reusing systems and components, and recycling building materials.

In addition to the requirements for a sustainable project and the characteristics of a sustainable material, the performance of a technological system, of a sustainable construction site, established starting from 1999 according to Agenda 21—CIB on Sustainable Construction, must be evaluated, which consist of:

- Choice and use of local materials, i.e. a sustainable material, component, or technological system in a specific physical location is not always sustainable in another; the reference to local cultures and ways of use as opposed to the approval of ways of building, as an international style, must be taken into consideration;

- Marking of the components, i.e. a widespread criterion in industrial production which allows tracing the manufacturer of the component, its technical characteristics and the interface and operating methods, to which will also be added the characteristics of environmental impact;

- Recyclable materials: recycling, together with reuse and reuse strategies, constitutes an obligatory step toward the sustainability of the production cycles of building materials;

- Minimization of transport, evaluating the impact of the construction activity on the transport system and on the quality of life of the entire context in which it operates;

- Construction systems that can be easily assembled/disassembled, which considers a modular or component-based design approach, contemplating the construction site as a place for assembly and disassembly of components of industrial origin rather than as a place for processing raw materials (water, sand, gravel, and cement) or of materials (bricks, blocks, interposed, etc.) that make up structures, closures, and partitions;

- Reusable construction systems, which imply a technologically complex challenge, which requires an update of the principles of assembly and prefabrication, but above all of correct selective disassembly of the components to be reused;

- Maintainability over time: the estimate of the useful life of the building product, unlike the industrial product, is measured in many decades or centuries, so it is important to have an in-depth knowledge of the aspects of durability and to counteract the degradation of materials, predict the life of the components, and manage the inevitable failures, pursuing the lengthening of the useful life [4] (**Figure 4**).

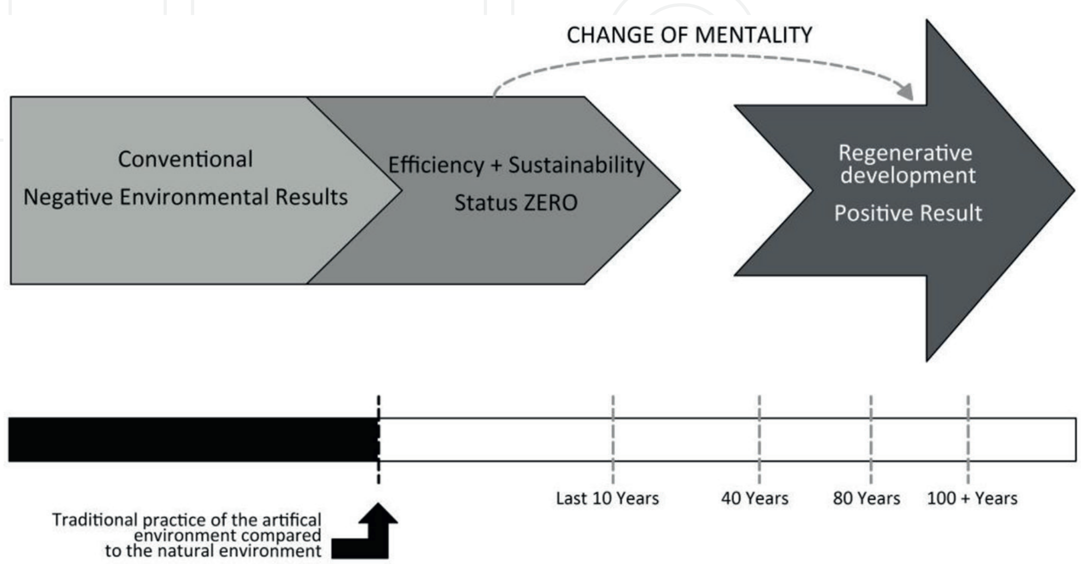

Figure 4.
Shifting the approach from traditional business to positive environmental outcomes.

3. The characterization of systems for the building design: the geographical and matter context

Considering the breadth of material possibilities and technical solutions offered by the market for the design and construction of the building, it is a difficult task to identify choices with characteristics suitable for the reference context, from a functional, economic, and above all environmental point of view. It is necessary for designers to have a conscious and coherent knowledge of the characteristics of building components, their expected performance and their environmental impact, and a critical observation of their real validity, for the purpose of making informed technological choices. The market seems to reward products that do not address the complexity of the problem, but only buffer it apparently, often responding to trends or "symptoms of the moment." This attitude only creates further confusion superficiality and lack of clarity. The choice of a component must not only be determined by its compliance with a function, but in the broader perspective of the use that will be made of it, a specific use linked to the environmental, temporal, and social context. In addition to the question "which form for which function," "which technology for which building," and "which material for which context" must immediately be correlated. The context, as well as in a static sense (the physical place), is linked to the use and users in a dynamic sense, with modifications and different approaches over time. A building arises from a specific, localized project pertinent to a technical and material culture, which is, even if not deriving from the whole, at least in part related to the society that produces it.

It is not enough to characterize the choice of materials and components for the building on the basis of product certifications, the CE quality marking of the manufacturing company or on technical sheets validated by scores on the level of eco-compatibility of the product. Extreme awareness of the environmental profile of the component contextualized with respect to the building in which it will be located is required; a choice of a component must be verified every time it is decided to insert it in a building in relation to the specific geographical, urban/suburban context. Each project, therefore each building, has its own story with respect to others or with respect to the context.

4. Environmental impacts in the life cycle of buildings

The construction of a building causes effects on the environment not only in the construction phase but also throughout the building process: the impacts generated by production, from the use phase, up to the impacts determined by the decommissioning of the building and the end of life of materials.

Among the main types of impact we mention air pollution, mainly due to the combustion processes used for the production of energy; chemical and biological pollution of water, mostly caused by urban, industrial, agricultural, and livestock waste; noise pollution, particularly important in urban centers and near airports and communication routes; the effects on the landscape and on the territorial structure due to the construction of large industrial and energy plants, the construction of infrastructures such as ports, airports, railways, and motorways; and the health and environmental effects, due to accidents that can occur in plants with a significant risk, such as nuclear power plants, hydroelectric plants, and chemical plants. These environmental effects have a common feature: they can be quantified. This makes it possible to use scientific methods to be able to assess their extent.

There are numerous types of impact, the global effects (greenhouse effect and acid rain) and the effects on the balance of ecosystems, which are only partially quantifiable and which therefore must be analyzed with empirical, conservative, semiquantitative or, depending on the case, simply dictated approaches by public acceptability requirements.

The pure scientific method is not sufficient to give a complete answer to the numerous environmental problems generated by the design of manufactured articles; however, attempts are underway to optimize the assessment of environmental impacts, the main objective of which is to investigate the compatibility between a given project and the environment. Some precautions must be taken at several levels in the building sector, to foresee (and not only ascertain) all the possible causes of environmental impact: at the design level by analyzing different alternatives of materials and technical elements, to obtain the suitable solution, with the best performance and minimum consumption; at the manufacturing industry level to control the quality of the production process and reduce waste and emissions into the environment during the processing chain; in the construction phase of a building, with an improvement in times and construction site processes; in the operational and management phase of the product, with an optimization of consumption (thermal, electrical) for air conditioning, lighting, and household appliances.

4.1 Impacts in the production phase

Building materials and components are the result of the transformation of raw materials, using energy. From the raw material to the semifinished products, to the finished product, to reach the waste product at the end of its function, each intermediate phase necessary for the processing of the material requires energy which accumulates in the product (as a quantity of incorporated energy) or is released in the environment in the form of heat. In going through the various subphases of the production processes of a building material, one learns how all the levels contribute to the impacts on the environment. In the procurement of raw materials, enormous quantities of materials from quarries and mines are eroded, disfiguring the landscape, as well as consuming nonrenewable materials. Furthermore, it is unthinkable to foresee the future use of only renewable sources, since these too, in addition to not being inexhaustible, have effects on the territory: to build in wood, extensive cultivation of trees is needed to procure raw materials. Once again, the importance of placing the choices in the context of the project and evaluating the exploitation of raw materials, whether exhaustible or inexhaustible, is evident.

The *impacts relating to transport* should not be underestimated. Unfortunately, today, with the globalization of markets and the evolution of construction technology, it is no longer possible to think about the local procurement of materials. Above all, given the heterogeneity of the products on the market, it is no longer easy to check the origin of the same, so the movements that a product carries out in the early stages of its life, up to its transfer to the construction site for which it is intended, cause significant impacts on the environment.

The *actual manufacturing phase* generates, due to the consumption of energy and emissions of waste materials and harmful substances, the greatest pollution in the supply chain, as well as in the entire life cycle of a building. The willingness of companies to reduce the resources and energy used (mostly lost during processes in the form of heat) is slowly entering, thanks also to actions coordinated by trade associations, as well as by national regulations; however, a certain difficulty remains in the management of waste from manufacturing scraps or industrial processes.

4.2 Impacts during the operational phase

There is a clear urgency to intervene on management consumption (heating, air conditioning, lighting, ventilation, consumption of household appliances, etc.) with greater attention to the efficiency of production processes and impacts on the environment.

Carbon dioxide emissions, responsible for climate change, are proportional to primary energy consumption, with different weights depending on the primary energy carrier (methane, LPG, petrol, diesel, fuel oil, and coal). It is necessary to analyze the consumption of primary energy, for the assessment of the environmental impacts of the national energy system. The forms of pollution linked to local energy consumption, due to the emission of toxic substances such as unburnt products such as carbon monoxide (CO), such as nitrogen oxides (NOx), and such as dust and specifically the articulated (PM10) are dangerous to human health, locally and in the short term, have practically no effect on the global climate.

However, pollutants are generated in concentrated points, such as industrial centers and urban areas. Around every large city, there is a cloud containing polluted gases and dust, noise and light disturbances, with local phenomena affecting health. The widespread distribution of pollution sources makes a systemic approach to their management difficult. We have to think that from these poles, pollution spreads over the entire planet.

Works that could contribute considerably are the rehabilitation of the existing envelopes, a more adequate design of the envelopes in new buildings; a regulation of the summer conditioning; the introduction of automated management systems and the use, where possible, of renewable energies. The restoration of the envelopes allows the reduction of consumption for heating and is a binding condition for the installation of summer air conditioning.

4.3 The post-consumption phase

At the end of the life span of single systems/components or of the whole building, we are faced with enormous volumes of waste, if we consider the high quantity of building materials used every year.

Due to the variety of substances contained in construction products, disposal operations are not always easy to plan: there are more and more substances that are highly harmful to the environment and human health, so disposal in landfills is not enough, but it is necessary to resort to the collection of special waste. And furthermore, while planning the demolition and disposal, right from the design stage, the time between the production stage and decommissioning is too long. Therefore, it is desirable to opt for preventive actions, i.e. designing buildings with reversible construction methods, which facilitate the disassembly and selective demolition of the parts, allowing, where possible, material recycling operations. It is necessary to introduce Design for Disassembling (DfD) among the design paradigms, trying to predict, in the design of a product, the scenario at the end of its useful life: this principle also affects the choice of construction technologies and materials and components, whose durability must be known. Being able to predict the treatment of a material or component at the end of its service life can imply the improvement of the manufacturing process and the orientation of construction choices toward precise technologies.

A material can be made with reduced impacts in the production chain, but, if landfill is destined, the initial advantage, in a life cycle balance, is compromised.

Predicting today an end of life in place only in a few years takes on a forecasting nature: now we know the means and processes of treatment in current practice, but the future scenario, through technological innovation and more in-depth knowledge of the temporality of new materials, can be completely different.

5. Application strategies in architecture

An essential certainty that is spreading in architecture and construction is the importance of disseminating knowledge of the long-term environmental impacts of materials, components, and technological solutions for buildings. It is now known how a design choice, in relation to materials and technological solutions and their production chain, can generate environmental impacts comparable to decades of energy consumption by a building, built without any energy-saving criteria. However, awareness-raising propaganda is still needed to make people understand how the application of the LCA methodology in architecture and the use of synthetic indicators of environmental impact must serve to optimize the life cycle of the "building system," in order to understand, from time to time and for each specific case, what are the phases on which to act to reduce environmental impacts. In the approach to the use of LCA in architecture, a complete optimization of all phases of the life cycle is not easily achievable; therefore, it is essential to define clear optimization objectives. If choices of materials and components are made by paying attention to the environmental impacts of the production and transport phase, to improve the pre-consumption phase, it is not obvious that this will lead to equally low impacts in the management and maintenance phase and at the end of life. The single strategy envisages pursuing a result with different characteristics, as well as contrasting ones, with respect to the result obtainable with a different strategy. The choice of strategy must be made in relation to the design context and the type of building, its form and function, its expected useful life. The translation of these concepts in terms of the LCA methodology consists in the definition of the objectives and boundaries of the system to be analyzed.

An important concept is that the role of the LCA environmental assessment must continue in parallel with the building design phases and not be just a final check, and it must be an operational and decision support tool with respect to the set objectives.

The types of LCA analysis that can be adopted in general are different, depending on the sectors involved or the phases considered, or the levels to be analyzed (material scale, component scale, technological subsystem scale, and building scale). The application of the LCA analysis can be done in detail in relation to the purpose and objectives of the study. The main levels of detail are:

a. **A product LCA** (defined as "simplified"), in which only the product in question is considered, not the secondary production processes, the impacts of the raw materials, fuels, and electricity used exclusively in the product line are calculated (are not considered process inputs and outputs deriving from upstream production, that of the raw material in the fundamental process); this analysis is rather simplified, and it uses generic data, both quantitative and qualitative, to make the evaluations as simple as possible. The purpose of the product LCA is to essentially provide some guidelines for the processes under investigation. Sometimes, however, the level of accuracy does not allow obtaining reliability on the results. The first objective to pursue is therefore to identify the information that can be omitted without compromising the result. The simplification of the method is based on three stages, which are iteratively linked:

- Investigation: identification of the most important parts of the life cycle or those with the largest data gaps;
- Simplification: from the results of the survey the work is set on the parts of the system considered most important;
- Evaluation of reliability: it is verified that the simplifications introduced do not significantly reduce the reliability of the overall result.

b. **An extended technology LCA** (defined as "selection") in which the products and processes correlated to the process under analysis are evaluated, used for raw materials and semifinished products during the fundamental process; however, at this level some minor processes are left out, it is commonly used when key actions for environmental improvement in the life cycle of products must be identified, in specific process parts. Its main feature is that of making use of calculation codes that help to manage the implementation of the LCA, referring to data already available from databases or estimated with approximation. From the obtainend results, and following a sensitivity analysis, the critical data on which it is necessary to intervene to improve their environmental quality are identified. It is a rapid system that allows to evaluate the important aspects of the life cycle, on which focusing attention.

c. **A complete LCA** (defined as "detailed"), which includes all the phases of the object in question and the related processes (it also implies processes of extraction and transport of fuels to the place of use, processes of production of equipment and buildings used in the various processes, direct impacts, indirect impacts, land use by the industrial warehouses where production takes place, etc.); this type of analysis involves examining many processes and, consequently, an even greater number of impacts on the environment. A detailed study foresees an improvement in data quality, instead of referring to standard data or secondary data; it is desirable to proceed with the collection and use of case-specific data provided by the companies themselves. It is the longest and most expensive method, but it is the one that provides the greatest reliability.

In the specificity of the LCA applied to the building and its parts, it would obviously be desirable to apply a complete or detailed level of study (c) of a building, quantifying: from the quantities of materials for the main structures and subsystems, going down in detail, up to understanding the quantities of materials for the electric cables, for the switches, for the sanitary fixtures, the pipes of the systems, and every single/small part of the product. The completeness of the application also implies considering all phases of the life cycle of the building, and for each component involved also its durability or duration and its possible end of life: all these aspects must be balanced in the LCI. For various reasons set out below, this level is not realistically usable in the building sector: information, of a design and construction nature, and the quantities relating to all parts of the building are not easily prosecutable.

In most of the cases and in the widespread practice, all the executive technical choices from the design phase are not always known, since they are often decided during the construction.

It is not the goal of the LCA application to architectural design and construction to exhaust the completeness of the data down to the smallest detail, rather than to use the potential of the methodology to compare similar solutions or contributions from different life cycle phases and understand where they are concentrated the major environmental impacts of the case considered.

The objective of the LCA applied to the building or its parts is not aimig to reach a single absolute final score, aimed at itself, but to allow for improvement judgments where an impact imbalance or, at least, awareness emerges (it often happens that in order to improve one aspect from the point of view of impacts, one is forced to accept the worsening of other aspects and, in this case, the comparison serves to understand which aspect causes less environmental damage).

In the construction sector, the utility of the comparative LCA between buildings, between subsystems, between different material, technological, and structural solutions for the same subsystem, between different components but with performances (mechanical, thermal, acoustic, fire resistance, etc.) clearly emerges at the same; from each comparison the limits and potential of each system considered emerge and, through an interpretative analysis of the LCA results, alternative solutions, or optimizations of some design aspects can be evaluated.

However, referring to the application studies of the sector available in the literature, the most widespread application sees the level of study with enlarged technology or selection (b).

For which they typically conduct:

- Comparative LCA of building materials, for one or more phases of the life cycle;
- Comparative LCA of technological components or systems, for one or more phases of the life cycle;
- Comparative LCA of building subsystems, for one or more phases of the life cycle;
- LCA of a building, in which the impacts of the different phases of the life cycle are compared: the pre-use phase with the phase of transporting materials from the company to the construction site, the construction phase, the management phase, with maintenance, end-of-life stage.

In the sector there are studies of application of the LCA methodology to the scale of the material and the component, which can be considered with a complete level of detail (c), with the aim of building the entire production process, from the cradle to the gate, therefore from the procurement of raw materials, to industrial processes up to packaging, considering all branches of the chain of flows with the environmental impacts of machinery (and their construction), the use of the land by industry and, upstream, by industries or sourcing quarries of raw materials, etc. These assessments serve to create the process entry relating to the environmental impact for a defined unit of building material (1 kg and 1 cubic meter of material), which constitute or are comparable to the entries contained in the reference databases for the LCA. Therefore, it can be affirmed that in the evaluations of an extended technological type, at the building scale, certainly many processes are included which, taken individually, can be considered as results of complete LCA. Regarding the LCA applications that compare phases of the life cycle of the building, scientific research works emerge that specifically analyze single phases, the pre-use phase of the building rather than the end-of-life phase of the building and components, with the objective of understanding, in one case, the production processes that have the greatest impact on the environmental impact of building construction [5–7] and, in the second case, the possible end-of-life scenarios and the advantages or limitations of each scenario (landfill, waste-to-energy, recycling, or reuse) [8–11].

The use of LCA as a methodology to support the design and optimization of production chains, in general, can be traced back to the early 1990s [12–16] and as a methodology with calculation codes that can be optimized for the building sector since 1996, at the building scale [17–25] and the scale of the material and component [26–31].

The wide use of comparative LCA in architectural design has been intensifying since 1996, with an increase in application cases, found in scientific literature, from year to year. There are now many application cases at the building scale: one trend sees the use of the methodology for assessing the environmental impact on a building, as a single-case study [32–35], which highlights the different impacts in the phases of the life cycle or the incidence of the various building systems with respect to the overall environmental and energy impact (e.g. the impact on the environmental effects of the structure or building materials respects the entire life cycle of the building [36]), as well as on several buildings compared to each other, whether they are residential buildings [37–42] or tertiary [43, 44], school [45] or public [46–48].

A widely codified use of the comparative LCA can be found at the subsystem scale, in which technologies with different materials or technological alternatives of products are compared, for example, two different structural systems are compared, steel versus wood or steel versus concrete, applied to the same building, in order to understand the most eco-efficient solution, with the same mechanical performance [49, 50]. Or, in the design phase, the comparison of the environmental impacts allows to have a complete scenario of the performances between alternative technical solutions (envelope, surface finish, facade or roofing systems, thermal insulation, roof slab, and flooring), as well as esthetic, thermal, acoustic, fire resistance, etc., also those of environmental impact [51–60]. The constant underlying the comparative applications of LCA is the functional unit U.F.: it is important to compare different products, components, systems on the basis of an equal unit of performance, in order to make the relative results comparable (e.g. U.F. equal to 1 sq.m. of envelope surface, if I compare facade systems, U.F. equal to 1 m2 of usable floor area, if we compare quantities which, in order to be compared, must be normalized with respect to a common denominator).

There are more recent application studies of the LCA to the life cycle of the building, which begin to calculate the effects of the life span of the same and the durability of its parts in the life cycle, considering the impact related to the maintenance and replacement of parties [61, 62]. Other studies focus on concepts of dynamic LCA (dynamic LCA), i.e. they evaluate the building's performance considering the temporal variations in the internal environment and the external conditions during the operational life of a building, incorporating the possibility of quickly updating the LCA results on the basis of changes to the project or on the variation of the functioning of the building (dynamic modeling scenarios) [63, 64].

Compared to the different architectural scales, there are different attitudes in the LCA application strategies regarding the consideration of all or only some of the synthetic environmental indicators: some applications adopt the strategy of simplification by carrying out an LCA evaluation which verifies only the energy consumption (indicator of Embodied Energy) and the equivalent carbon dioxide emissions (global warming potential indicator) [65–68], with the consequent facilitation in the immediate comparison of the results between the phases of the life cycle, as well as a dissemination of the final values more user-friendly, since energy savings and CO_2eq. emissions are more commonly known and widespread concepts with respect to the environmental problems of water and soil acidification, rather than SO_2eq. emissions for the depletion of the ozone layer.

Certainly, there are still advances to be pursued in the transfer of this methodology to the architecture sector, harmonizations in procedures, in order to make the results of similar studies, carried out in different research or application contexts, much more comparable. It is necessary to make designers more aware of the assessment of the environmental problems generated by the design and construction act and to make them understand how, once again, environmental issues cannot be simplified to avoid complexity or manipulated to obtain brands or labels, but they must be taken seriously and fully understood. In any case, it is understandable how it is not easy from the LCA application theory to be able to match completeness and correctness in the eco-efficiency of the solutions adopted in a building and for all phases of the life cycle. Each situation is singular and unique, linked to a physical, territorial, and social context, and it is possible to calibrate the architectural and constructive choice on this, not forgetting the verification of the environmental impacts, perhaps not for all phases of the life cycle, but adopting design and construction strategies that we have in mind the building and the possible scenarios in the different phases.

6. Conclusions

The world of academic research has the task of focusing on increasingly precise answers so that environmental protection is not just a slogan. As Gianfranco Bologna states about the sustainable development formula: "Keeping the conceptual contours of this formula vague, albeit extremely difficult, and not comparing the real problems that derive from the implementation of sustainability in our development processes means proceeding with an unjustified action from a scientific point of view and incorrect from a social, economic, and political point of view" [69]. But university research also has the task of strenuously defending a vision of the relationship between design and environmental sustainability that knows how to understand all the problematic wealth that characterizes it, opposing the reductive simplifications that partisan interests often impose.

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