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LCA and LCC as decision-making tools for a sustainable circular building process

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Abstract. Resilience can be interpreted as the capacity to overcome sudden negative events, including those caused by environmental impacts, by minimizing their effects. Through the application of circular economy, built environment can be more resilient, decoupling the human well-being by resources consumption and waste generation. Within a circular approach, buildings are considered “material banks” and materials reuse/recycling is promoted. In this context, it is important to verify the life cycle sustainability of the new circular practices, linking the economic and environmental sustainability with circularity. In fact, resource efficiency and waste management in term of reduction of material flows, don’t represent certainly sustainable solutions. In this paper, LCA and LCC methodologies, which are scientific methodologies used to quantitatively assess the environmental and economic impacts, are investigated. Through a literature review, the paper analyses the state of the art regarding the application of Life Cycle tools for evaluating circular strategies, at the building level and at material level; then the use of Life Cycle tools for decision-making in the circular design process is investigated. Through the scientific literature review, the methodological assumption to assess the sustainability in decision-making is shown. Finally, the limitation of the methodology is highlighted and the improvement necessary to promote the use of Life Cycle tools in decision-making is discussed.

1. Introduction

The “resilience” is the system’s capability to adapt itself to a traumatic and unpredictable event, changing different behavioral properties to react to an external shock [1]. Hence, it is possible to state that the current economic system, called linear system, focused on the consumption of goods, heavily dependent on non-renewable energy sources and virgin raw materials, is not resilient in a planet with a limited stock of resources. Indeed, today natural resources are increasingly scarce and the big amount of waste are contaminating oceans and lands.

A circular economic system, based on the resource decoupling concept [2], is more resilient, because it can decouple the economic growth and human wellbeing to resource consumption.

Circular economy applied in the built environment, leads to change the concept of building. The building becomes a stock of resources to maintain as long as possible and to reuse or recycling at the end of its life. The renovation of existing buildings, necessary to achieve European’s objectives for 2020 and 2050, whereas decarbonisation and resource conservation, becomes a strong field of circular economy application. Circular practices have to be activated throughout the building renovation process, in order to increase the value of the materials already in use, considering buildings as material



banks, and to reduce resource consumption and the amount of waste generated by construction and demolition processes, also prolonging the service life of materials and buildings.

According to Marchese et al. [3], there are a lot of studies that consider the sustainability as a contributing factor to resilience. These studies claim that *“increasing the sustainability of a system makes that system more resilient, but increasing the resilience of a system does not necessarily make that system more sustainable”* [3]. Moreover, other studies [4][5] argue that circularity and in particular circular strategies, such recycling process, are not always sustainable [45][46]. Hence, scientific sustainability assessment of circular practices is fundamental.

In order to assess the sustainability of buildings and related circular strategies, quantifying the environmental and economic impacts, the internationally recognized and standardized scientific methodologies are Life Cycle Assessment (ISO 21930:2017; EN 15978:2011) and Life Cycle Costing (ISO 15686-5:2017; EN 16627:2015). LCA is the environmental assessment methodology that considers the entire phases of building life, starting from the production of materials, transport, construction phase, use phase until the end of life phase [6]. LCC is the economic assessment methodology for selecting the most cost-effective alternative over a particular time frame, taking into consideration its initial cost (construction), operational cost and maintenance cost [34].

Life Cycle tools have a great potentiality to support decision-making, evaluating different (circular) scenarios in advance, on the base of defined requirements and properties related to the case study [37][7]. Hence, LCA and LCC, for example, can be a support for deciding which renovation strategy is better, among to demolish and build a new building or to renovate the existing one, or to reuse some building's elements; for deciding the design criteria of new buildings, among design for disassembly/replacement or design for adaptability or design for durability. Moreover, the Life Cycle tools can be a support during the decision-making of the end-of-life of construction and demolition waste, for deciding if it is more effectiveness reusing or remanufacturing or recycling the materials, considering transport and transformation process impacts.

The paper shows the state of the art of the use of life cycle tools in scientific paper about the circular strategies, in order to show if the level of interest within this theme is increasing or decreasing, and to identify the obstacles and, consequently, the future improvements to diffuse the sustainability assessment within circular strategies.

2. Life Cycle tools to assess circular strategies: trends of the last years

The literature review analyses how often the Life Cycle tools are applied in scientific papers in relation to circular strategies at material level (management of construction and demolition waste) and at building level (design for disassembly, design for deconstruction and design for reuse). Secondly the research analyses the use of Life Cycle tools as decision-making support, analysing the different applications, the limits and assumptions. The analysis considers the scientific papers published until February 2019 (in order also to include the most recent papers). The citation report counts the number of time the scientific papers (published until February 2019) are cited by other scientific papers until 2018 (because the year 2019 is not representative).

2.1. Life Cycle tools applied to circular strategies at materials level

At first, the scientific papers related to the use of Life Cycle tools at materials level are analysed. At material level, they are typically applied to define the more sustainable way to manage construction and demolition waste. A Web of Science research (for titles which contain the words “Life Cycle” and “demolition waste” or “Life Cycle” and “CDW” or “LCA” and “LCC” and “CDW”) shows that there are 11 scientific paper [8][9][10][11][12][13][14][15][16][17][18], of which half written in 2018.

The analysis (Figure 1) shows that there is a great increase of citations in 2018 (the total of 11 papers are cited 70 times), in comparison to the quantity of citation in 2015 (the total 11 papers are cited only 5 times). This means that the theme of Life Cycle evaluation of CDW in last three years has become more discussed, probably for the circular economy policies promoted by European Commission [19][20] which stress the necessity to solve the problem of waste in the construction sector.

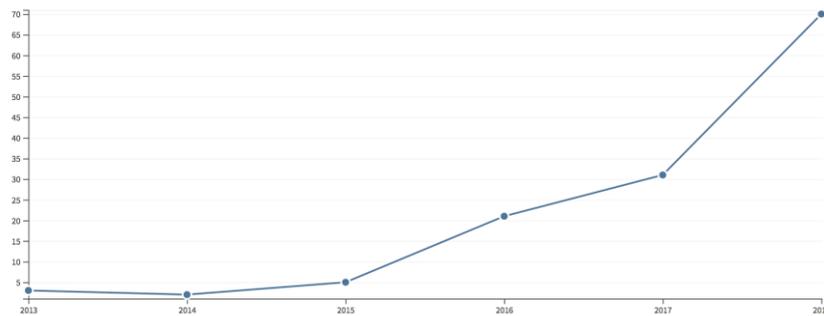


Figure 1. Citation report of 11 papers.

These researches consider the sustainability of strategies aimed at solving the problem of waste. In most cases, they consider the sustainability of recycling rather than landfill. Hence, these researches have a ‘downstream approach’ in the circular economy, focusing on waste management when waste has been already generated.

2.2. Life Cycle tools applied to circular strategies at building level

In order to avoid the generation of waste, circular economy promotes also different design approaches, such as design for disassembly, design for reuse or design for deconstruction. These design strategies have an ‘upstream approach’, considering possible building adaptability or disassembly and building’s components reuse, in order to extend the lifespan of building and to avoid the generation of waste in its end-of-life.

Nevertheless, a Web of Science research (for titles which contain the words “life cycle (or LCA)” and “design for disassembly” or “life cycle” and “design for reuse” or “life cycle” and “design for deconstruction”) shows that there are few research papers [21][22][23][24][25] that consider the Life Cycle tools for evaluating different design approaches, specifically only 5 papers, written in different years.

The analysis shows that, also, in this case, the citations are increasing in the last years, but the largest number of citations was in 2016 (Figure 2). However, the citations are less than the citations of papers regarding CDW management. It means that the ‘upstream approach’ strategies are less common in scientific researches.

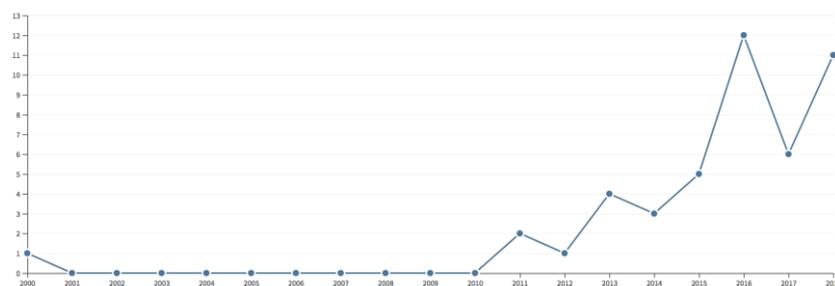


Figure 2. Citation report of 5 papers

2.3. Life Cycle tools as decision-making tool

Finally, the analysis investigates the use of Life Cycle tools as a support to the decision-making process for the transformation of the built environment, hence considering the theme with a wider approach.

A Web of Science research (for titles which contain the words “Life Cycle” and “decision-making” and “buil*”) shows that there are 16 scientific papers [26][27][28][29][30][31][32][33][34][35][36][37][38][39][40][41]. The analysis shows that the papers

have been published mainly in 2012 and in 2015. Through a citation analysis (Figure 3) it is possible to note, that the theme of Life Cycle tools in decision-making became more analysed in the last two years. This represents that there is a recent interest in this topic.

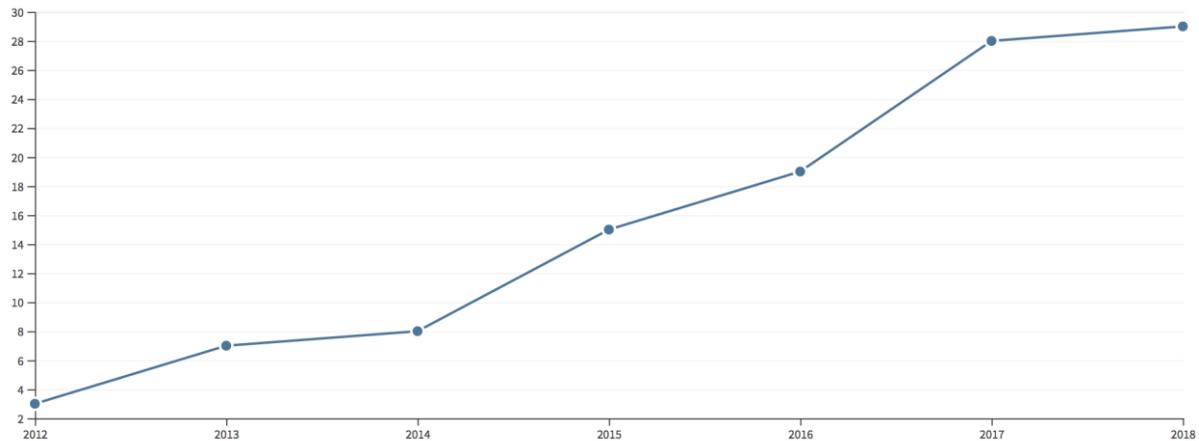


Figure 3. Citation report of 16 papers

Regarding the 16 studies, 9 of these apply the LCA as decision-making, 5 of these apply the LCC and 2 of these apply both the evaluations.

However, for the circular economy point of view, it is important to apply Life Cycle tools during the decision-making to optimize the use of materials, not only to reduce energy consumption in the use phase of building. Among the 16 selected papers, only 7 studies consider the application of Life Cycle tools to materials decision-making; 5 studies, in fact, take into account the design decision-making only to reduce the operational energy of the building, or to achieve NZEB. The rest of the papers discuss LCA and LCC tools and database for design decision-making.

In order to give an explanation of the 7 papers which consider the application of Life Cycle tools to building materials decision-making, three different studies are discussed. These studies are representative of the different approaches: the first regards the LCA application to decide the materials of new construction; the second regard the use of LCA to decide the material solution for retrofitting an existing building; the third, instead, regards the application of LCC to optimize the maintenance cost in the building life cycle.

De Cozar et al. [37] use LCA as decision-making for a very specific issue: the decision of the better building system for a temporary installation for an event held in the Roman Theatre heritage site in Spain. The paper set in advance the requirement of the installation: easy disassembly lightweight and industrialised off-site construction, every element needs to be reversible and reusable. Hence, the research compares a building system constructed with aluminum elements, an industrialised timber system (painted and unpainted), and industrialised profiles in tubular steel system. The lifespan considered for the case studies was 50 years, with the building system to be assembled and disassembled every two years. The LCA analysis includes the production phase (raw materials extraction, transport of materials to the factory and manufacture A1-A2-A3), construction, deconstruction phase (transport to the construction site, construction process, deconstruction process and transport of waste to landfill or recycling plant A4-A5-C1-C2), and end-of-life phase (including waste processing for reuse, recycling and final disposal C3-C4). The study considers only two environmental indicators: global warming potential and cumulative energy demand.

Vandenbroucke et al. [30] use the LCA in the decision-making about a building requalification process (the considered building take also part of the Pilot Projects of BAMB research). This paper considers various design strategies and considers not only the maintenance, but also, the future refurbishment of the building, showing that this impact cannot be neglected. The study considers the “initial environmental impacts”, as the impact of stripping or demolishing the elements, the impact of

producing and transporting the new building materials, and the impact of (re)constructing the elements; then, the study considers the “Life cycle environmental impacts” adding to the “initial environmental impacts”, the impacts for maintenance, reparation, replacements, energy consumption (during the use phase), demolition, waste transport and waste treatment (for end of life). The study, hence, shows the significant environmental impacts saving through refurbishing the building, rather than to demolish and built a new one (the impacts of refurbishment, in this case, are less than a quarter of a new building with similar energy efficiency). The reduction of impact is mainly due to the reduction of the need for new construction materials. Hence, LCA is used to help the designer to decide the more sustainable transformation among various scenarios, considering conventional and demountable solutions.

Liu et al. [36] study is an example of the application of LCC. The papers consider the use of the influence of maintenance, repair and reinforcement, and the deterioration speed of existing structure in whole life cycle cost, applying LCC to decide the best economy and reasonable maintenance scheme of an existing structure.

The analysis shows that Life Cycle tools could be used for different applications and possible use, not only for evaluating the impacts of waste management, or considering only the operational energy of the use phase. However, every study highlights the critical methodological issues and the limit in data availability. The studies have done necessary assumptions in data and information, many times data are assumed by previous studies in the literature.

3. Limitations and assumptions

The literature review on scientific papers regarding the application of Life Cycle tools as decision-making shows that there is a lack of data for the phases of construction, maintenance, retrofit and recycling. Every study that analyses these phases makes a lot of assumptions or references to different previous scientific studies.

Horvath et al. [33] declare in the paper the data assumed, which are, for the construction phase: 15 MJ/m² of diesel for transports; 2 kWh/m² of electricity based on the Ecoinvent data, and +5% of building mass for construction waste. For the operation phase, the energy demand of the building is calculated according to the Energy Performance of Buildings Directive. For the maintenance Horvath et al. assume an entire substitution of materials based on the lifespan of each material (the lifespan is based on literature), 1 kWh/m² of electricity. For modeling the retrofit, Horvath et al. decrease the energy consumption in use phase for the rest of building lifespan; the production, transport and installation of new materials and the transport and disposal of old materials are also considered. In detail, the end of life contains separation, transport and processing of end-of-life materials. The demolition process is assumed as 30 MJ/m² of diesel based on the Ecoinvent data.

In the study of Vandenbroucke et al. [30], the assumption of reference life of the building is interesting. They consider a lifespan of the concrete structure of 120 years and the age of the existing building (41 years old). So they consider in the analysis the possible maximum remained lifespan of 79 years. Instead, the frequency of maintenance is based on literature. The impact of maintenance and repair of finishing layers is considered by an average percentage of respectively 1% and 5% materials losses.

However, every study chooses different references to model these stages, because there is a lack of data in the database. This leads to a difficult comparison among different studies.

Another important issue, that creates criticality in Life Cycle evaluations for reusing/recycling materials, regards the methodological approach to share the environmental impact of the material between two (or more) life-cycle. It represents an important methodological challenge, because different allocations lead to different results [42][43].

For example, in LCA studies [21] the lifespan of material is prolonged, assuming that the materials have two (or more) life-cycle. In order to assess the effectiveness of reuse or of design for disassembly, the environmental impact of production is subdivided in the total number of assume life-cycle, showing the benefit of reuse.

Otherwise, other studies [24] assess the benefit of design for deconstruction and reuse (within module D) through the calculation of avoided impact thanks to the reuse of materials which avoid new material's production process.

4. Discussion

In the last years, a lot of researches studied the way to make more efficient the use phase of building life cycle, reducing energy consumption through insulation and technologically advanced systems. However, these practices sometimes do not decrease the environmental impacts, but only shift the impacts from the use phase to the construction phase.

Within circular economy, the current tendency is to improve efficiency also of materials consumption during the building life-cycle, promoting reuse and recycling of building components and materials. Obviously, the use of less quantity of material, bring to decrease the impacts, only if the production phase is assessed. However, it is important to assess also the other possible impacts caused by "reused/recycled materials logistics", such as the transport of materials, the energy used for disassembly, and the energy use for reconditioning or recycling processes.

The application of Life Cycle tools (related to the whole building life cycle) during the design process can forecast and assess the environmental impacts of different solutions for building energy and material efficiency. Nevertheless, as the literature review showed, there are still some problems in the application of LCA and LCC for the whole building life cycle, mainly related to the lack of data and information for construction phase (mainly for innovative practices like dry assembly and disassembly) and for the end-of-life phase (mainly because the lifespan of building is long and need assumptions).

Despite the methodological limit and assumptions, in the last years, Life Cycle tools are becoming more available to the AEC practitioners [31], maybe also thanks to the recent development of user-friendly tools, that could be compatible with the digital technologies used in the design process, like Building Information Model (BIM) and other thermal modeling software [44]. According to Means et al. [31], there are different types of LCA tools available to the AEC practitioner, summarized in four general categories:

- materials databases, usually accessible with a fee and not transparent, that provide embedded energy and other environmental impacts from cradle to the construction site;
- econometric calculation: that provides environmental impacts on the base of broad values, such as the financial cost and purpose of the building using a generalized model;
- specific material LCAs: values that come from EPD or from LCA tools developed by some industries for materials and products produced by their sector;
- comprehensive LCAs: tools to model the building's life cycle.

However, in every case, some life cycle phases are excluded, or if they are not excluded the origin of data is not declared.

In this context, it is necessary to improve the available data related to construction /deconstruction and end of life stages, in order to avoid assumptions and to develop a standardized methodology, from the definition of the reference service life to the allocation approach choice.

5. Conclusion

The paper gives a state-of-the-art of the application of Life Cycle tools for evaluating circular strategies at material level and building level, and for decision-making. The paper shows that these topics are becoming more discussed in the last years, after circular economy policies. However, Life Cycle tools are more applied to studies regarding the construction and demolition waste management ('downstream approach') rather than design approaches ('upstream approach').

Moreover, it possible to note that also the studies regarding Life Cycle Assessment and Life Cycle Cost as decision-making tools are increasing in the last years. The Life Cycle tool more applied in the scientific publications is LCA. The paper shows examples of different applications of Life Cycle tools in decision-making, such as to decide the sustainable material solution, the sustainable type of retrofitting and the circular strategy. However, the paper shows also the limits and assumptions

necessary in the modeling. The main critical issue is the lack of data for construction phases, maintenance, retrofit and reuse/recycling. Moreover, different studies show different methodological approach to allocate the impact between two life-cycle. Since the Life Cycle tools for the decision-making design process is slowly spreading in AEC thanks to the diffusion of user-friendly tools compatible with BIM, it is important a data improvement, in particular for the most critical building phase, and a methodology harmonization, in particular regards the allocation approach.

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