Combining circular and LCA indicators for the early design of urban projects

Saadé, M.[1], Erradhouani, B.[2], Pawlak, S.[3], Appendino, F.[4], Peuportier, B.[5], Roux, C.[6]

1 EMGCU Laboratory, MAST, Université Gustave Eiffel, myriam.saade@univ-eiffel.fr

2 EIVP, Lab'Urba, bilal.erradhouani@eivp-paris.fr

3 MINES ParisTech Center for Energy efficiency of Systems, stephane.pawlak@mines-paristech.fr

4 ESPI Paris, Lab'URBA and ESPI2R Laboratories, f.appendino@groupe-espi.fr

5 MINES ParisTech Center for Energy efficiency of Systems, bruno.peuportier@mines-paristech.fr

6 Navier Laboratory, Ecole des Ponts ParisTech, University Gustave Eiffel, CNRS, charlotte.roux@enpc.fr

Abstract

Purpose: The built environment is a key sector for the transition towards a so-called circular economy, contributing to solve the global environmental challenges humanity is facing. As buildings interact with other sectors like transport and energy, a systemic approach is needed to assess the environmental relevance of circular economy practices. The purpose of this study is to develop and test an approach for the evaluation of overall environmental performance of urban projects.

Methods: Combining Material Flow Analysis (MFA), Material Circularity Indicator (MCI) and Life Cycle Assessment (LCA) indicators allows relating means (material recovery) and performance (protection of human health, biodiversity and resources).

Results and discussion: The study shows the ability of LCA to evaluate circular economy practices at the scale of an urban project. It also highlights its limitation and the research needs to improve eco-design LCA tools for instance on resource depletion evaluation and biogenic carbon. Results show that the MCI, one of the main circular indicators in use today, and MFA provide interesting information complementary to LCA at the project scale but are unable to evaluate the environmental performance of circular practices.

Conclusions: Circularity indicators are complementary to LCA indicators and should not replace them in the eco-design process. Rather than setting circularity targets, it is advisable to set environmental targets in a program so that designers use circularity combined with other means to reach these targets in a systemic way. The choice and implementation of environmentally-sound circular actions and strategies are at stake.

Keywords: Life Cycle Assessment, Circularity indicator, Building, Urban Project, Circular Practices, Eco-Design

1. Introduction

Human societies are consuming too much resources, too quickly. This obvious statement introduces the European Circular Economy Action Plan (CEAP), released in 2020 (European Commission 2020). Constituting one element of the new growth strategy announced with the European Green Deal (European Commission 2019), it reaffirms the objective of climate neutrality for Europe in 2050. It also pleads for an inclusive, sustainable and competitive economy decoupled from primary resources extraction and use.

Among the sectors considered in the CEAP, the built environment is of particular interest. Constructing buildings and infrastructures requires large amounts of resources, especially mineral sand and aggregates, representing 50% of all extracted materials in Europe (European Commission 2020). In 2018, 1135 million tons of sand and gravels were taken from the environment to supply the EU economy (UEPG 2018). Moreover, of the 40 to 50 billion tons extracted worldwide in 2012, half was used for construction purposes (UNEP 2019). As linear processes, construction, renovation and demolition consequently generate between 25% (Cottafava and Ritzen 2021) and 35% of total European waste (European Commission 2020), estimated at 374 million tons in 2016 (Eurostat 2019). This value constitutes a lower bound since it excludes excavated soils (Eurostat 2019).

The built environment is also a major contributor to climate change, responsible for 19% of the global greenhouse gases (GHG) emissions (IPCC 2018). 5 to 12% of these emissions are related to the extraction of raw materials, the manufacturing of construction products, the construction, renovation and demolitions processes (Bertin 2020). With the improvement of the energy performance of buildings during their use stage, this share is likely to increase (Blengini and Di Carlo 2010) provided that no rebound effect occurs. Improving the energy efficiency for heating, cooling or ventilation may induce an increase in the energy demand, due to decreasing prices of energy services (Greening et al 2000; Haas et Biermayr 2000; Hertwich 2008; Sorrell et al 2009). In the case of Austrian building retrofit measures for example, Haas & Biermayr (2000) showed that changes in the consumer behavior reduced by 20 to 30% the expected energy savings. Alongside energy performance efforts, the adoption of circular practices in the building sector could reduce by up to 61% the embodied GHG emissions (EEA 2020).

Circular economy (CE) is viewed as an alternative to the current linear economic system. Broadly, it relies on the idea of a decoupling of human societies' development and resources exploitation. Despite its ubiquity, CE is not a consensual concept (Kirchherr et al. 2017; Homrich et al. 2018). Definitions of CE range from restrained ones, such as the maximization of both resource use efficiency and economic value creation, to a paradigm shift founded on a redefinition of the relationship between human populations and their surrounding environments (Arnsperger and Bourg 2016), implying a move from consumerism to material sobriety. Friant et al (2020) identified four types of circularity discourses, with diverging framings of what should be the goal of a circular economy, and by extension of a circular society, leading to different implications in terms of means to reach this goal. From the technocentric understanding of circular economy - believing in the capacity of technologies to decouple economic growth and environmental burdens, to the transformational circular society - considering that a total reconfiguration of current socio-political behaviors is necessary to avoid ecological collapse, each discourse carries a particular worldview and appreciation of the current mainstream economic and political system, namely capitalism.

Given the environmental burdens associated with built assets, there is nowadays a large interest for the application of CE principles to the construction sector (Pomponi et al. 2017; Munaro et al. 2020). According to its supporters, implementation of CE in the built environment and particularly in cities calls to rethink the way buildings and urban projects are designed, and how material flows circulate during the project life cycle (EEA 2020). It implies to shift from construction and demolition waste management to the exploitation of secondary resources, considering cities and buildings as mines from which it is possible to extract materials (Brunner 2011; Cheshire 2016; Heisel and Rau-Oberhuber 2020).

In the European and French contexts, promoted circular practices in the building sector are emerging (Petit-Boix and Leipold 2018; Joensuu et al. 2020, Benachio et al 2020). CE initiatives and actions are multiplying, and several cities have adopted strategic plans and policies to make their economy more circular. A number of circular urban projects are also experimenting innovative CE practices. A wide variety of practices are tested, even though attention is mostly placed on construction and demolition waste management, valorization, reuse of buildings, elements and materials and eco-construction (Appendino et al. 2019).

However, recirculating materials and objects may have more environmental impacts than benefits. Several examples show that increasing the circularity of a given system can worsen its environmental footprint, or generate environmental trade-offs (Haupt and Zschokke 2017; Schaubroeck 2020). Consequently, Blum et al. (2020) argue that circularity is a means to reach sustainability and not an end in itself. Circular initiatives shoud then be selected knowingly, to keep CE within the planetary boundaries (Desing et al 2020).

In that sense, there is a need to ensure that circular strategies, actions and practices implemented in urban areas, particularly through urban projects, do have a positive impact on the environment. It is also necessary to inform about circular actions that present the higher environmental benefits. Because of their diversity and lack of maturity, such evidence is missing, as well as appropriate methods to assess circular actions (Appendino et al. 2019).

Consequently, tools informing about the environmental trade-offs associated with such strategies, actions and practices are to be developed (Lacy and Rutqvist 2016; Haupt and Zschokke 2017). The Life cycle assessment (LCA) community is currently working to improve ways to assess circular practices. In a recent position paper (Peña et al. 2021), the Life Cycle Initiative promotes the application of LCA to evaluate CE strategies. It advocates for the advancement of methodologies and metrics appropriate to CE, with a focus on raw materials and resources.

LCA is used to evaluate the environmental performance of buildings since the 1990’s, in an eco-design perspective (Adalberth 1997; Mak et al. 1997; Peuportier et al. 1997). It was later on applied at neighborhood scale (Popovici and Peuportier 2004; Lotteau et al. 2015). Long considered too data intensive to be used on complex systems such as buildings and urban projects, it is now performed at early stages of building design (Chouquet 2007; Basbagill et al. 2013; Peuportier et al. 2020). Extensive literature now exists on building LCA, addressing a wide scope of building types and issues, ranging from component to building and up to district eco-design, and from refurbishment strategy, target setting, eco-management to certification (Ortiz et al. 2009; Zabalza Bribián et al. 2009; Anand and Amor 2017).

More recently, LCA has been applied to evaluate circular practices in the construction sector or in cities (Hossain and Ng 2018; Benachio et al. 2020), at the scale of the material (Krause and Hafner 2019), constructive element (Eberhardt et al. 2019a; Buyle et al. 2019), or built asset (Rasmussen et al. 2019; Eberhardt et al. 2019b). Appling LCA to an office building, Eberhardt et al. (2019b) for example highlighted the influence of material composition, component reuse cycles, as well as material and building service lifetime on the environmental performances of designed for disassembly (DfD) concrete structures. They stressed the importance of further developing the LCA methodology to consistently assess CE and fully understand the conditions for which the environmental performance of circular practices in the building sector are guaranteed.

The literature on CE metrics however shows that specific circular indicators are more widely used than LCA (Haupt and Zschokke 2017; Giorgi et al. 2017), , at the micro scale of materials as well as at the meso scale of buildings. LCA is often considered limited (Franklin-Johnson et al. 2016), complex and data intensive (Elia et al. 2017), despite its relevance (Corbett 2015; Scheepens et al. 2016; Smol et al. 2017; Fregonara et al. 2017). Other limitations of LCA for the evaluation of CE practices have been discussed, regarding allocation issues (Reap et al. 2008; Schrijvers et al. 2016), end-of-life modelling (Sandin et al. 2014), existing indicators for resource depletion (Steen 2005; Yellishetty et al. 2011; Klinglmair et al. 2013; Rørbech et al. 2014) and dissipation (Beylot et al. 2021).

Circular metrics have been recently and abundantly developed to measure the efforts made to shift from a linear to a circular economy. At urban scale, pioneering works relate to the development of indicator systems for Chinese cities (Su et al. 2013; Guo et al. 2017). Systematic reviews further proposed taxonomies of CE indicators found in the literature, particularly based on their integration of a life cycle perspective. Elia et al. (2017) analyzed 16 environmental assessment methodologies (among them LCA) on their ability to evaluate the circularity of a system at micro scale, as defined by (EEA 2016). Saidani et al. (2017) identified 55 indicators or indicator systems measuring circularity; 18 circularity indicators rely on a life cycle perspective, but not necessarily on LCA as defined by the ISO 14'040 and 14'044 standards. The indicators were classified according to 8 criteria, such as CE implementation scale, the type of performance (focus on resource efficiency or other impacts), etc. Parchomenko et al. (2019) classified 63 indicators, indicator systems and assessment tools measuring circularity performance according to particular CE definitions and fields of application. They identified 24 elements constitutive of circularity metrics, and proposed a simplified scheme to represent them. Corona et al. (2019) proposed another classification based on the review of 19 metrics and evaluation methods (Input/Output analysis, MFA and LCA), distinguishing between the measurement of the circularity degree and the assessment of the effects of circularity. Material Flow Analysis (MFA) for instance can be in turn a prerequisite for the calculation of circularity metrics (Franklin-Johnson et al 2016) or a method used to assess the circularity of systems, at different scales (Haas et al 2015, Voskamp et al 2017, Lonca et al 2020). Specific reviews are also produced, for example at company scale (Vinante et al. 2021).

Mostly focusing on materials, products or companies, reviews generally point out the limited capacity of quantification tools to embrace the complexity of CE, particularly downcycling and the multiplicity of life cycles (Haupt et al. 2017; Helander et al. 2019). Distinguishing between metrics and the methods underlying them, Walzberg et al (2021) particularly question the usefulness of developing new tools to assess the environmental impact of CE and suggest to combine existing methods - ranging from MFA and LCA to Operations Research – to answer specific research questions. They however stress the need for improved circularity metrics,

Among many, one of the most discussed and used circularity indicators is the Material Circularity Indicator (MCI), developed by the Ellen MacArthur Foundation (EMF and Granta 2015, 2019). Initially developed at product and company scales, the MCI was adapted to measure the circularity of constructions. Verbene (2016) proposed the Building Circularity Indicator (BCI) to quantify the disassembly potential of a building based on design criteria validated by experts of the field. The BCI was further modified (van Viet 2018; Alba Concept 2018; van Schaik 2019) to integrate information about the origin and fate of the materials used in a given building, the technical and functional lifespan or the connection type and accessibility. The BCI was applied to different case studies: building foundations in the Netherlands (van Schaik 2019), building demonstrators located in different European countries (Cottafava and Ritzen 2021). For the latter, the Predictive BCI was proposed as a way to forecast the rate of material recovery in residential constructions by integrating design criteria for the calculation of the MCIs of each element.

Other material circularity metrics such as the Reuse Potential Indicator (Park and Chertow 2014) the Circular Economy Index (Maio and Rem 2015), or Product level circularity metric (Linder et al. 2017) are completing the list of indicators that have been applied or are applicable at the scale of an urban project.

Measuring circularity differs from quantifying the environmental impacts of CE in a life cycle perspective. Instead of developing *ad hoc* indicators devolved to the assessment of the environmental performances of circularity, LCA can be used to evaluate circular practices, in combination with indicators measuring the efforts made to recirculate matter. In that sense, Lonca (2018) developed a framework for the evaluation of the environmental performance of CE strategies, that involves both the circular use of resources and mitigation of environmental impacts in a life cycle perspective. Combining LCA with the MCI, the approach highlights four possible pathways: the coupling of linearity and high environmental impacts, trade-off on resources, trade-off on pollution, and the decoupling of environmental impacts and resource consumption. They applied the assessment framework to tire end-of-life scenarios in Brazil and Europe. LCA and MCI were further applied simultaneously to various systems: for example beer packaging (Niero and Kalbar 2019), alkaline batteries (Glogic et al. 2020), or plastic bottles (Lonca et al. 2020). The MCI is currently integrated in the GaBi software through the GaBi circularity toolkit (GaBi website).

Despite the impressive growth of studies and papers addressing, first, the measurement of buildings circularity, and second, the environmental trade-offs of circular practices and strategies involving particular products or processes, nothing concerns the comprehensive quantification of the environmental performance of circular buildings (and by extension, neighborhoods or urban projects), through the combined measurement of circularity and assessment of environmental performance of buildings/urban projects over their life cycle.

The aim of this study is to propose and test an approach combining flows, circularity and LCA indicators for the evaluation of the overall environmental performance of urban projects. Circularity is here understood as material circularity (Niero and Kalbar 2019; Lonca et al. 2020), aiming at closing material loops and optimizing resource use efficiency. The term “resource” here corresponds to a narrow definition of the term, accounting for abiotic resources such as minerals and metals, and biotic resources such as wood, used in construction. Energy, water and land resources are excluded. We applied the approach to an urban project located in Paris, France, and compared scenarios corresponding to various material recovery options, ranging from linear to regulatory and maximum recovery levels. The local and national context has been accounted for, using contextualized data for electricity production for instance. Our contribution proposes a tool for stakeholders involved in the early design of urban projects, to inform about the environmental impacts of circular practices, and to provide evidence for the sound choice and prioritization of such practices. This work also highlights research needs to improve the accuracy of eco-design tools based on LCA at the urban scale. Since they rely on a particular case study, results should be interpreted carefully to avoid abusive generalization.

This contribution articulates the following sections. Section 2 explains the approach, the chosen circularity indicators and LCA method. Section 3 introduces the case study as well as the data used to illustrate the method. Section 4 presents the results of the case study, further discussed in section 5. Section 6 concludes on the limitations and perspectives raised by such a work.

2. Methods

2.1 Overview of the methodology

The overall approach developed in this paper consists of calculating material circularity and life cycle impact scores for alternatives of a given urban project (a building, building block or entire neighborhood) considering different material recovery scenarios. Possible options range from linear projects, incorporating primary materials as inputs, and generating waste that are landfilled or incinerated, to circular projects, integrating practices of secondary material incorporation during the construction and use stages or material recovery during the deconstruction stage.

The proposed methodology relies first on the selection of a set of limited but relevant material circularity indicators, based on a review of existing metrics, some of them being adapted to urban projects; second on the choice of LCA indicators. After CE scenarios modeling and dynamic energy simulation, LCA and material flow analysis (MFA) are performed on a case study, the Saint-Vincent-de-Paul project in Paris, France. Material Flow Analysis (MFA) is used to extract the data needed to calculate circularity indicators and to interpret the results via Sankey diagrams. Results enable a comparison between a circularity approach and an LCA approach (Figure 1).

2.2 Selection of indicators measuring material circularity at the scale of an urban project

Four circularity indicators are selected to measure the circularity of the urban project: the recycling rate, the recovery rate, the recovered content and the Material Circularity Indicator adapted to urban project MCI_{UP}. The recycling rate, the recovery rate and recovered content are classical and complementary material circularity indicators. The recycling rate and recovery rate account for the recovery of secondary materials and waste at the EoL of the urban project. The recovered content corresponds to the incorporation of secondary materials (i.e. reused or recycled materials) during the construction stage of the urban project. These indicators are highly relevant for the construction sector. The amount of secondary material incorporated in construction is one of the indicators computed to produce French EPDs following the EN 15804 standard. It is related to the recovered content. At the other side of the urban project cycle, the recycling rate is used by the City of Paris in demolition contracts, among other indicators. The details of their calculation are given in the supporting information.

We also chose to adapt the MCI as a synthesis of the three previously described circularity indicators. The MCI_{UP}, similarly to the original MCI (Ellen MacArthur Foundation 2015, 2019), integrates material recovery at the beginning and at the end of an urban project, considering reuse or recycling practices (Supporting Information). The adapted indicator differs from the BCI developed by Verbene and followers (Verbene 2016; van Viet 2018; Alba Concept 2018; van Schaik 2019; Cottafava and Ritzen 2021) as it relies on the estimation of the theoretical material recovery at the urban project scale. The idea is not to quantify the material recovery potential at building scale but to provide a measure of circularity that can be compared to environmental impacts calculated using LCA. The main changes made to the original MCI are detailed in the following paragraphs. Calculation details are given in the supporting information.

The MCI_{UP} considers bio-based materials, corresponding here to materials produced totally or partly from biomass, understood as terrestrial and marine plants, biogenic residues and waste (Weiss et al. 2012). Our argument for their inclusion in the indicator relies on the fact that bio-based materials are processed materials, some of them containing resin glue, other treated with chemicals. The original MCI excludes such materials because they are supposed to be renewable. The classification of materials as bio-based does not guarantee their renewability, which depends on resources management practices. Solid wood is not a renewable resource if the supplying forest is exploited in an unsustainable manner. The separation of biological and technological cycles implied by the MCI is then not necessarily relevant since bio-based materials hybridize both biological and technological cycles.

The MCI_{UP} is calculated as the weighted average of constructive elements MCI_e (eq. 1), the weight being the mass of each element M_e (eq. 2). It considers the flows of materials used for the construction and deconstruction/demolition stages of the building blocks, seeing the urban project as a “product”. The indicator then excludes flows associated to the renovation and use stages, assuming that flows of materials for building renovation during its lifetime are negligible compared to the overall flows crossing the system during the whole life cycle of the urban project. This will be discussed in section 4. Integration of renovation and use phases are discussed in section 5. Contrary to the original MCI, MCI_{UP} excludes the flows of unrecoverable waste generated during the production of secondary materials incorporated during the construction stage, and the flows of unrecoverable waste generated during the EoL recycling processes. For the sake of simplicity, the different layers of a building - element, component, system and building - are not been considered.

$$MCI_e = 1 - 0,9 \times \frac{V_e+W_e}{2M_e} \qquad \text{(eq. 1)}$$

$$MCI_{UP} = \frac{1}{M}\sum_{e=1}^{n} MCI_e \times M_e = \frac{1}{M}\sum_{e=1}^{n} M_e - 0,9 \times \frac{V_e+W_e}{M_e} \qquad \text{(eq. 2)}$$

2.3 LCA of urban projects

2.3.1 Building and district LCA tool

The LCA tool used for the case study is a building and district LCA software linked with a dynamic building energy simulation software (Polster et al. 1996; Peuportier et al. 2013, 2017). Given the important contribution of the building use phase to environmental impacts (Sartori and Hestnes 2007; Sharma et al. 2011; Cabeza et al. 2014), LCA is associated with dynamic building energy simulation to account for the interactions between construction material and operational energy use. The LCA tool relies on the ecoinvent database. The cutoff option is chosen, because specific end of life scenarios and avoided impacts are modeled in the LCA tool.

2.3.2 Goal and scope definition

2.3.2.1 Functional unit

In our case, the goal of LCA is to compare urban project scenarios at the scale of the building block. The functions considered are dwelling and activities such as co-working and shops related to a number of persons occupying the areas dedicated to each function in a building block (25,000 m^2 dwelling corresponding to 1000 inhabitants, and 3,500 m^2 activities to 280 persons), a duration (80 years) and a quality (thermal comfort associated to a heating set point, air quality to a ventilation flow-rate etc.). LCA impact scores can be expressed per m^2 useful area and per year in order to be compared to benchmark values, considering the same % of dwelling and activities. The defined functional unit is therefore: “providing 1 m^2 useful floor area for dwelling (88%) and activities (12%) during one year”.

2.3.2.2 System boundaries

2.3.3 The considered stages of the urban project are the construction, use (including consumption of energy and water during the occupancy of the buildings) and deconstruction/demolition stages. System boundaries exclude the deconstruction of previous buildings and site preparation comprising earth excavation. Treatment of excavated earth and domestic waste is considered in sensitivity analysis, as it addresses material recovery. Transportation of building occupants is excluded from the system because it is not directly related to circular strategies. The system boundaries defined for LCA differ from the limits considered in the calculation of circularity indicators (Figure 2). The latter only consider the material flows circulating during the construction and deconstruction/demolition stages. Modeling assumptions

Allocation

In line with the framework developed by Schrijvers et al. (2016), a 50-50 allocation method is used to account for reuse or recycling benefits. It avoids double-counting and balances benefits between supply and demand of secondary materials (ref). The method is a simplified consequential approach neglecting market effects considered too volatile on the long term.

Biogenic carbon

Biogenic carbon is accounted for at the production stage for bio-based products, when wooden materials are supplied from forests with sustainable management certification. Biogenic greenhouse gases emitted during the EoL (particularly CO_2 and methane) are also accounted for, depending on the waste treatment modelled for wood (landfilling, material recovery, incineration with or without heat recovery).

Hourly electricity mix modelling

Electricity is accounted for through the method developed by Herfray and Peuportier (2012) considering hourly variation of the electricity production mix and specific end-use electricity mix.

Database contextualization

The ecoinvent v3.4 database is used. Processes are contextualized to the French situation, mostly through the adaptation of the electricity mix.

2.3.4 Impact assessment

Eleven indicators are considered in this study, 9 midpoint and 2 endpoint indicators : Cumulative Energy Demand (GJ or kWh)(Frischknecht et al. 2007), Global Warming Potential GWP100 (t or kgCO2eq)(IPCC 2013), Water Consumption (m^3), Inert Waste (t or kg), Radioactive Waste (dm^3)(Frischknecht et al. 2007), Acidification (kg SO_2 eq.), Eutrophication (kg PO_4 eq.), Abiotic Resource Depletion (kg Sbeq.), Photochemical

Ozone Formation (kg C_2H_4 eq.) (Guinée 2002), Damage to Biodiversity (PDF.m².an) and Damage to Human Health (DALY) (Goedkoop and Spriensma 2001).

The three endpoint LCA indicators (Human Health, Ecosystem Quality and Resources) have been complemented with important midpoints contributing to these endpoints (climate change, photooxidant formation, acidification, eutrophication, energy and water demand). Waste is also considered because it is a meaningful concern in the building sector, particularly when dealing with circular economy. Radioactive waste is significant in the French context where over 70% of the electricity is produced in nuclear plants and over 60% of the electricity is consumed in buildings. Some environmental issues like ozone depletion are considered less important given the efforts made globally to reduce their severity, following international agreements.

3 Case study: Saint-Vincent-de-Paul

3.1 Description of the case study

The case study focuses on the Saint-Vincent-de-Paul project, located in the 14th arrondissement of Paris, France. Urban programming includes the creation of 43,140 m^2 dedicated to housing, 6,345 m^2 to activities and shops, 6,000 m^2 to private equipment devoted to collective purposes, 5,390 m^2 to public equipment. The neighborhood is divided in six building blocks. The project seeks to minimize its carbon footprint thanks to an ambitious environmental approach. To that end, Saint-Vincent-de-Paul aims to become a CE showcase. Several practices are tested, from reuse of buildings and components to energy and materials recovery, some of which included in the scenarios below.

3.2 Selected building blocks

Four blocks with similar functions (mostly dedicated to housing) were chosen for the assessment: two blocks to be completely rebuilt (block N1 and N2, namely Chaufferie and Petit), two blocks to be renovated (R1 and R2, included in the Façade Denfert).

The first building block N1 consists of 3 buildings separated by pedestrian paths. External walls are made of bricks, with internal insulation made of wood wool and cork board. Internal walls are composed of concrete or OSB panel, with phonic insulation using cork board. Intermediate floors comprise acoustical false ceiling, cross-laminated timber floor, concrete and insulating screed, solid wood parquet floor.

The second building block N2 consists of 5 buildings with a shared green courtyard in-between. External walls are double-skinned, including an external limestone shell and a thermal envelope made of OSB panels and wood wool. External finish is in ceramic, internal finish in plasterboard. Internal walls are made of plaster with phonic insulation in cellulose fiber.

In both N1 and N2 new buildings, carpentry consists of double-glazed windows (wood/aluminum) and wooden doors (insulated if outer). A heat recovery ventilation is foreseen, as well as photovoltaic modules for onsite renewable energy production (300 m² for N1, 316 m² for N2).

Building blocks R1 and R2 are parts of the historical buildings of the site, constructed respectively in the 17th and 19th centuries. The renovation scheme requires the same technical specification for both projects. It consists of preserving the facades, implementing insulation and structural reinforcements to ensure that both thermal and structural performances respect the current legislation. Limestone external wall are kept in place and lined with hemp concrete. Internal finish is made with lime-hemp plaster. Some of the internal walls are preserved. Low and intermediary wooden floors are kept in place, punctually reinforced and insulated with hemp concrete or cellulose fiber for soundproofing. The roof structure is preserved and isolated using wood wool. A new roof covering in slate is planned. Carpentry consists to double simple-glazing windows with double windows with double-glazing and wooden doors with insulation outdoor, no insulation indoor. Renovated building blocks will both include a heat recovery ventilation system.

Floor areas are given in Table 1. Detailed technical specifications used for calculation are given in the supporting information.

3.2.1 Scenarios

Four scenarios on CE practices during the construction and deconstruction stages have been defined (Table 2): a linear scenario LIN where 100% of construction materials and elements are new, 100% of inert construction and demolition waste are being landfilled and the rest incinerated. A second scenario CIR integrates French regulations for the recovery of construction and demolition material at the EoL of a building, setting at 70% the recycling of concrete, and reuse of bricks and limestone for example. It also includes the specific objectives of the Saint-Vincent-de-Paul project in terms of secondary material incorporation during the construction stage, particularly recycled metals. Such objectives are specified in the pre-sketch stage project documents provided by the urban design team. Based on CIR, the third scenario CIR+ increases the rate of secondary materials incorporated during the construction stage. It considers for example a recovered content of 30% for aggregates recycled in concrete elements, 30% for wooden structural elements, 70% for reused OSB boards. The fourth scenario CIR++ further improves the recovery of construction materials during the deconstruction stage, particularly through the reuse of inert materials and structural elements. Two complementary scenarios $\text{CIR+}_{\text{incinerable}}$ and $\text{CIR+}_{\text{Metals}}$ are defined based on the third scenario CIR+, and favor EoL recovery of respectively incinerable materials or metals. Details of the scenarios are given in the supporting information. For the EoL material recovery rate, the proposed alternatives are based on the theoretical technical potential of materials and building components recovery. The recovered content of the different construction materials is estimated based on expert knowledge addressing practices currently tested in the French construction sector. The different scenarios have been validated by the urban design team (project developer and reuse expert).

3.3 LCA tool and main assumptions

The PLEIADES® tool allows first to establish a digital model of a building or building block; second to perform a dynamic energy simulation; then to perform a life cycle assessment. The building energy simulation model has been set when possible according to project documentation given by the urban planner. For each building block, energy simulation is performed according to the specificities of the pre-sketch stage project.

Main assumptions for the LCA cover the lifetime of buildings (set to 80 years) and components (windows and doors: 30 years, flooring and wall cladding: 10 years, equipment: 30 years). Water and space heating are provided by a district heating network: 2019 data are used for the heat generation mix, mainly composed of waste incineration – 43%, gas – 38% and coal – 12%. Heat losses are estimated to be 10%. Hourly data are used for the electricity mix (Herfray and Peuportier 2012). Water consumption is estimated at 100 L/day/person of cold water and 40L/day/person of hot water in dwellings, 1 L/day/person of cold water and 2 L/day/person of hot water in others spaces (accounting for rainwater recovery). Domestic waste is accounted for. The detail of modeling assumptions (climatic data, envelope composition, occupancy rates, heating set-point temperature, electricity consumption for domestic appliances, ventilation, etc.) are given in the supporting information.

3.4 Data sources

The digital model of each building block relies on data and documents provided by the urban design team with the agreement of the project developer. They include the early design project composed of plans and elevations, as well as technical documents providing technical specifications of buildings (wall compositions, equipment…). Data about recycled content in construction and recovery rate during the EoL are extracted from the project documentation and validated by the urban design team.

4 Results

Results presented below address the measurement of the scenarios' circularity (section 4.1) and their environmental performances using LCA (4.2). A combined assessment evaluating the environmental performance of MCI_{UP}-equivalent scenarios is then proposed, in section 4.3. More details are available in the supporting information about the operational energy needs (heating and specific electricity) and material flows accounted for in the circularity indicators, visualized with Sankey diagrams.

4.1 Material flow analysis and circularity indicators

Based on the flows of primary and secondary materials during the life cycle of the four studied building blocks (excluding domestic waste and excavated earth), renovating a building decreases the amount of requested primary materials at the beginning of the life cycle. Even with the first step scenario (CIR+), corresponding to regulatory requirements, an important share of material is recovered during the end-of-life stage. However, recycling of demolition inert waste mainly corresponds to downcycling (Zhang et al. 2020).

The calculation of different circularity indicators at building block scale show that the retrofitted projects reach a recovered content exceeding 80% of the total input material, without any further efforts to implement circular actions (Figure 3). A main difference is also found between LIN and CIR scenarios for all indicators. However, differences between CIR, CIR+ and CIR++ depends on the indicator: they are more pronounced with the MCI_{UP}, but only small differences occur (< 20%) with the recycling rate and recovery rate. Main differences between CIR and CIR+ are related to a higher recovered content of input materials. Another difference is the choice of reuse for bricks instead of recycling, which lowers the recycling rate without affecting the recovery rate.

4.2 Life cycle assessment

In Figure 4 hereunder, each axis corresponds to an environmental indicator. The linear scenario LIN is considered as a reference and the impact scores corresponding to the other scenarios are expressed as relative values compared to this reference: the waste indicator of scenario CIR++ applied to N1 building block is 20% of the waste indicator of the LIN scenario for example.

Results of the LCA of the four CE scenarios for each building block show contrasted conclusions depending on the considered indicator. Global warming and cumulative energy demand, two of the most studied issues in the building sector, show very little reduction related to circular scenarios (less than 10%). However, the influence of CE on abiotic resource depletion is more significant, with a reduction of impacts exceeding 20%. Waste generated during the construction and demolition stages is even more significantly reduced: about 80% for new constructions, and almost 90% for renovated building blocks (Figure 4).

4.3 Comparative results between MCI_{UP} and LCA indicators

Combining life cycle impact scores and material circularity performances shows different environmental profiles according to the type of impact and building block (Figure 5). For the different case studies, and with respect to global warming, environmental performances slightly improve when increasing the material circularity performance, especially when shifting from a linear scenario to a regulatory-based one. Important efforts to recover building materials are not followed by a significant reduction of global warming scores. This is especially true when bio-based (wooden) materials are incorporated in the building, and biogenic CO_2 accounted for. As for cumulative energy demand, the energy consumption remains quite the same whatever the circularity performance.

The picture is different for other impact categories such as the depletion of abiotic resources, human health and ecosystem quality: impact scores decrease when improving circularity performances. Furthermore, the MCI_{UP} and the production of waste are strongly correlated. For a given circularity performance, retrofitting projects generate more waste per FU than new constructions. This is due to the high material content of old buildings accounted for in the end-of-life step (heavy and thick stone walls compared to light wooden structure for new buildings). Interestingly, the relationship between abiotic resource depletion or human health impacts scores and MCI_{UP} seems linear considering the four case studies.

For a given value of MCI_{UP}, the scenarios for renovated building blocks have environmental scores that are similar to the scenarios for new constructions, except for climate change (slightly higher impacts), CED (lower impacts). For ecosystem quality, the scenarios for retrofitting projects present a relation between life cycle impact scores and MCI_{UP} similar to scenario N1. Scenario N2 present slightly higher impacts for the same circularity performance.

4.4 Environmental performances for a fixed circularity performance

Two additional scenarios with the same circularity performance are compared to CIR+ (Table 1) for building blocks N1 and N2 (MCI_{UP} of, respectively, 0,526 and 0,559). CIR+ $_{\text{Incinerable}}$ assumes the material recovery of wood and materials that are incinerated in CIR+, particularly insulation and plastic materials. The incorporation rate of secondary material for incinerable (during construction stage) is about 50%, the EoL material recovery rate is about 90%. The recovery rate for minerals is adjusted to reach the same MCI_{UP} (from 40 to 60% in construction and 60 to 70% in deconstruction/demolition). Metals are of primary production in the construction stage and landfilled after deconstruction of the building blocks. CIR+ $_{\text{Metals}}$ maximizes the recovery of metals (steel, aluminum and copper). The recovery rate is assumed to be 90% during the construction and demolition stages. The recovery rate for mineral elements is adjusted to keep the same MCI_{UP}, and ranges from 50 to 60% in construction and 90% during the EoL stage. Wood or incinerable are incinerated or landfilled.

Reference scenario CIR+ generally presents lower impact scores for most categories (Figure 6). Based on mass, the amount of minerals (concrete, stones…) dominates the building blocks' bill of materials. Reaching a high circularity performance is possible without efforts made to recover materials other than minerals. However, elements such as wood and metals induce higher impacts per kg/unit on ecosystem quality, resource depletion or aquatic eutrophication than concrete. This explains the increasing impacts when the recovery rate of such materials decreases.

5 Discussion

5.1 Relevance of tested indicators for the assessment of circular urban projects

The framework proposed in this paper relies on three types of indicators, informing about different aspects of an urban project, and considering different system boundaries (Figure 2 and section 5.2):

- material flows, following an MFA approach, providing absolute amounts of materials crossing the urban system;
- material circularity indicators, informing about the closing of material loops through the use of recovered secondary materials as inputs, or the implementation of material recovery options at the EoL of the urban project. The circularity performance is relative in the sense that it refers to a baseline linear scenario, without material cycling;
- life cycle environmental impact indicators, quantifying the potential environmental effects

The four CE indicators tested on the case of the Saint-Vincent-de-Paul project also illustrate each different facets of circularity, and of the efforts made at the (temporal and spatial) scale of the project to recirculate matter. The recovery rate looks more interesting than the recycling rate at first sight, the latter being more restricted in scope and missing important solution such as reuse. This could disqualify this indicator for evaluating global material circularity of a project. Contrary to the recovered content looking only at secondary material incorporation or the recycling rate and recovery rate looking at end-of-life, the MCI summarize efforts made on both sides of the life-cycle. In that sense, MCI_{UP} provides a synthetic view of such efforts, spatially delimited to the geographic boundaries of the project, made to shift from linear to circular urban projects, as its accounts for both the incorporation of secondary material during the construction or retrofitting; and the reuse of elements and recycling of waste during the EoL of an urban project. However, it does not help to priorize between reuse, recycling and downcycling as they are all mixed up in the same metric, even if they could have different environmental consequences.

5.2 System boundaries

CE can be applied to building materials, but also to packaging and domestic waste. Excavated earth also corresponds to a large mass and induces significant impacts for transport and possible decontamination processes if it is not reused on site like in the Saint-Vincent-de-Paul project. Comparing the total mass of building components stored during the lifetime of the project with the mass of excavated earth prior to construction and domestic waste generated during the project use stage shows values of the same order of magnitude for new constructions. Conversely, renovating buildings avoids the excavation of earth. Flows of materials required for the renovation and maintenance of buildings during their life cycle is comparatively low. Including excavated earth and domestic waste in the calculation of circularity indicators with no further recovery attempt logically decreases their value (Figure 7).

A sensitivity study has been performed in order to evaluate the influence of domestic waste on LCA indicators. According to this study, the potential reduction of GHG emissions is the same order of magnitude (up to 20%) as the reduction obtained by construction materials recovery. It highlights the importance of integrating this contributor to the study, since a circular economy approach should also address the sorting and recycling of domestic waste.

5.3 Weighting

So far, MCI_{UP} has been calculated as the weighted average of constructive elements MCI_e, based on mass. Since circular economy is about maintaining the value of things, a sensitivity analysis has been performed on the weighting of MCI_e. MCI_{UP} is calculated using respectively weights based on the mass and economic values of constructive elements. M_e is then replaced by the monetary value of each constructive element used in the project, weighted by the total value of the materials incorporated during the construction stage, instead of the total mass of the building. According to the adopted weighting, the raking between scenarios changes since CIR+ presents the highest MCI_{UP} value (Figure 8). Other weighting could be tested, particularly in relation with the criticality of materials used in the constructive elements, accounting for the level of renewability of bio-based materials and the integration of renewable resources management practices (particularly the pace of exploitation)..

Mass weighting is more robust compared to economic values, which can be volatile. Economic values might also be difficult to estimate, due to low transparency on this matter in the construction sector. Still, the economic weighting seems better to represent the embodied technology and potential economic interest in improving the circularity of the material or construction component. However, it might be inaccurate to approximate the value of a constructive element through its market value only, as the added-value might either correspond to higher technology inputs (materials, energy, etc.) or to efforts at lowering its environmental impacts. Ideally, the value of the material or element should encompass both the service provided to the occupants, and by extension to society, and the environmental externalities related to its life cycle. Weights calculated based on market prices from which such externalitites are substracted could be a possibility. Considering such weighting alternatives could put the emphasis on materials and components whose recovery generates or preserves more value to society, then integrating the economic and social dimensions of CE and sustainable development. This could be particularly relevant for urban projects involving architectural or structural components with high heritage value.

5.4 Scales of circular practices

Based on the calculation of LCA impact scores and mass-weighted MCI_{UP}, reuse or recovery of architectural elements such as doors, windows are not visible at building or neighborhood scale. Despite the fact that such practices are not part of the most efficient strategies to decrease the environmental impacts of a building project, they could still be important at the component and industrial scales, as part of a sectoral strategy, or as cultural assets. The use of different weighting approaches, based on monetary or “heritage” value, or criticity of materials could also provide a different picture. Green procurement is an important leverage and should promote the reuse and recycling of products, but considering a construction project, they come long after the improvement of the building envelope.

5.5 Plausibility of the material fate after deconstruction related to the EoL of the building block

The EoL recovery scenarios assessed in this case study are based on assumptions founded by regulatory requirements and technical or theoretical recovery potential. They are best-case scenarios. Several authors point out the fact that, due to technical and design constraints, the part of recoverable materials is far lower than the experts' appraisals. Cottafava and Ritzen (2021) estimate the recoverable percentages to vary between 24% to 86% according to the type of building and the location. Arora et al. (2019) considered the percentage of recoverable materials to be between 12 and 20% depending on the type of building component or element. To validate the plausibility of recovery scenarios, it should be necessary to integrate building site's waste management information, and to construct scenarios based on existing end-of-life practices, taking into account different technical, economic constraints – partly covered by the DfD criteria proposed by several authors (Verbene 2016; Cottafava and Ritzen 2021). In this optical, comparing ex-ante and ex-post assessments would be interesting to validate the estimated quantities for the different materials and elements derived from the modeled projects with bills of materials (BoM) for each project.

5.6 Biotic and abiotic materials in LCA

Despite being a documented issue (Torres et al. 2017; Bendixen et al. 2019), there is still a lack of adequate impact categories and indicators regarding some building materials, especially related to structural elements (sand, aggregates). Ongoing work, for instance (Schulze et al. 2020a, b) may hopefully soon reach a consensus on this research area and greatly improve application of LCA to the building sector and construction industry. We can however still note that circularity indicators do not provide a better option to solve this issue.

Biogenic carbon accounting is a perennial debate in LCA (Lippke et al. 2011; Cherubini et al. 2012; Levasseur et al. 2013; Matthews et al. 2014; Head et al. 2021). The current method used in this paper could lead to higher climate change impact of reused wood compared to new products, depending on EoL assumptions: reusing wood avoids the production of wood (i.e. negative CO_2 emissions if the wood is produced in a certified forest) and end of life (which may not compensate the negative emissions of the production if the wood is not incinerated). This is balanced by higher impact related to land-use and influencing biodiversity endpoint impacts. However, a deeper methodological work is needed to check to what extent reused wood products reduce deforestation and to determine if biogenic carbon accounting could or should be distributed over several life cycles. Current work on holistic evaluation of biotic and non-biotic resources may also lead to overcome these issues (Beylot et al. 2020).

6 Conclusions

With the promotion of CE as an alternative to the linear economy, there is a need to provide evidence about the environmental benefits and possible trade-offs associated with circular practices, particularly in the building sector. Despite recent efforts and awareness, the development of a relevant assessment framework is still at an early stage. This study proposes and tests an approach distinguishing between the measurement of material circularity and the evaluation of environmental performance in a life cycle perspective, applied to an urban project. It provides an original framework for the early design of urban projects that clearly distinguishes circularity from its environmental impacts thus avoiding confusion between means and ends in CE. Such approach could be applied to other circular urban projects, first to compare quantitatively the circular ambitions of the projects, second to provide guidance for the choice of circular actions to be integrated within the projects, based on their life cycle environmental performances. First developed in an ex-ante perspective, the framework could also be applied for ex-post evaluation of urban projects, to check the relevance of effectively implemented circular actions. The framework could also be applied in a follow-up perspective at city scale, to monitor the actions and impacts of circular strategies applied to the building and construction sector, such as the current Circular Economy Plan of the City of Paris.

Circularity indicators like the MCI_{UP} inform about the means - recirculating matter - implemented to reach a goal - improving environmental performances of systems or projects to enable human societies to attain a sustainable and harmonious development. Circularity indicators tested in our case study quantify the circularity performance of an urban project, understood as a measure of the efforts made to recirculate matter during the construction and demolition stages, and possibly during the other stages of the project. The considered circularity indicators are however limited in their scope since they do not characterize the environmental impacts related to the recirculation of matter within an urban project, occurring locally and remotely, as well as environmental issues related to health and biodiversity. LCA is therefore required to inform about the environmental relevance of CE applied to urban projects. Various measures are actually proposed to reduce environmental impacts of urban projects, such as energy efficiency improvement, soft mobility, or circular actions. Specific indicators like MCI and its adaptations, percentage of renewable energy and cycle path length correspond to silo approaches. LCA enables to assess the different measures in an integrated manner, allowing a more global and systemic decision-making process. Rather than setting circularity targets, it is then advisable to set environmental targets in a program, so that designers use circularity combined with other means to reach these targets in a systemic way. Circularity indicators are then complementary to LCA indicators and should not replace them in the eco-design process. Environmental relevance of circular practices shall be validated using a holistic assessment method such as LCA. The choice and implementation of environmentally-sound circular actions and strategies are at stake.

There are however still research needs; first to overcome current limitation of LCA regarding the criticality of some building materials (sand and gravel), the ecosystemic consequences of their extraction, as well as the assessment of biogenic carbon and land use changes; second to understand the conditions for which the environmental performances of CE implemented in urban projects are guaranteed; and third to account for the non-environmental aspects of CE. As a first approach, we adopted a narrow definition of circular economy, circumscribed to the recovery of materials and components during the construction and EoL of the buildings. Broadening the system boundaries would enable to account for other circular actions. Further studies could focus on practices currently tested in circular urban projects, related to the local management of rainwater, recovery of waste generated during the use stage or temporary occupation of urban lands, thus broadening the type of resources considered. Another avenue would be to consider socio-economic implications of applying CE to urban projects. The discussion on value weightings constitutes a first step. Further research is needed in that direction.

Acknowledgments

This article draws on the results of the PULSE-Paris research project, funded by the French Environmental and Energy Management Agency (ADEME) with strong collaboration with the City of Paris and the Saint-Vincent-de-Paul urban project team.

References

Adalberth K (1997) Energy use during the life cycle of buildings: a method. Build Environ 32:317–320. https://doi.org/10.1016/S0360-1323(96)00068-6

Alba Concept (2018) Building Circularity Index [BCI]

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

Appendino F, Roux C, Saadé M, Peuportier B (2019) Circular economy in urban projects: a case studies analysis of current practices and tools. Venise, p 16

Arnsperger C, Bourg D (2016) Vers une économie authentiquement circulaire. Réflexions sur les fondements d'un indicateur de circularité. Rev OFCE 1:. https://doi.org/10.3917/reof.145.0091

Arora M, Raspall F, Cheah L, Silva A (2019) Residential building material stocks and component-level circularity: The case of Singapore. J Clean Prod 216:239–248. https://doi.org/10.1016/j.jclepro.2019.01.199

Basbagill J, Flager F, Lepech M, Fischer M (2013) Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts. Build Environ 60:81–92. https://doi.org/10.1016/j.buildenv.2012.11.009

Benachio GLF, Freitas M do CD, Tavares SF (2020) Circular economy in the construction industry: A systematic literature review. J Clean Prod 260:121046. https://doi.org/10.1016/j.jclepro.2020.121046

Bendixen M, Best J, Hackney C, Iversen LL (2019) Time is running out for sand. Nature 571:29–31. https://doi.org/10.1038/d41586-019-02042-4

Beylot A, Ardente F, Marques A, et al (2020) Abiotic and biotic resources impact categories in LCA: development of new approaches : accounting for abiotic resources dissipation and biotic resources.

Beylot A, Ardente F, Sala S, Zampori L (2021) Mineral resource dissipation in life cycle inventories. Int J Life Cycle Assess 26:497–510. https://doi.org/10.1007/s11367-021-01875-4

Blengini GA, Di Carlo T (2010) The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings. Energy Build 42:869–880. https://doi.org/10.1016/j.enbuild.2009.12.009

Blum NU, Haupt M, Bening CR (2020) Why "Circular" doesn't always mean "Sustainable." Resour Conserv Recycl 162:105042. https://doi.org/10.1016/j.resconrec.2020.105042

Brunner PH (2011) Urban Mining A Contribution to Reindustrializing the City. J Ind Ecol 15:339–341. https://doi.org/10.1111/j.1530-9290.2011.00345.x

Buyle M, Galle W, Debacker W, Audenaert A (2019) Sustainability assessment of circular building alternatives: Consequential LCA and LCC for internal wall assemblies as a case study in a Belgian context. J Clean Prod 218:141–156. https://doi.org/10.1016/j.jclepro.2019.01.306

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

Cherubini F, Guest G, Strømman AH (2012) Application of probability distributions to the modeling of biogenic CO2 fluxes in life cycle assessment. GCB Bioenergy 4:784–798. https://doi.org/10.1111/j.1757-1707.2011.01156.x

Cheshire D (2016) Building Revolutions: Applying the Circular Economy to the Built Environment. RIBA Publishing

Chouquet J (2007) Development of a method for building life cycle analysis at an early design phase - Implementation in a tool - Sensitivity and uncertainty of such a method in comparison to detailed LCA Software. Thèse de doctorat, Université de Karlsruhe

Corbett CJ (2015) Life Cycle Assessment (LCA) as an Introduction to the Circular Economy. Logistyka Odzysku 61–63

Corona B, Shen L, Reike D, et al (2019) Towards sustainable development through the circular economy—A review and critical assessment on current circularity metrics. Resour Conserv Recycl 151:104498. https://doi.org/10.1016/j.resconrec.2019.104498

Cottafava D, Ritzen M (2021) Circularity indicator for residential buildings: Addressing the gap between embodied impacts and design aspects. Resour Conserv Recycl 164:105120. https://doi.org/10.1016/j.resconrec.2020.105120

Eberhardt L, Birgisdottir H, Birkved M (2019a) Comparing life cycle assessment modelling of linear vs. circular building components. IOP Conf Ser Earth Environ Sci 225:012039. https://doi.org/10.1088/1755-1315/225/1/012039

Eberhardt LCM, Birgisdóttir H, Birkved M (2019b) Life cycle assessment of a Danish office building designed for disassembly. Build Res Inf 47:666–680. https://doi.org/10.1080/09613218.2018.1517458

EEA (2020) Cutting greenhouse gas emissions through circular economy actions in the buildings sector — European Environment Agency. https://www.eea.europa.eu/themes/climate/cutting-greenhouse-gas-emissions-through/cutting-greenhouse-gas-emissions-through. Accessed 26 Mar 2021

EEA (2016) Circular economy in Europe, Developing the knowledge base, European Environment Agency, EEA Report No 2.

Elia V, Gnoni MG, Tornese F (2017) Measuring circular economy strategies through index methods: A critical analysis. J Clean Prod 142:2741–2751. https://doi.org/10.1016/j.jclepro.2016.10.196

Ellen MacArthur Foundation (2015) Circularity Indicators. An approach to mesure circularity.

EMF, Granta (2015) Circularity Indicators. An approach to mesure circularity.

EMF, Granta (2019) Circularity Indicators - An approach to measuring circularity. Methodology

European Commission (2020) Circular Economy Action Plan - For a cleaner and more competitive Europe

European Commission (2019) The European Green Deal

Eurostat (2019) Generation of waste by waste category, hazardousness and NACE Rev. 2 activity. https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=env_wasgen&lang=en. Accessed 25 Mar 2021

Franklin-Johnson E, Figge F, Canning L (2016) Resource Duration as a Managerial Indicator for Circular Economy Performance. J Clean Prod. https://doi.org/10.5465/AMBPP.2016.11617

Fregonara E, Giordano R, Ferrando DG, Pattono S (2017) Economic-Environmental Indicators to Support Investment Decisions: A Focus on the Buildings’ End-of-Life Stage. Buildings 7:65. https://doi.org/10.3390/buildings7030065

Frischknecht R, Jungbluth N, Althaus HJ, et al (2007) Overview and methodology. Ecoinvent Rep

GaBi website GaBi Circularity Toolkit - Circular Economy Software. http://www.gabi-software.com/international/software/gabi-software/gabi-circularity-toolkit/. Accessed 25 Mar 2021

Glogic E, Young SB, Sonnemann G (2020) Confronting challenges of combining and comparing Material Circularity Indicator with Life Cycle Assessment indicators: a case of alkaline batteries. p 2

Goedkoop M, Spriensma R (2001) The Eco-indicator99: a damage oriented method for life cycle impact assessment: methodology report

Guinée JB (2002) Handbook on life cycle assessment operational guide to the ISO standards. Int J Life Cycle Assess 7:311–313. https://doi.org/10.1007/BF02978897

Guo B, Geng Y, Ren J, et al (2017) Comparative assessment of circular economy development in China’s four megacities: The case of Beijing, Chongqing, Shanghai and Urumqi. J Clean Prod 162:. https://doi.org/10.1016/j.jclepro.2017.06.061

Haupt M, Vadenbo C, Hellweg S (2017) Do We Have the Right Performance Indicators for the Circular Economy?: Insight into the Swiss Waste Management System: Circular Economy: Do We Have the Right Indicators? J Ind Ecol 21:615–627. https://doi.org/10.1111/jiec.12506

Haupt M, Zschokke M (2017) How can LCA support the circular economy?—63rd discussion forum on life cycle assessment, Zurich, Switzerland, November 30, 2016. Int J Life Cycle Assess 22:832–837. https://doi.org/10.1007/s11367-017-1267-1

Head M, Magnan M, Kurz W, et al (2021) Temporally-differentiated biogenic carbon accounting of wood building product life cycles. SN Appl Sci 3:. https://doi.org/10.1007/s42452-020-03979-2

Heisel F, Rau-Oberhuber S (2020) Calculation and evaluation of circularity indicators for the built environment using the case studies of UMAR and Madaster. J Clean Prod 243:118482. https://doi.org/10.1016/j.jclepro.2019.118482

Helander H, Petit-Boix A, Leipold S, Bringezu S (2019) How to monitor environmental pressures of a circular economy: An assessment of indicators. J Ind Ecol 23:1278–1291. https://doi.org/10.1111/jiec.12924

Herfray G, Peuportier B (2012) Evaluation of electricity related impacts using dynamic a LCA model. Nantes, juillet 2012, p 9

Homrich A, Galvao G, Gamboa Abadia L, Carvalho MM (2018) The circular economy umbrella: Trends and gaps on integrating pathways. J Clean Prod 175:. https://doi.org/10.1016/j.jclepro.2017.11.064

Hossain MdU, Ng ST (2018) Critical consideration of buildings' environmental impact assessment towards adoption of circular economy: An analytical review. J Clean Prod 205:763–780. https://doi.org/10.1016/j.jclepro.2018.09.120

IPCC (2013) IPCC fifth assessment report, climate change 2013: The physical science basis. IPCC 31–39

Joensuu T, Edelman H, Saari A (2020) Circular economy practices in the built environment. J Clean Prod 276:124215. https://doi.org/10.1016/j.jclepro.2020.124215

Kirchherr J, Reike D, Hekkert M (2017) Conceptualizing the circular economy: An analysis of 114 definitions. Resour Conserv Recycl 127:. http://dx.doi.org/10.1016/j.resconrec.2017.09.005

Klinglmair M, Sala S, Brandão M (2013) Assessing resource depletion in LCA: a review of methods and methodological issues. Int J Life Cycle Assess 19:580–592. https://doi.org/10.1007/s11367-013-0650-9

Krause K, Hafner A (2019) Relevance of the information content in module D on circular economy of building materials. In: Proceedings of the 6th International Symposium on Life-Cycle Civil Engineering. p pp 1627e1633

Lacy P, Rutqvist J (2016) Waste to Wealth: The Circular Economy Advantage. Springer

Leising E, Quist J, Bocken N (2018) Circular Economy in the building sector: three cases and a collaboration tool. J Clean Prod 176:976–989. https://doi.org/10.1016/j.jclepro.2017.12.010

Levasseur A, Lesage P, Margni M, Samson R (2013) Biogenic Carbon and Temporary Storage Addressed with Dynamic Life Cycle Assessment. J Ind Ecol 17:117–128. https://doi.org/10.1111/j.1530-9290.2012.00503.x

Linder M, Sarasini S, van Loon P (2017) A Metric for Quantifying Product-Level Circularity: Product-Level Circularity Metric. J Ind Ecol 21:545–558. https://doi.org/10.1111/jiec.12552

Lippke B, Oneil E, Harrison R, et al (2011) Life cycle impacts of forest management and wood utilization on carbon mitigation: knowns and unknowns. Carbon Manag 2:303–333. https://doi.org/10.4155/cmt.11.24

Lonca G (2018) Does material circularity rhyme with environmental efficiency? Case studies on used tires. J Clean Prod 12

Lonca G, Lesage P, Majeau-Bettez G, et al (2020) Assessing scaling effects of circular economy strategies: A case study on plastic bottle closed-loop recycling in the USA PET market. Resour Conserv Recycl 162:105013. https://doi.org/10.1016/j.resconrec.2020.105013

Lotteau M, Loubet P, Pousse M, et al (2015) Critical review of life cycle assessment (LCA) for the built environment at the neighborhood scale. Build Environ 93, Part 2:165–178. https://doi.org/10.1016/j.buildenv.2015.06.029

Maio FD, Rem PC (2015) A Robust Indicator for Promoting Circular Economy through Recycling. J Environ Prot 6:720–726. https://doi.org/10.4236/jep.2015.610096

Mak J, Anink D, Knapen M, et al (1997) ECO-QUANTUM development of LCA based tools for buildings. pp 49–58

Matthews R, Sokka L, Soimakallio S, et al (2014) Review of literature on biogenic carbon and life cycle assessment of forest bioenergy. Forest Research

Munaro MR, Tavares SF, Bragança L (2020) Towards circular and more sustainable buildings: A systematic literature review on the circular economy in the built environment. J Clean Prod 260:121134. https://doi.org/10.1016/j.jclepro.2020.121134

Niero M, Kalbar PP (2019) Coupling material circularity indicators and life cycle based indicators: A proposal to advance the assessment of circular economy strategies at the product level. Resour Conserv Recycl 140:305–312. https://doi.org/10.1016/j.resconrec.2018.10.002

Ortiz O, Castells F, Sonnemann G (2009) Sustainability in the construction industry: A review of recent developments based on LCA. Constr Build Mater 23:28–39. https://doi.org/10.1016/j.conbuildmat.2007.11.012

Parchomenko A, Nelen D, Gillabel J, Rechberger H (2019) Measuring the circular economy - A Multiple Correspondence Analysis of 63 metrics. J Clean Prod 210:200–216. https://doi.org/10.1016/j.jclepro.2018.10.357

Park JY, Chertow MR (2014) Establishing and testing the “reuse potential” indicator for managing wastes as resources. J Environ Manage 137:45–53. https://doi.org/10.1016/j.jenvman.2013.11.053

Peña C, Civit B, Gallego-Schmid A, et al (2021) Using life cycle assessment to achieve a circular economy. Int J Life Cycle Assess 26:215–220. https://doi.org/10.1007/s11367-020-01856-z

Petit-Boix A, Leipold S (2018) Circular economy in cities: Reviewing how environmental research aligns with local practices. J Clean Prod 195:1270–1281. https://doi.org/10.1016/j.jclepro.2018.05.281

Peuportier B, Kohler K, Boonstra C (1997) European project REGENER, life cycle analysis of buildings. In: 2nd International Conference “Buildings and the Environment.” Paris, 9-12 Juin 1997, p 8

Peuportier B, Leurent F, Roger-Estrade J (2020) Eco-Design of Buildings and Infrastructure: Developments in the Period 2016–2020. CRC Press

Peuportier B, Roux C, Pannier M-L, Kotelnikova N (2017) Using LCA to assess urban projects, a case study

Peuportier, Thiers S, Guiavarch A (2013) Eco-design of buildings using thermal simulation and life cycle assessment. J Clean Prod 39:73–78. https://doi.org/10.1016/j.jclepro.2012.08.041

Polster B, Peuportier B, Blanc Sommereux I, et al (1996) Evaluation of the environmental quality of buildings towards a more environmentally conscious design. Sol Energy 57:219–230. https://doi.org/10.1016/S0038-092X(96)00071-0

Popovici E, Peuportier B (2004) Using life cycle assessment as decision support in the design of settlements. Eindhoven, p 6

Rasmussen F, Birkved M, Birgisdóttir H (2019) Upcycling and Design for Disassembly – LCA of buildings employing circular design strategies. IOP Conf Ser Earth Environ Sci 225:012040. https://doi.org/10.1088/1755-1315/225/1/012040

Reap J, Roman F, Duncan S, Bras B (2008) A survey of unresolved problems in life cycle assessment. Int J Life Cycle Assess 13:374–388. https://doi.org/10.1007/s11367-008-0009-9

Rørbech JT, Vadenbo C, Hellweg S, Astrup TF (2014) Impact Assessment of Abiotic Resources in LCA: Quantitative Comparison of Selected Characterization Models. Environ Sci Technol 48:11072–11081. https://doi.org/10.1021/es5023976

Saidani M, Yannou B, Leroy Y, Cluzel F (2017) How to Assess Product Performance in the Circular Economy? Proposed Requirements for the Design of a Circularity Measurement Framework. Recycling. https://doi.org/10.3390/recycling2010006

Sandin G, Peters GM, Svanström M (2014) Life cycle assessment of construction materials: the influence of assumptions in end-of-life modelling. Int J Life Cycle Assess 19:723–731. https://doi.org/10.1007/s11367-013-0686-x

Sartori I, Hestnes AG (2007) Energy use in the life cycle of conventional and low-energy buildings: A review article. Energy Build 39:249–257. https://doi.org/10.1016/j.enbuild.2006.07.001

Scheepens AE, Vogtländer JG, Brezet JC (2016) Two life cycle assessment (LCA) based methods to analyse and design complex (regional) circular economy systems. Case: making water tourism more sustainable. J Clean Prod 114:257–268. https://doi.org/10.1016/j.jclepro.2015.05.075

Schrijvers D, Loubet P, Sonnemann G (2016) Developing a systematic framework for consistent allocation in LCA. Int J Lyfe Cycle Assess 21:. https://doi.org/10.1007/s11367-016-1063-3

Schulze R, Guinée J, van Oers L, et al (2020a) Abiotic resource use in life cycle impact assessment—Part I- towards a common perspective. Resour Conserv Recycl 154:104596. https://doi.org/10.1016/j.resconrec.2019.104596

Schulze R, Guinée J, van Oers L, et al (2020b) Abiotic resource use in life cycle impact assessment—Part II – Linking perspectives and modelling concepts. Resour Conserv Recycl 155:104595. https://doi.org/10.1016/j.resconrec.2019.104595

Sharma A, Saxena A, Sethi M, et al (2011) Life cycle assessment of buildings: A review. Renew Sustain Energy Rev 15:871–875. https://doi.org/10.1016/j.rser.2010.09.008

Smol M, Kulczycka J, Avdiushchenko A (2017) Circular economy indicators in relation to eco-innovation in European regions. Clean Technol Environ Policy 19:669–678. https://doi.org/10.1007/s10098-016-1323-8

Steen BA (2005) Abiotic Resource Depletion Different perceptions of the problem with mineral deposits. Int J Life Cycle Assess 11:49–54. https://doi.org/10.1065/lca2006.04.011

Su B, Heshmati A, Geng Y, Yu X (2013) A review of the circular economy in China: moving from rhetoric to implementation. J Clean Prod. https://doi.org/10.1016/j.jclepro.2012.11.020

Torres A, Brandt J, Lear K, Liu J (2017) A looming tragedy of the sand commons. Science 357:970–971. https://doi.org/10.1126/science.aao0503

UEPG (2018) Figures - UEPG. https://uepg.eu/pages/figures. Accessed 25 Mar 2021

UNEP (2019) Sand and sustainability: Finding new solutions for environmental governance of global sand resources. GRID-Geneva, United Nations Environment Programm, Geneva, Switzerland

van Schaik C (2019) Circular building foundations: A structural exploration of the possibilities for making building foundations contribute to a circular economy

van Viet M (2018) Disassembling the steps towards building circularity: redeveloping the building disassembly assessment method in the building circularity indicator. Master thesis, Eindhoven University of Technology

Verbene (2016) Building circularity indicators : an approach for measuring circularity of a building. Eindhoven University of Technology

Vinante C, Sacco P, Orzes G, Borgianni Y (2021) Circular economy metrics: Literature review and company-level classification framework. J Clean Prod 288:125090. https://doi.org/10.1016/j.jclepro.2020.125090

Yellishetty M, Mudd GM, Ranjith PG (2011) The steel industry, abiotic resource depletion and life cycle assessment: a real or perceived issue? J Clean Prod 19:78–90. https://doi.org/10.1016/j.jclepro.2010.08.020

Zabalza Bribián I, Aranda Usón A, Scarpellini S (2009) Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification. Build Environ 44:2510–2520. https://doi.org/10.1016/j.buildenv.2009.05.001

Zhang C, Hu M, Yang X, et al (2020) Upgrading construction and demolition waste management from downcycling to recycling in the Netherlands. J Clean Prod 266:121718. https://doi.org/10.1016/j.jclepro.2020.121718

Tables

Table 1 : Building block characteristics

	Total floor area (sqm)	Living space of housing (sqm)	Useful surface for activities (sqm)	Rooftop PV (sqm)
N1	10751	7815	1414	300
N2	13500	11169	1403	316
R1	6330	5448	605	-
R2	2844	1915	615?	-

Table 2 : Recovery rated for the different scenarios

	Secondary material recovery (construction stage)	EoL material recovery (deconstruction stage)
LIN	0%	0%
CIR	40% of metals	70% of the minerals and wood, 90% of metals
CIR+	30% minerals and hard wood, 40% of metals, 70% soft wood	70% of the minerals and wood, 90% of metals
CIR+ $_{\text{Incinerable}}$	30% minerals and hard wood, 40% of metals, 70% soft wood	70% for the minerals and wood, 90% of metals
CIR+ $_{\text{Metals}}$	90% of metals, 50 to 60% minerals, 0% hard or soft wood	90% of the minerals, 90% of metals, 0% for wood and other incinerable
CIR++	30% minerals and hard wood, 40% of metals, 70% soft wood	90% of the minerals and hard wood, 70% of soft wood, 90% of metals

Figure captions

Figure 1 Overview of the methodology
Figure 2 System boundaries considered for the evaluation of the circularity and environmental life cycle performances of an urban project
Figure 3: Calculating circularity indicators at building block scale
Figure 4: Life cycle impact scores of the four circular economy scenarios
Figure 5: Circularity and environmental performances at building scale
Figure 6: Environmental performances for scenarios with a fixed circularity performance for two building blocks (new constructions)
Figure 7: a) Material flows generated during the life cycle of building blocks. Stored materials are the materials incorporated in a building block during its life cycle. Renovation materials are the materials used to renovate the building block during its life cycle. b) Values of MCI_{UP} calculated with or without renovation flows, excavated earth and domestic wastes, for building block N1.
Figure 8: Values of MCI_{UP} weighted based on mass or economic value of the constructive elements for building block N1

Figures

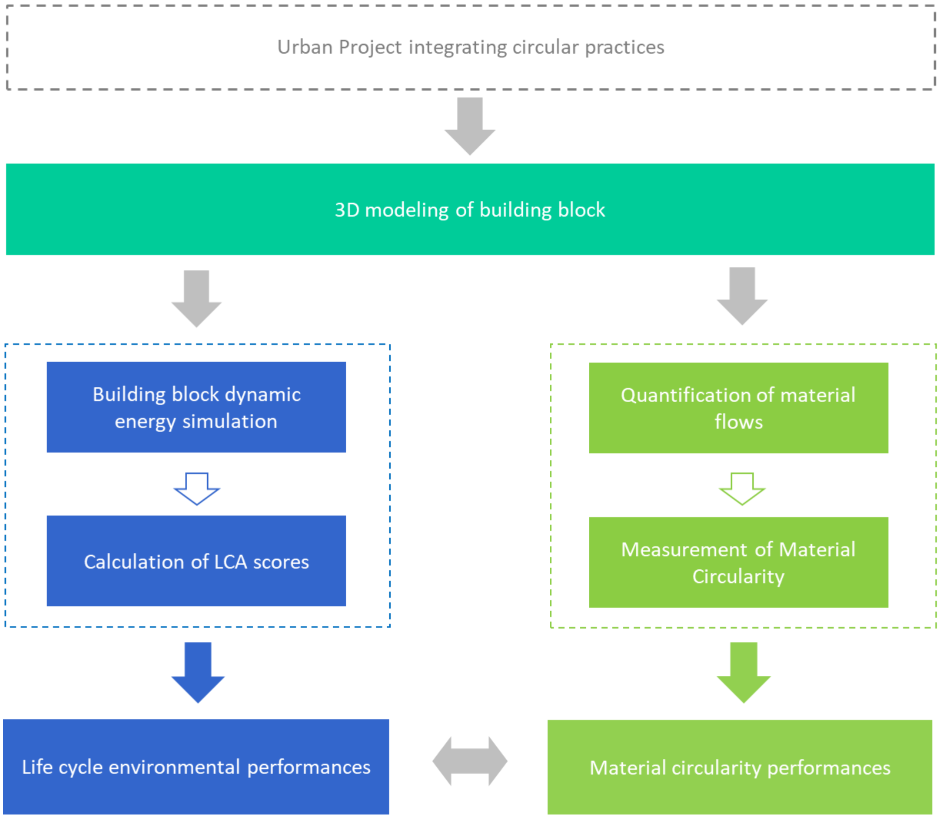


Figure 1 Overview of the methodology

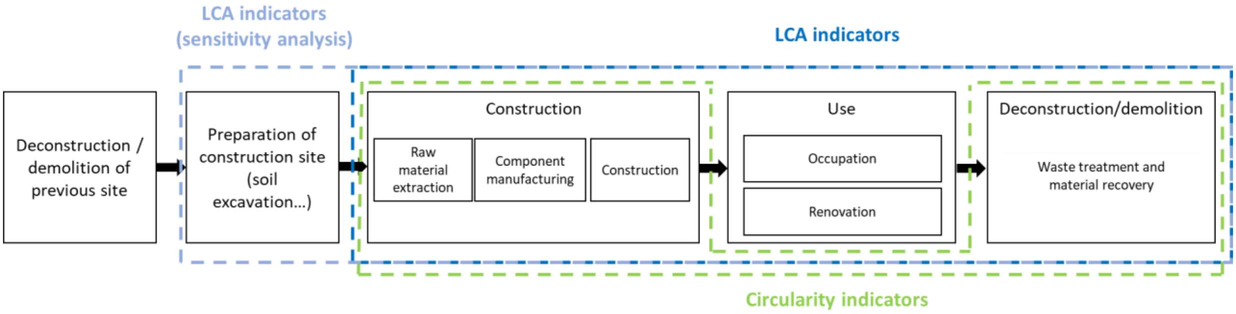


Figure 2 System boundaries considered for the evaluation of the circularity and environmental life cycle performances of an urban project

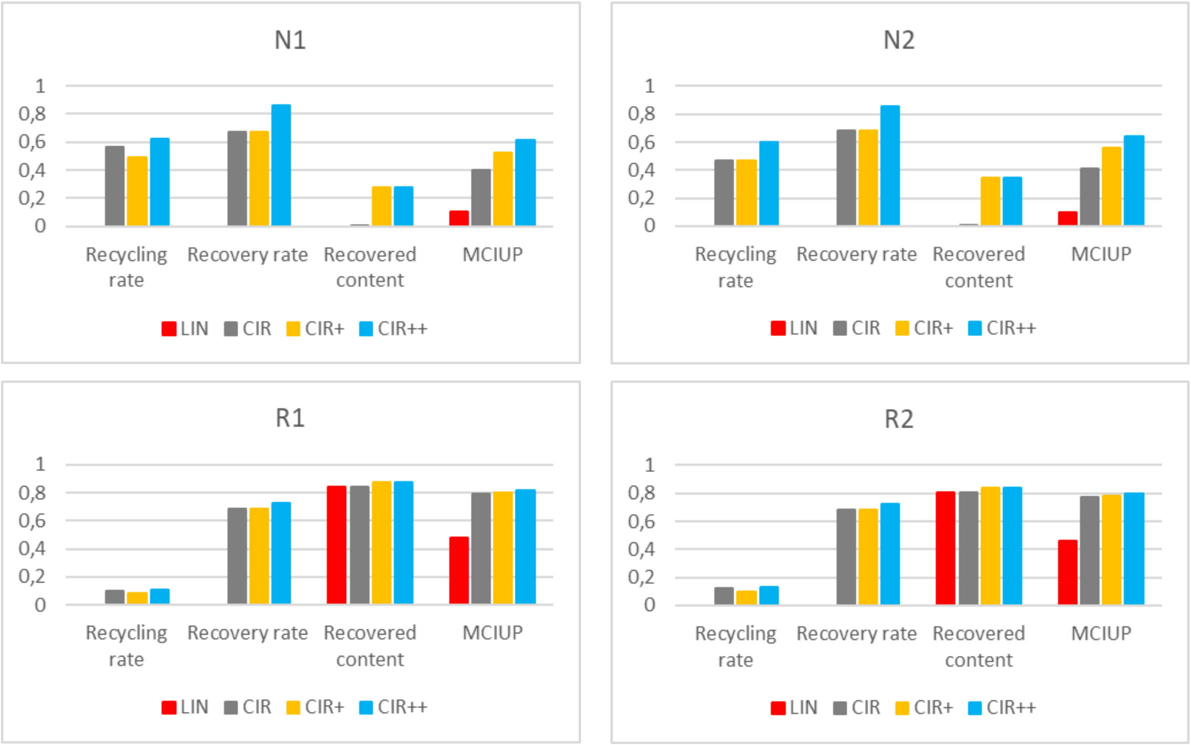
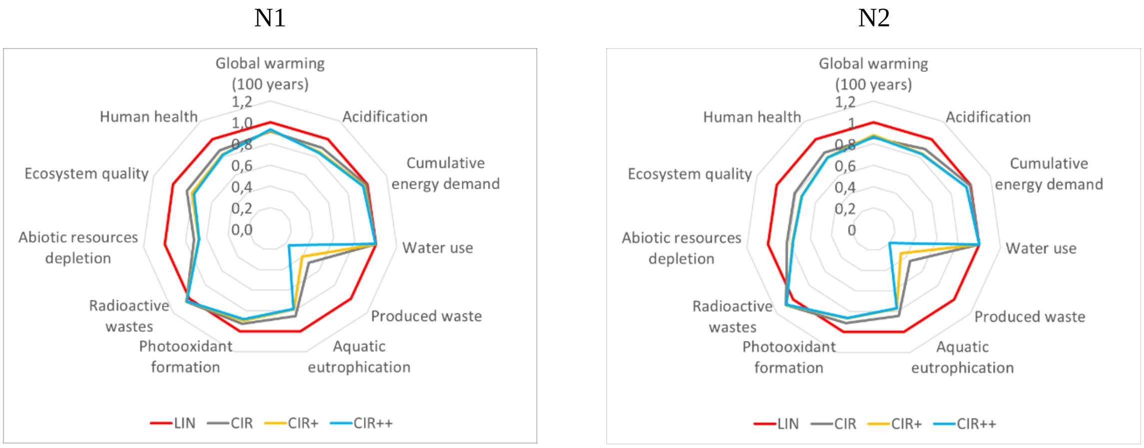


Figure 3: Calculating circularity indicators at building block scale



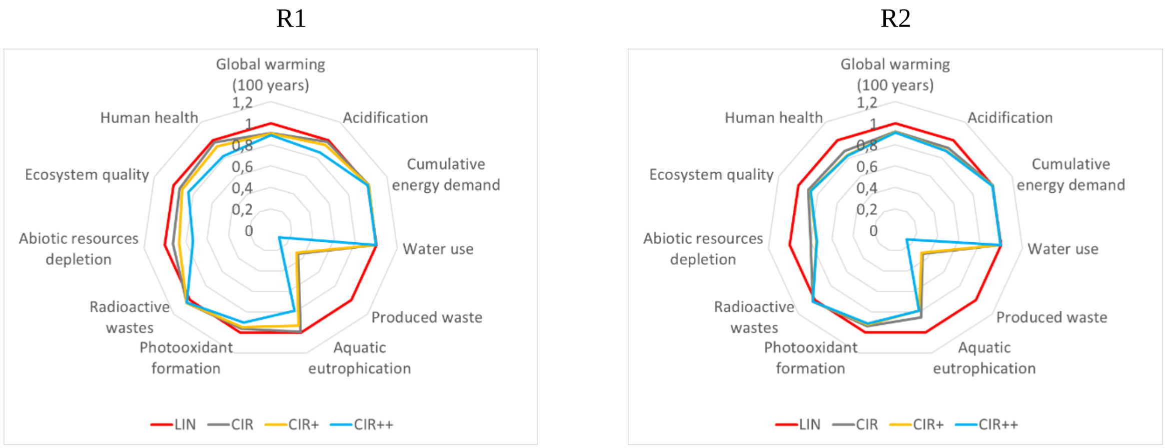


Figure 4: Life cycle impact scores of the four circular economy scenarios

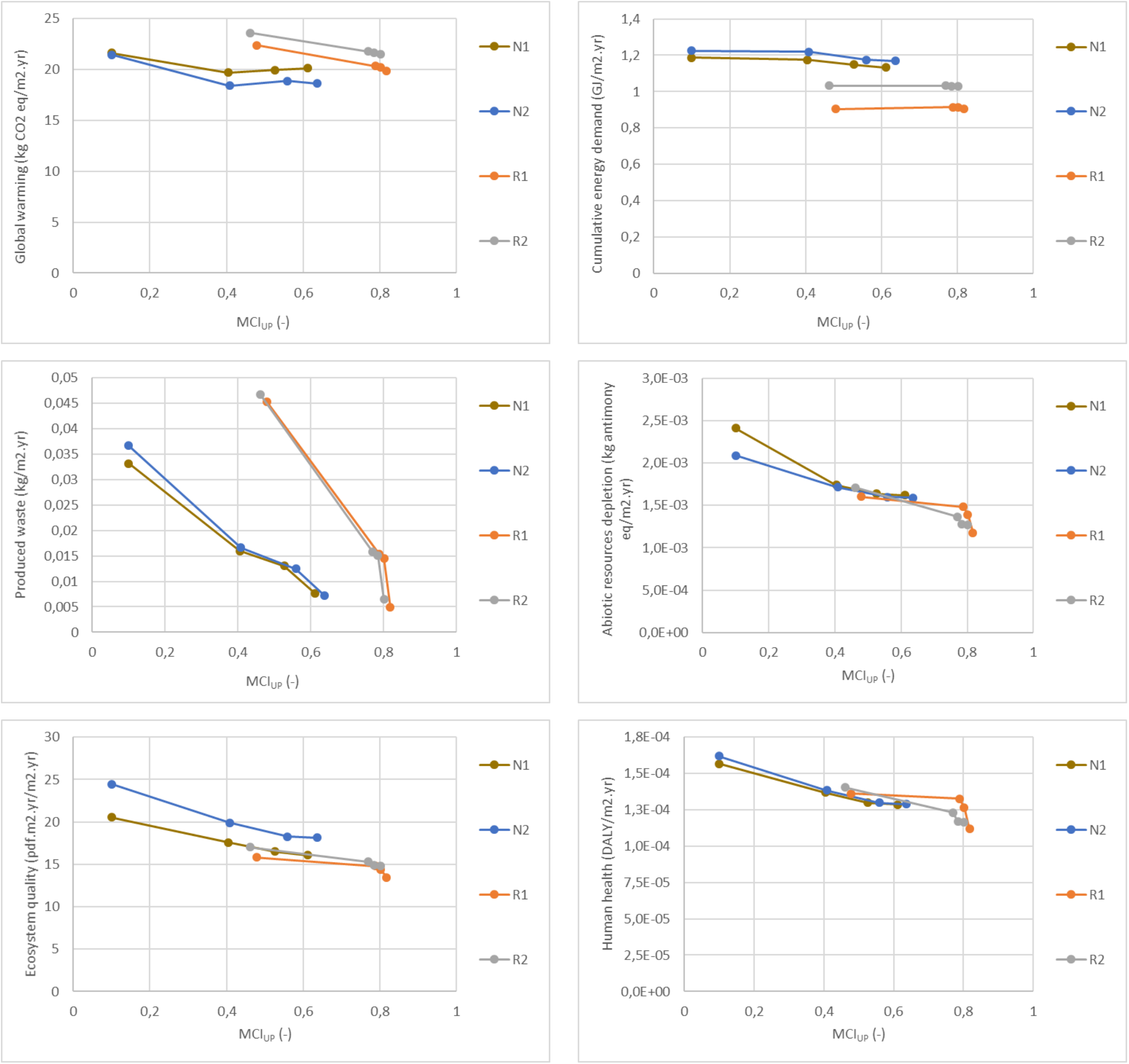


Figure 5: Circularity and environmental performances at building scale

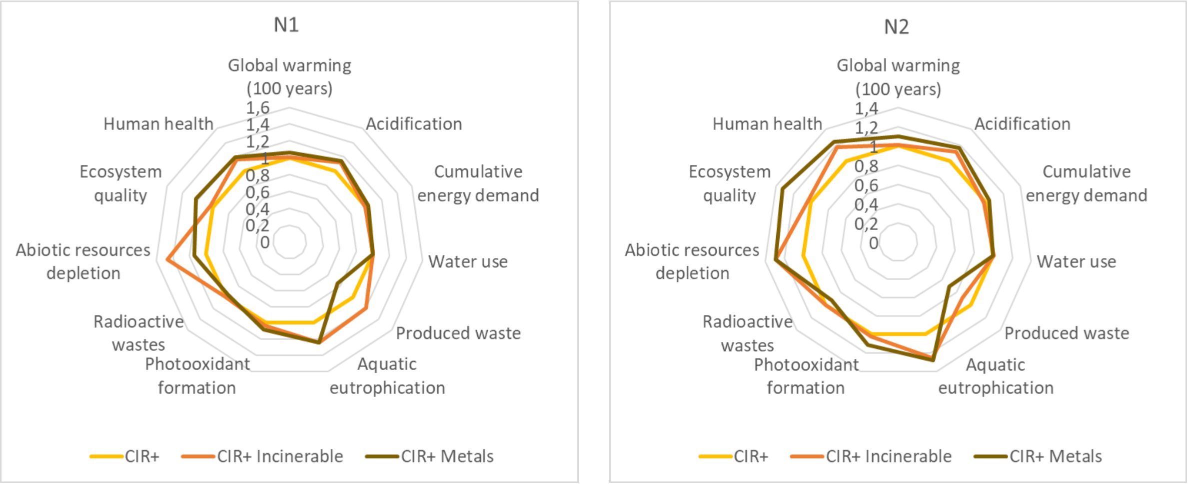
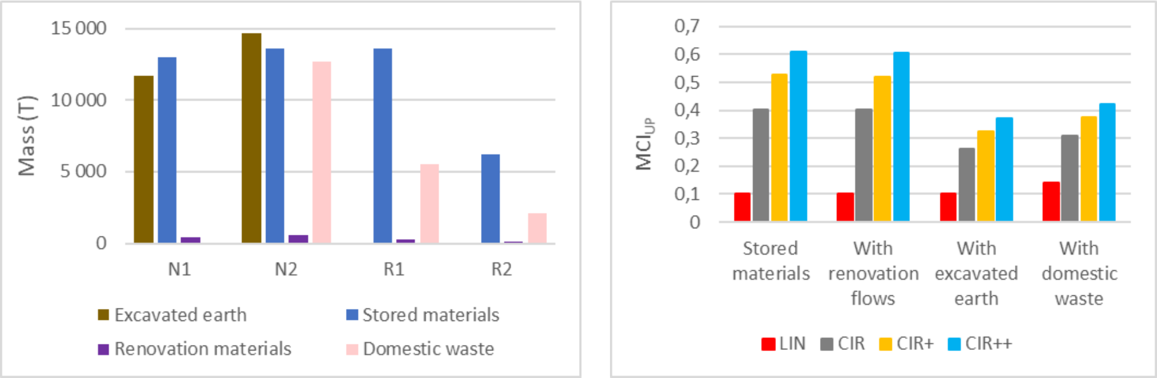


Figure 6: Environmental performances for scenarios with a fixed circularity performance for two building blocks (new constructions)



a

b

Figure 7: a) Material flows generated during the life cycle of building blocks. Stored materials are the materials incorporated in a building block during its life cycle. Renovation materials are the materials used to renovate the building block during its life cycle. b) Values of MCI_{UP} calculated with or without renovation flows, excavated earth and domestic wastes, for building block N1.

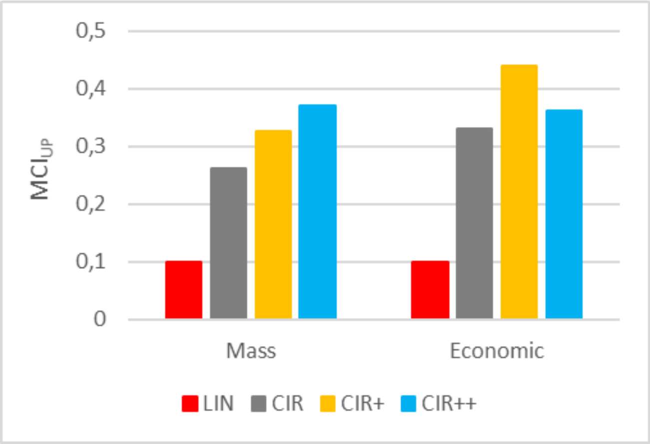


Figure 8: Values of MCI_{UP} weighted based on mass or economic value of the constructive elements for building block N1