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The future of circular environmental impact indicators for cultural heritage buildings in Europe

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Abstract

Background: The European building and construction sector is extremely resource-intensive. This makes the renovation of existing buildings, including the adaptive reuse of cultural heritage buildings (ARCH), important for reducing the materials and energy intensity of the sector. Currently, Europe is embarking on a Circular Economy (CE) strategy that directly affects the environmental indicators for buildings and landscapes, including ARCH. However, there is a misalignment between macro-level European CE policy goals and micro-level renovation and management of existing buildings and ARCH. The analysis shows that macro European Union-level indicators are too narrowly defined to effectively guide the implementation of CE at the micro-project level for ARCH.

Results: This policy study develops a comprehensive ARCH Circular Environmental Impact Indicator Framework to close this gap by: (1) defining the research question; (2) identifying the causal network; and (3) selecting the best indicators. The study compares Circular Environmental Indicators for ARCH projects to current and developing European management schemes. Best practices in environmental impact assessment at the project level are highlighted for the building and construction sector in Europe.

Conclusions: The proposed new framework is a comprehensive and suitable list of explicitly circular environmental indicators for ARCH. The framework has immediate practical applications for practitioners and policymakers interested in the CE regime for buildings in Europe.

Keywords: Circular economy, Environmental indicators, Adaptive reuse, Cultural heritage, Buildings, Sustainability, Transition, Europe, Policy

Background

This article focuses on a subset of existing building renovations, the adaptive reuse of cultural heritage (ARCH) buildings. Its purpose is to contribute to better alignment between macro-level European Circular Economy (CE) policies with micro-level renovation and management of existing buildings and ARCH. With this aim, the article proposes a new ARCH Circular Environmental Impact Indicator Framework.

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The new framework is a research-based comprehensive list of explicitly circular environmental indicators for ARCH. CE indicators for ARCH are examined in the context of the existing and forthcoming decision-making landscape in Europe. The framework has practical application to the European Union (EU) CE regimes for existing buildings, particularly ARCH.

European buildings are strikingly resource-intensive, responsible for 40% of Europe's consumed energy each year [1]. From a life-cycle perspective, European buildings generate: "40% of greenhouse gas emissions; half of raw materials; and a third of water consumption" [2]. As a result, this sector is critical for the transformation to a sustainable economy in Europe. The renovation of

existing buildings, including ARCH, is central to achieving climate change, clean energy, resource efficiency and material reduction goals. The stock of ARCH buildings "holds unique significance to the past, present, and future of human communities—including their environmental impacts" [3].

Circular economy environmental indicators and ARCH

For the purposes of the current study, Circular Economy (CE) is defined as follows:

> *"Circular Economy is a production and consumption process that requires the minimum overall natural resource extraction and environmental impact by extending the use of materials and reducing the consumption and waste of materials and energy. The useful life of materials is extended through transformation into new products, design for longevity, waste minimization, and recovery/reuse, and redefining consumption to include sharing and services provision instead of individual ownership. A CE emphasizes the use of renewable, non-toxic, and biodegradable materials with the lowest possible life-cycle impacts. As a sustainability concept, a CE must be embedded in a social structure that promotes human well-being for all within the biophysical limits of the planet Earth." [4]*

The political framing of CE as sustainability is adopted in Europe despite well-reasoned criticisms of CE as: an untested economic theory; prone to co-optation by financial interests; cornucopian; a window-dressing for business-as-usual; lacking in theoretical explanation; focused on recycling; and an empty promise of decoupling consumption from economic growth [5–8]. Another criticism is that CE falls short of today's theories of sustainability and transition. Whereas sustainability now incorporates social justice and equality, in addition to protecting ecosystems, CE does not readily address these important issues. Kirchherr et al. [9] found that only 18–20% of the 114 definitions of CE included "social equity". CE's roots are in industrial ecology and waste reduction; therefore, it is not an advanced and comprehensive sustainability concept. Although the CE concept is challenged in the literature as too narrowly defined, it is increasingly adopted in European politics and policy as a sustainability strategy, without due consideration of non-environmental aspects. Without disregarding the principle that "CE must be embedded in a social structure that promotes human well-being for all" [4], the scope of the present study is limited to the environmental impacts of existing buildings and ARCH. The scope of the article corresponds to the current political and policy framing of CE in Europe for buildings (described below) that targets environmental rather than social aspects.

Notwithstanding this article's environmental focus, it is clear that social equity and social inclusion are relevant to ARCH in Europe because of the need to democratize access to cultural heritage as a common good [10, 11]. Further, rehabilitation of underused buildings is often accompanied by an increase in housing cost and gentrification. This article is a result of the EU Horizon 2020 research project "Circular models Leveraging Investments in Cultural heritage adaptive reuse (CLIC)". CLIC includes non-environmental aspects of CE for ARCH, a topic that other colleagues are addressing in other publications. It is imperative that social equity and social inclusion are not ignored as the EU applies CE to ARCH.

In 2015, the EU launched its CE Action Plan, which states "The transition to a more circular economy, where the value of products, materials and resources is maintained in the economy for as long as possible, and the generation of waste minimized, is an essential contribution to the EU's efforts to develop a sustainable, low carbon, resource efficient and competitive economy." [12]. The 2019 Green New Deal calls for a CE-inspired "wave of renovation" of existing buildings. The 2020 EU CE Action Plan reiterates CE for renovation of existing buildings and announces the EU's "Strategy for a Sustainable Built Environment" [13]. Furthermore, there are two additional European Commission macro-level policies like CE, Resource Efficiency and the Energy Union Strategy, that together are setting a new path forward for the construction and building sector. These macro policies employ environmental indicators to manage and measure policy success or failure.

Environmental indicators are essential tools of environmental and sustainability policy. The choice of indicators defines how environmental management and policy are implemented at all levels. EU policy relies on aggregate and country-level indicators that are relevant to ARCH. The EU aggregate macro-level indicators for measuring the CE are published by the European Union's office of statistics, Eurostat. The first relevant aggregate indicator (which is also available for each country) is the circular material use rate, which is a percentage of total material use.

> *"The indicator measures the share of material recovered and fed back into the economy—thus saving extraction of primary raw materials—in overall material use. The circular material use, also known as circularity rate is defined as the ratio of the circular use of materials to the overall material use. (....) A higher circularity rate value means that more secondary materials substitute for primary raw mate-*

rials thus reducing the environmental impacts of extracting primary material" [14].

The most recent use rate for Euro-27 countries was in 2017 at 11.2 percent [14]. The second aggregate indicator relevant to ARCH is the "contribution of recycled materials to raw materials demand—end-of-life recycling input rates", including aggregates, aluminium, and lime [15]. The purpose of these indicators is to track the use of secondary raw materials.

"use of secondary raw materials [that] can help to improve the EU's security of supply, reduce the extraction pressure on natural resources—and therefore, reduce related pressures on the environment, and contribute to developing a solid CE at sub-national, national and European scales" [16].

Aggregate measures incorporate diverse waste streams and policy instruments. Eurostat publishes disaggregated indicators for each EU country relevant to ARCH, for example the recovery rate of construction and demolition waste. The complete list of CE indicators can be found on the Eurostat webpage [17].

European macro-level policies directly affect the micro-level management of environmental impacts of existing building renovations and reuse projects. Achieving CE at the building project level at sufficient scale across Europe will determine if the macro-level policies are successful. The present study shows that the environmental indicators for the refurbishment of existing buildings, specifically the adaptive reuse of cultural heritage buildings, remains an unfilled gap in Europe's CE policy. The lack of explicitly CE environmental indicators for adaptive reuse of cultural heritage buildings persists for three reasons:

- First, the micro-level (building project-level) indicator regimes of the past were not explicitly CE, and these have not yet been adjusted to the fast-moving political macro-level CE movement in Europe.
- Second, although existing buildings are targeted at the macro-level, ARCH buildings represent a recent shift in preservation practice. Today, ARCH is motivated by preservation and restoration and reuse and sustainability. This logic shift is evidenced by the 2018 "Leeuwarden Declaration", which is endorsed by the organizations Architect's Council of Europe, Future of Religious Heritage, Europa Nostra and others. The Leeuwarden Declaration endorses adaptive reuse of built heritage and emphasizes the economic, cultural, social, and environmental opportunities of ARCH [18].
- Third, consistent with the many different definitions and conceptualizations of CE, there are several CE indicator schemes and frameworks in the literature [19, 20], yet very few comprehensively include the key principles of CE [21, 22]. As Kristensen and Mosgaard explain, "There is no commonly accepted way of measuring circular economy in general at the micro level" [23]. Similarly, there are no commonly accepted CE indicators for ARCH.

Implementing CE for buildings and ARCH is a difficult task because, in general, CE research "lacks advice" [24]. Likewise, the academic literature on CE for buildings is conceptual, whilst the retrofitting and rehabilitation literature is practical. The full lifecycle environmental impacts of buildings, including ARCH are clear. Current ARCH environmental indicators do not progress the material reduction targets of a CE approach [3]. While the need for a CE approach to ARCH is clear, the choice of which environmental indicators should be used as management tools to implement CE, is not. Closing this gap is vital because a lack of awareness and a lack of practical advice are barriers to implementing CE strategies for buildings, particularly ARCH [4, 25].

The current work addresses the described policy and knowledge gap with policy analysis and environmental indicator development. In brief, the results establish that the macro-level regimes are not well synced with building-level indicators for ARCH and should be improved. The proposed solution is the comprehensive ARCH Circular Environmental Impact Indicator Framework. The framework may be used for setting targets, monitoring, and evaluating the impacts of renovations of existing buildings and ARCH.

The article's remaining sections are organized as follows. The "Methods" section documents the research method and research design of this study. Next, the "Results and discussion" section presents and discusses the findings of the analysis. Finally, the "Conclusions and recommendations" section concludes with the implications and potential uses of this article, new research avenues, and policy recommendations.

Methods

This section provides an overview of the study's research methods, design, and data. Policy analysis is a central purpose of socioeconomic research. It is the process of examining policies that are meant to guide societal progress towards politically decided outcomes. The analysis may critique, challenge, or seek to more efficiently and effectively implement political decisions by improving or complimenting existing policies. According to Blackmore and Lauder [26] "Policy studies does not have a distinctive set of methodologies, but calls upon a range of methodological positions and methods in order to achieve the

most powerful explanations for policy questions". The current article is "research for policy" because the analysis develops an ideal framework of environmental indicators as a research-based policy option [26].

The policy option proposed herein is the ARCH Circular Environmental Indicator Framework. The method for developing this policy option roughly follows Niemeijer and de Groot (2008) "conceptual framework for selecting environmental indicator sets" [27]. This method includes three steps: (1) Define the research question; (2) Identify the causal network; and (3) Select the best indicators [27]. The research design incorporating this method is described below.

Research design

Define the Research Question: As clarified in the introduction, the scope of the study is the environmental indicators that may be used to implement and measure European CE policy for existing buildings and ARCH. The primary research question is, "What are the ideal CE environmental indicators for ARCH?" The secondary research question is, "Are the ideal indicators reflected in existing and developing macro-level EU sustainability policies relevant to ARCH?"

Define the causal network: The causal network is the European environmental policy micro-to-macro landscape that drives environmental outcomes, measured by indicators. For example, increased longevity of whole buildings and building components, reductions to greenhouse gasses, water, and energy are CE goals measured by indicators. The state-of-the-art of the CE indicators most prevalent in ARCH projects (without consideration of the policies that drive them) are published in [3]. The current work identifies existing sustainability micro-level regimes for buildings and ARCH in Europe that drive indicators as: Life Cycle Analysis-based standards; environmental impact assessment; and green building certifications. These sustainability regimes are in flux; therefore, the forthcoming circular green building rating and certification schemes and a new EU project called Level(s) are relevant. The macro-level environmental goals for buildings and ARCH in Europe were outlined in the "Background" section as circular economy, resource efficiency, and low-carbon energy efficiency. The dataset comprises publicly available policy documents representing each environmental regime at the micro- and macro-level. The analysis was carried out between autumn 2019 and spring 2020. A limitation of this study is that the publicly available documents during this period may not reflect the policy statements (public and under development) at the time this article is published.

Define the best indicators: Indicators measure policy progress, success, or failure and assign importance and shape our view of "objective" reality. While pragmatism is necessary, choosing environmental indicators must not be arbitrary. Political prioritization, subjective choices, and data availability concerns must be made transparent [27, 28]. Indicators must be "policy-relevant, reliable, measurable/clearly defined, simple/easily communicated, broad in scope, and limited in number", and have a "transparent and well-defined procedures [to] ensure relevance and validity of an assessment" [28].

The underlying principles of the CE indicators chosen are related to cultural heritage and healthy ecosystems. The planetary boundaries concept proposes that human provisioning systems rely on healthy ecosystems [29]. The current use of natural resources and resultant environmental impacts of the European construction and building sector are unsustainable, harmful and must change. Preserving European cultural heritage buildings is essential to transitioning to a sustainable economy. Using monetary proxies and market-based indicators for environmental impacts implicitly places monetary considerations above environmental outcomes [30]. Further, monetary valuations of ecosystems health and cultural heritage have failed to preserve either; therefore, are rejected as reliable indicators of CE. Given the principles of indicator selection stated above, the framework's indicators were selected based on the literature reviewed by Foster (2020) and Foster and Kreinin (2020) [3, 4]. The starting point was the list of most prevalent CE indicators [3]. Additional indicators were chosen to achieve the environmental and cultural goals of the causal network. Each indicator of the ARCH Circular Environmental Indicator Framework is defined according to its CE goal, scope, and unit of measure. In a final step, the ideal indicators were then compared to macro-level EU sustainability policies to identify omissions.

In summary, the research design is a coherent strategy to conduct the policy analysis and develop the framework of indicators for ARCH. The next section presents and discusses the results of the policy analysis.

Results and discussion

Analysis of current and forthcoming environmental indicators for ARCH

This section provides the research results of the analysis of building project-level environmental indicators that are best practice in Europe today. Current and emerging best practice is explained, and representative documents are analysed to create a benchmark for environmental and cultural heritage regulation and practice. The section presents the findings for Life Cycle Analysis (LCA), Environmental Impact Assessment (EIA), and Green Building Certifications (GBCs) as well as emerging best-practice models (Building Research Establishment Environmental

Assessment Method (BREEAM) with CE, and Level(s)). Table 1 summarizes the findings.

Life Cycle Analysis-based international standards: LCA underpins the theoretical CE concept. The fundamental CE principle, reducing the need for extracting virgin materials from the environment, is grounded in LCA. In theory, LCAs quantify the total environmental footprint of a building. There are many published LCA methods and software packages (a full discussion of their uses for buildings is beyond the scope of this study). The use of LCA in the building sector can assist decision-making regarding rival building designs [31]. In addition, LCA thinking underpins international standards (i.e. ISO standards) for building sustainability.

Core indicators for the ecosystem and natural resources domains are set out in "ISO 212929-1:2011 Sustainability in building construction" [32]. These are global warming potential, ozone depletion potential, non-renewable resource consumption, fresh water consumption, waste generation, access to facilities such as public transport, adaptability and maintainability [32]. Consistent with the international standards, the European Standards for buildings and building products rely on LCA. These are "EN 15978:2011 Sustainability of construction works—Assessment of environmental performance of buildings—Calculation method" and "EN 15804:2012: Sustainability of construction works—Environmental product declarations—Core Rules for the product category of construction products." These standards are criticized for being too narrow, and not including common environmental impact categories ordinarily included in LCA tools [33].

The LCA-based indicators in international standards align with CE and the CE indicators in actual ARCH projects. For example, Cultural heritage is listed as one of a building's "core area of protection" and adaptation and refurbishment are included (ISO212929:2011). Also, recovery, reuse and recycling are noted as waste management options [32]. Therefore, these standards are relevant to ARCH.

Environmental impact assessment: For the building and construction sector and particularly for ARCH, EIAs differ from the LCA-based standards because an EIA is usually a legislated and/or regulatory requirement rather than a voluntary exercise. EIAs are usually triggered by the type, size, or location of a proposed project. These rules are primarily for industrial facilities and major infrastructure projects. An EIA may apply LCA tools (software), physical tests, and additional analyses. EIAs are designed to establish a baseline environmental performance (footprint) and desired outcomes. They may also include a comparison of alternative approaches. Further, an EIA is used as a vehicle for public consultation during its development as well as consideration of the projects' impacts. EIA development and consideration are an integral step in the decision-making process (permitting) for large projects. The EU Directive 2014/52/EU is the latest version of the EIA rules in Europe. Environmental impacts and cultural heritage impacts are included under Article 3 [34].

Most EIA formats include cultural heritage and are designed to protect it. However, they are not explicitly circular. The EU Directive on Environmental Impact Assessment states the following as one of its purposes.

> *"For the protection and promotion of cultural heritage comprising urban historical sites and landscapes, which are an integral part of the cultural diversity that the Union is committed to respecting and promoting (…) the definitions and principles developed in relevant Council of Europe Conventions…* **In order to better preserve historical and cultural heritage and the landscape, it is important to address the visual impact of projects, namely the change in the appearance or view of the built or natural landscape and urban areas, in environmental impact assessments**." *(emphasis added) [34]*

Generally, and as applied to ARCH, EIAs for historic buildings, for example in city centres, are determined by local and national legislation and/or regulation. An example is Scotland, which requires an EIA for major housing estates and "Urban development projects, including the construction of shopping centres and car parks, sports stadiums, leisure centres and multiplex cinemas" [35]. The ARCH literature includes many examples of reuses of historic buildings. Many developers commission EIAs voluntarily because an EIA assists them to better understand the proposed project and communicate that to the community and local permit authorities.

EIA requirements change over time to reflect current societal concerns expressed as policy. For example, the 2014 update of the EU Directive on EIA states that analyses for decision-making should include "environmental issues, such as resource efficiency and sustainability, biodiversity protection, climate change, and risks of accidents and disasters, [that] have become more important in policy making" [36]. The full range of environmental impacts are included in a standard EIA for an ARCH project in Europe.

CE is not explicitly mentioned in the current EIA Directive. This may reflect the timing of the latest EIA Directive amendment of 2014. The EU Action Plan for CE was not adopted until 2015 and the key elements of the package including the monitoring framework were released in 2018 [12]. The amendment does have the specific goal of increasing resource efficiency in line

Table 1 This table summarizes the results of the analysis of existing and emerging micro-level regimes for buildings and ARCH discussed in the "Analysis of current and forthcoming environmental indicators for ARCH" section. The table shows the prevalence or absence of common circular environmental indicators in each of the regimes

Comparison of current circular environmental indicators [3] to current and developing environmental indicators relevant for ARCH				
	Life Cycle Analysis-based standards [32]	**Environmental Impact Assessment [36]**	**Green Building Certifications (w/CE) [37]**	**Level(s) [38]**
The current CE indicators prevalent in ARCH building projects in [3]				
1. Indicators of direct reductions to new natural materials extraction due to the adaptive reuse				
Maintain embodied energy in reused concrete, stone, brick, steel, etc. (CO_2 equiv. GHGs per ton avoided or tons avoided/reused)	Should include the entire life cycle (all phases including deconstruction); however, it depends on the LCA boundary. For example, the construction phase of an existing building may be excluded. Theoretically, this indicator is included as Global Warming Potential	Although energy and emissions during construction operation and decommissioning are included, embodied energy in reused materials is not explicitly included	Included, under minimize energy consumption, "During the design phase, elements, components and/or materials are selected by the least amount of embodied energy."	Indicator "1.2 Life cycle Global Warming Potential kg CO_2 equivalents per square meter per year (kg CO_2 eq./m^2/yr.)." This applies to separate phases of the life cycle. Cumulatively, all life cycle would apply to ARCH
Increase water efficiency/freshwater consumption (kilolitres/person/year)	Included as amount of fresh water consumed	Water efficiency is included under raw materials efficiency	"Minimize water consumption" is an explicit strategy	"3.1 Total water consumption m^3 of water per occupant per year" allows for establishing a baseline and tracking change
Reduce C&D waste to landfill through recovery and reuse on or off-site (tons or cubic meters)	Includes type(s) of wastes	The description of the project includes type and quantity waste produced during construction in line with EU Waste Framework Directive	The indicator "landfill/unknown: % of volume that goes to landfill or of which the destination is unknown, including Corresponding volume/weight" is included under "inventory of existing real estate."	"2.3 Construction and demolition waste and materials kg waste and materials per m^2 of total useful floor area (per life cycle and project stage reported on)"
Increase land use efficiency due to the adaptive reuse (square meter reductions to space requirements of new purpose)	Material flow reductions would capture this indicator if a comparison of alternate project designs were made. Otherwise, the material flows are calculated as part of the LCA	Included generally, but not specifically under resource efficiency of land. Unlikely to cover the efficient use of building space generally	Included in strategy, "M.1.1.2—A feasibility study is performed on the possibilities of minimizing the square meters…"	Level(s) includes a simplified LCA with which compares the buildings' useful space over its lifetime to the bill of materials. Also, it includes scenarios that are designed to assess the adaptive reuse potential For office buildings, users' space requirements are included
2. Indicators of direct reductions to energy use due to the adaptive reuse				
Greenhouse gas emissions (CO_2 equiv. GHGs tons/year)	Global Warming Potential	Greenhouse gases emitted or avoided using LCA	Included in energy cycle	Indicator "1.2 Life cycle Global Warming Potential kg CO_2 equivalents per square meter per year (kg CO_2 eq./m^2/yr.)
Increase energy efficiency/consumption per (megawatt hours or kilojoule/user/year)	Energy flows are calculated under Global Warming Potential	Energy efficiency is included	Included under minimize energy, "The building consumes during the use phase a minimal amount of energy."	Included as "1.1 Use stage energy performance. 1.1 Use stage energy performance-kilowatt hours per square meter per year (kWh/m^2/yr.)"

Table 1 (continued)

Comparison of current circular environmental indicators [3] to current and developing environmental indicators relevant for ARCH				
	Life Cycle Analysis-based standards [32]	**Environmental Impact Assessment [36]**	**Green Building Certifications (w/CE) [37]**	**Level(s) [38]**
Increase amount of non-renewable vs. renewable energy use. Potentially achieving a net zero carbon or energy producing building (megawatt hours or kilojoules)	Amount of non-renewable energy consumed, and renewable energy consumed are reported	Included under "Resource Use Indicators."	Included in sustainable and local energy, with the goal of supplied electricity and heat being 100% renewable	Renewable energy is noted separately in the primary energy calculation above
3. Indicators of direct environmental improvements due to the adaptive reuse				
Reductions to air emissions including CO_2, nitrogen oxides (NO_x), sulphur oxides (SO_x), and particulate matter	Direct emissions to air are included at all phases of the life cycle	Included under "gaseous and particulate emissions generated by the project"	These could be included in the sub-strategy, "Prevent pollution during construction, use phase and deconstruction." (…) "However, the indicators are not yet elaborated."	Other than CO_2, the air quality indicators seem to be focused on outdoor air pollution as a source of indoor air quality
Improve water quality measured as eutrophication potential based on nutrient loads (phosphorous or nitrogen g/litre or dissolved oxygen)	Water quality measured as eutrophication and acidification potential are included	Water quality, specifically eutrophication, is included	Not included. The water strategies focus on minimizing freshwater use	Included in the LCA, particularly eutrophication. Otherwise, water consumption/efficiency is measured
4. Indicators of indirect reductions to energy use or pollution due to the adaptive reuse				
Maintain embodied energy in reused concrete, stone, brick, steel, etc. (CO_2 equiv. GHGs per ton avoided)	Included in the Global Warming Potential as noted above	Although energy and emissions during construction operation and decommissioning are included, embodied energy in reused materials is not explicitly included	This indicator is relevant to the material minimization, reuse, and recycling indicators, "M.1.1—Reduce amount of materials", M.2.1—Maximise amount of reused materials" and "M.3.1—Maximise amount of renewable materials", "M.4.1.1—A building material passport…"	The indicator is embedded in the 2.3 Construction and Demolition waste estimates. Level(s) uses a scenario analysis to estimate the quantity of materials for reuse, recycling, and recovery
Limit land use change (farmland maintained or reduction to urban sprawl in hectares)	Measures land use change avoided (conversion of land not previously built on)	Included under project description, "Baseline: Aspects of the Environment", and "Prediction of Direct Effects." The land use change can be calculated from the two required aspects	Not included in the CE Indicators. It is part of the current BREEAM	"Direct land use change" is part of the global warming potential calculation. It is not a standalone indicator
Indirect emission reductions due to the adaptive reuse, e.g., reduction in vehicle use (CO_2 equiv. GHGs per year avoided)	Can be included under "Access to services" referring to access to public transport for occupants	Included as "Transport infrastructure: increased or avoided carbon emissions associated with energy use for the operation of the Project."	Not included in the CE Indicators. The BREEAM communities' tool is for master planning	Not included

with the "Roadmap to a Resource Efficient Europe" that was available at the time.

Green Building Certifications: All major Green building rating and certification schemes (GBCs) apply to cultural heritage buildings. Two well-known GBCs are Leadership in Energy and Environmental Design (LEED) and Building Research Establishment Environmental Assessment Method (BREEAM). In general, refurbishments of historic buildings are assessed and rated in the same way as non-historic buildings, while there are often extra points for historic or listed buildings. For example, BREEAM 2014 provides a separate scale for benchmarking heritage buildings' energy demand that includes extra points for implementing a report by a heritage specialist. However, the GBCs may obscure specific CE goals because they tend to provide a single aggregate assessment, such as number of points, or gold or silver designation. For example, how much the project eliminated waste could not be known by the aggregate assessment.

New Emerging Regimes—BREEAM with CE and Level(s): There are two current initiatives that are likely to impact the CE indicators for buildings and ARCH landscape in Europe and worldwide. Both are advanced, have been released to the public, and are currently undergoing testing. The first is the initiative "A framework for Circular Buildings—indicators for possible inclusion in BREEAM" hereinafter referred to as BREEAM. The second is Level(s), an EU initiative that is "a reporting framework to improve the sustainability of buildings" that explicitly uses CE [37].

It is likely that in future the GBCs will incorporate specific CE indicators. The scope and reach of BREEAM and other GBCs such as LEED, particularly for ARCH, are likely to make the CE developments in this branch of the building and construction sector impactful. BREEAM—The BREEAM report was written by a consortium of organizations working to expand CE [37]. The original BREEAM (which applies to building refurbishment) has issued building certifications for over 500,000 buildings and operates in 83 countries. The report proposes a definition of a circular building as:

> *"A building that is developed, used and reused without unnecessary resource depletion, environmental pollution and ecosystem degradation. It is constructed in an economically responsible way and contributes to the wellbeing of people and the biosphere. Here and there, now and later. Technical elements are demountable and reusable, and biological elements can also be brought back into the biological cycle" [37].*

Level(s)—The EU Commission's sustainable building reporting framework, published in 2017, is developing common EU indicators for the resource efficiency of buildings (office and residential) [38]. Level(s) provides a set of common indicators and metrics for measuring the environmental performance of office and residential buildings, "which considers their full lifecycle impacts" [39]. It is indicator driven, with the following key indicator areas: "greenhouse gas emissions, resource efficiency, water use, health and comfort, resilience and adaptation, and cost and value" [39]. Level(s) is intended to underpin a new EU regulatory initiative and "is not just a voluntary performance reporting framework—it provides a foundation for European sustainable building policy" [39].

Level(s) is designed for major renovations of residential and office buildings in Europe but does not target cultural heritage. The review of publicly available material indicates that cultural heritage is not explicitly addressed in Level(s). Nevertheless, the scope of Level(s) is sufficiently broad that it would apply to cultural heritage buildings too. Also, the Beta v1.1 version of Level(s) currently being tested contains indicators and tools that directly apply to ARCH. Explicit inclusion of cultural heritage is preferable and it would bring Level(s) in line with the existing regimes.

Level(s) can help mainstream CE indicators if it becomes a "common language" for sustainable buildings [40]. If Level(s) becomes a new EU regulatory initiative, it will mainstream CE as EIAs mainstreamed LCA. In addition, Level(s) and GBCs are already linked. The EU reports that "Certification tools including BREEAM (UK/NL/Spain/Norway/Sweden/Germany/International), DGNB (Germany), HPI (Ireland), HQE (France) and Verde (Spain) support the development of Level(s), and all have stated their intention to explore alignment between their schemes and Level(s)" [40]. According to its website, Level(s) was released for testing in April 2018. The 2-year testing and public consultation will be concluded in 2020.

The results of the indicator analysis are summarized in Table 1. The CE indicators for ARCH per Foster and Kreinin [3] appear in the left column. The next four columns document the presence, absence, or similarities of these with indicators in the four regulatory/practice regimes (LCA, EIA, GBC with CE, and Level(s)). The table provides an overview and a crosscutting view of the causal network for building project-level CE indicators for ARCH.

ARCH circular environmental indicator framework

This section describes the ARCH Circular Environmental Indicator Framework. In addition, it presents the results

Table 2 This table presents the new ARCH Circular Environmental Impact Indicator Framework comprising 20 indicators shown in the first three columns. In addition, the table summarizes the results of the analysis of European macro-level policies relevant to implementng CE for buildings and ARCH. The table shows that several essential micro-level indicators are not captured at the macro-level

Comparison of ARCH Circular Environmental Indicator Framework (micro-level) to relevant indicators of EU Policy Initiatives (macro-level)					
ARCH Circular Environmental Indicator Framework Micro-level These 3 columns show the ideal CE indicators for an ARCH building project. Each indicator is explained with its unit, CE goal, and scope			**EU Policy Initiatives Macro-level These 3 columns show if the ideal CE indicators for ARCH are present or not Exemplar documents appear in brackets**		
Indicator and unit of measure	**CE goal of indicator**	**Scope**	**Relevant indicator if included in EU resource efficiency scoreboard? [42]**	**Relevant indicator if included in EU CE indicators? [17]**	**EU Energy Union indicators [43]**
	Reduce environmental pollution, reduce extraction of materials, regenerative capacity, reduce energy and water consumption, encourage low-carbon energy, replace fossil fuels, limit land-use change	**Energy and climate change, water, land, air, waste generation, ecosystems and biodiversity conservation, heritage conservation**			
1. Indicators of direct reductions to new natural materials extraction due to the adaptive reuse					
Maintain embodied energy in onsite reused concrete, stone, brick, steel, etc. (CO_2 equiv. GHG tons/year avoided or avoided/reused)	Reduce extraction of materials, reduce energy consumption, encourage low-carbon, replace fossil fuels	Energy and climate change	Domestic material consumption per capita (tons)	Recovery rate of construction and demolition waste (percentage)	None
Reuse materials and objects onsite Description and volume (kg/metric tons/m^3) (input)	Reduce extraction of materials	Waste	Domestic material consumption per capita (tons) Generation of waste (excluding major mineral wastes) (kg/capita)	Generation of municipal waste per capita (kg per capita) End-of-life recycling input rates (EOL-RIR) (percentage) The circular material use rate (CMU rate) is defined as the ratio of the circular use of materials (U) to the overall material use (M) CMU = U/M where domestic material consumption (DMC) M = DMC + U Macro-financial measures Generation of waste excluding major mineral wastes per GDP unit (kg/thousand euro, chain linked volumes (2010))	None
Traditional and/or biomass and/or local sustainable materials description and volume (kg/metric tons/m^3)	Reduce extraction of materials Low carbon energy	Energy and climate change, Ecosystem and biodiversity Heritage Conservation	None	None	None

Table 2 (continued)

Comparison of ARCH Circular Environmental Indicator Framework (micro-level) to relevant indicators of EU Policy Initiatives (macro-level)					
ARCH Circular Environmental Indicator Framework Micro-level These 3 columns show the ideal CE indicators for an ARCH building project. Each indicator is explained with its unit, CE goal, and scope			**EU Policy Initiatives Macro-level These 3 columns show if the ideal CE indicators for ARCH are present or not Exemplar documents appear in brackets**		
Indicator and unit of measure	**CE goal of indicator** **Reduce environmental pollution, reduce extraction of materials, regenerative capacity, reduce energy and water consumption, encourage low-carbon energy, replace fossil fuels, limit land-use change**	**Scope** **Energy and climate change, water, land, air, waste generation, ecosystems and biodiversity conservation, heritage conservation**	**Relevant indicator if included in EU resource efficiency scoreboard? [42]**	**Relevant indicator if included in EU CE indicators? [17]**	**EU Energy Union indicators [43]**
Increase water efficiency/freshwater consumption (litres/person/year)	Reduce water consumption	Water	Macro-financial measures Water exploitation index and water productivity EUR/m^3 fresh water abstracted (PPS/m^3 fresh water abstracted)	Reducing freshwater consumption could be captured by this indicator for reused water. The circular material use rate (CMU rate) is defined as the ratio of the circular use of materials (U) to the overall material use (M) (M = DMC + U)	None
Implement water collection, storage and reuse systems onsite—volume of water (litres/person/year) ALSO: recovered water consumption	Reduce water consumption Regenerative capacity	Water	None	The circular material use rate (CMU rate) is defined as the ratio of the circular use of materials (U) to the overall material use (M) (M = DMC + U), so collecting and reusing water can be captured here	None
Reduce C&D waste to landfill through recovery and reuse on or off-site (kg/metric tons/m^3 avoided)	Reduce extraction of materials Regenerative capacity	Waste	Landfill rate of waste (excluding major mineral wastes) (% of total waste)	Macro-financial measure Generation of municipal waste per capita (kg per capita) Generation of waste excluding major mineral wastes per GDP unit (kg/thousand euro, chain linked volumes Generation of waste excluding major mineral wastes per domestic material consumption (percentage)	None

Table 2 (continued)

Comparison of ARCH Circular Environmental Indicator Framework (micro-level) to relevant indicators of EU Policy Initiatives (macro-level)					
ARCH Circular Environmental Indicator Framework Micro-level These 3 columns show the ideal CE indicators for an ARCH building project. Each indicator is explained with its unit, CE goal, and scope			**EU Policy Initiatives Macro-level These 3 columns show if the ideal CE indicators for ARCH are present or not Exemplar documents appear in brackets**		
Indicator and unit of measure	**CE goal of indicator** **Reduce environmental pollution, reduce extraction of materials, regenerative capacity, reduce energy and water consumption, encourage low-carbon energy, replace fossil fuels, limit land-use change**	**Scope** **Energy and climate change, water, land, air, waste generation, ecosystems and biodiversity conservation, heritage conservation**	**Relevant indicator if included in EU resource efficiency scoreboard? [42]**	**Relevant indicator if included in EU CE indicators? [17]**	**EU Energy Union indicators [43]**
Increase land use efficiency due to the adaptive reuse (square meter reductions to space requirements of new purpose)	Reduce extraction of materials, reduce energy and water consumption, limit land-use change	Energy and climate change, water, land	This is a financial measure not suited to the micro-level. Productivity of artificial areas (million EUR (PPS)/km^2.) Built up areas (km^2/% of total land)	None	None
2. Indicators of direct reductions to energy use due to the adaptive reuse					
Greenhouse gas emissions (CO_2 equiv. GHGs tons/year)	Reduce energy consumption, encourage low carbon energy	Energy and climate change	Greenhouse gas emissions per capita (tons CO^2 equivalent/capita)	None	GHG intensity (tons CO_2 eq/million EUR, 2010 prices) Greenhouse gas emissions reductions, base year 1990 (Unit: %)
Increase energy efficiency/consumption per (kWh/user/year)	Reduce energy consumption	Energy and climate change	Macro-financial measure Energy productivity (EUR or PPS/kg of oil equivalent)	None	Primary and final energy consumption (Mtoe/capita) Final energy consumption per m^2 in residential sector, at normal climate (kgoe/m^2)
Increase amount of non-renewable vs. renewable energy use (% of kWh/user/year from renewable sources on or off-site)	Reduce energy consumption, encourage low carbon energy	Energy and climate change	Share of renewable energy in gross final energy consumption (%) Final energy consumption in households by fuel (%)	None	Share of renewable energy in gross final energy consumption (Unit: %)

Table 2 (continued)

Comparison of ARCH Circular Environmental Indicator Framework (micro-level) to relevant indicators of EU Policy Initiatives (macro-level)

ARCH Circular Environmental Indicator Framework Micro-level These 3 columns show the ideal CE indicators for an ARCH building project. Each indicator is explained with its unit, CE goal, and scope			**EU Policy Initiatives Macro-level These 3 columns show if the ideal CE indicators for ARCH are present or not Exemplar documents appear in brackets**		
Indicator and unit of measure	**CE goal of indicator** **Reduce environmental pollution, reduce extraction of materials, regenerative capacity, reduce energy and water consumption, encourage low-carbon energy, replace fossil fuels, limit land-use change**	**Scope** **Energy and climate change, water, land, air, waste generation, ecosystems and biodiversity conservation, heritage conservation**	**Relevant indicator if included in EU resource efficiency scoreboard? [42]**	**Relevant indicator if included in EU CE indicators? [17]**	**EU Energy Union indicators [43]**
3. Indicators of direct environmental improvements due to the adaptive reuse					
Reductions to air emissions including CO_2, nitrogen oxides (NO_x), sulphur oxides (SO_x), and particulate matter (micrograms per cubic meter)	Reduce environmental pollution	Air	Urban population exposure to air pollution by PM2.5 and 10 (ug/m^3)	None	None
Improve water quality measured as eutrophication potential based on nutrient loads (phosphorous or nitrogen g/litre or dissolved oxygen)	Reduce environmental pollution regenerative capacity	Water	None for water specifically, as the indicator focuses on run-off from agricultural land Gross nutrient balance in agricultural land—nitrogen and phosphorous (kg/ha)	None	None
Improvements to water, air, or soil pollution, e.g., brownfield remediation (identify pollutant(s) and concentration in ppm)	Reduce environmental pollution	Water, land, air	Air pollutants and water pollutants as noted (PM, phosphorous, nitrogen, etc.)	None	None
Implement natural heritage conservation of site (legally protected landscape m^2 or hectares and % of project)	Limit land-use change	Land, ecosystems and biodiversity, heritage conservation	None	None	None
Provide habitat for specific endangered or culturally relevant species (description of species and impact)	Limit land-use change regenerative capacity	Land, ecosystems and biodiversity, heritage conservation	None. Focuses instead on common farmland bird species and landscape fragmentation (number of meshes per 1 000 km^2)	None	None

Table 2 (continued)

Comparison of ARCH Circular Environmental Indicator Framework (micro-level) to relevant indicators of EU Policy Initiatives (macro-level)

ARCH Circular Environmental Indicator Framework Micro-level These 3 columns show the ideal CE indicators for an ARCH building project. Each indicator is explained with its unit, CE goal, and scope			**EU Policy Initiatives Macro-level These 3 columns show if the ideal CE indicators for ARCH are present or not Exemplar documents appear in brackets**		
Indicator and unit of measure	**CE goal of indicator** **Reduce environmental pollution, reduce extraction of materials, regenerative capacity, reduce energy and water consumption, encourage low-carbon energy, replace fossil fuels, limit land-use change**	**Scope** **Energy and climate change, water, land, air, waste generation, ecosystems and biodiversity conservation, heritage conservation**	**Relevant indicator if included in EU resource efficiency scoreboard? [42]**	**Relevant indicator if included in EU CE indicators? [17]**	**EU Energy Union indicators [43]**
Implement cultural heritage preservation designation of site (legally protected building and/or landscape m^2 or hectares and % of project)	Limit land-use change	Land, ecosystems and biodiversity, heritage conservation	None	None	None
4. Indicators of indirect reductions to energy use or pollution due to the adaptive reuse					
Maintain embodied energy in off-site reused concrete, stone, brick, steel, etc. (CO_2 equiv. GHG tons) avoided	Reduce extraction of materials, reduce energy consumption, encourage low-carbon	Energy and climate change, waste	Domestic material consumption per capita (tons)	End-of-life recycling input rates (EOL-RIR) (percentage)	None
Reuse materials and objects off-site description and volume (kg/metric tons/m^3) (output)	Reduce extraction of materials	Waste	Domestic material consumption per capita (tons) Generation of waste (excluding major mineral wastes) (kg/capita)	Recycling rate of all waste excluding major mineral waste (percentage)	None
Limit land use change (farmland maintained or reduction to urban sprawl in hectares)	Limit land-use change	Land	Landscape fragmentation (number of meshes per 1 000 km^2)	None	None
Indirect emission reductions due to the adaptive reuse, e.g., reduction in vehicle use (CO_2 equiv. GHG tons/year avoided)	Reduce environmental pollution, limit land-use change	Air, land	Pollutant emissions from transport—NO_x, NMVOC and PM10	None	None

of the analysis of the macro-EU-level environmental indicators. The analyses are summarized in Table 2.

The ARCH Circular Environmental Indicator Framework—the framework's purpose is to address a practice and research gap. A comprehensive and suitable list of explicitly circular environmental indicators for existing buildings, particularly ARCH buildings is not yet available. The Framework focuses on the unique nexus of cultural heritage adaptive reuse and CE; however, the majority of the indicators are valid for any existing building renovation motivated by CE. The Framework is designed to be easy to understand and use. Each indicator is intended for the building project at the micro-level. Direct and indirect impacts due to the adaptive reuse are grouped in separate categories. Implementing the Framework begins with four central assumptions:

1. The cultural heritage significance of the project is already established. Implementing a cultural heritage designation is included, but there are no criteria for doing so herein. There is a mosaic of locally determined rules and practices governing how communities determine cultural heritage significance and possible legal protection.
2. The full lifecycle of the project is analysed. The analysis is backward and forward looking in time from the point of renovation of the cultural heritage project. Therefore, the material and energy input to the original production of the object is considered in addition to the end-of-life stage. Certainly, an LCA is useful here.
3. Most of the data are available through measurement or estimation. This is the pragmatic reason that the analysis began with the most prevalent indicators.
4. An environmental impact rather than a market value approach is desired. Several CE indicators are designed to capture market value of materials and energy. For example, market values are captured as investment, GDP or PPS, or total cost of end-of-life options [20, 23, 41]. The Framework established here corresponds to an EIA or LCA logic, placing environmental impact (rather than economic impact) at the centre.

The Framework's indicators are not all mutually exclusive. For example, the indicator for implementing water collection systems will off-set the indicator for a project's freshwater consumption. For decision-making, alternative ARCH designs may be compared. This concept is in line with the current use of EIAs and LCAs as project evaluation tools. The Framework may be used in decision-making as a standalone tool or in combination with EIAs, LCAs, etc.

Table 2 presents the ARCH Circular Environmental Indicator Framework in its first three columns. There are 20 indicators, spanning direct and indirect impacts. Each indicator is defined with its unit of measure and CE goal and scope. For example, "Reduce Extraction of Materials" is one of the central CE goals. The Framework designates the scope of each indicator (Energy and Climate Change, Water, Land, Air, Waste Generation, Ecosystems and Biodiversity Conservation, or Heritage Conservation). Heritage Conservation applies to both cultural and natural heritage. Legal heritage protection of the site is according to local methods and regulatory processes. The last three columns demonstrate the concurrence or discordance between the Framework and the EU macro-level CE policy initiatives.

Discussion of results

The findings indicate that the majority of the 12 most prevalent ARCH environmental indicators correspond to well-known best practice indicators at the building project level in Europe. In addition, most building project-level regimes in Europe explicitly include provisions for cultural heritage. This is good news for policy-makers hoping to build a culture of circular environmental indicators in the construction and building sector. These findings indicate that ARCH practitioners are somewhat familiar with several CE indicators, because many correspond to the existing best practice in the sector.

On the other hand, the majority of ARCH projects currently do not measure and report environmental indicators at all (Foster and Kreinin [3]). Therefore, there is a knowledge gap amongst practitioners. The findings demonstrate that even the next best practices relevant to CE and ARCH, Level(s) and BREEAM with CE do not fully address the gap. The analysis confirms that:

- Embodied energy and land use change are currently not routinely and consistently reported.
- Energy consumption, efficiency, and focus on renewable energy is important and consistent in all best practice and next practices reviewed.
- Water consumption efficiency and reducing freshwater demand is important and consistent; however, water quality definitions are not consistent.
- Construction and demolition wastes are important in all best practice and next practices reviewed.
- The scope of the project's LCA matters in terms of what building life cycle phases are included.
- The project boundary (building only or surrounding environment) matters if indirect impacts including emissions to air and urban sprawl reduction impacts are calculated.

Level(s) and BREEAM with CE, and other GBCs, should highlight cultural heritage and community participation. For example, Level(s) is broad enough to include ARCH but does not specifically mention cultural heritage. It is critical that the Level(s) initiative specifically addresses adaptive reuse and refurbishment of cultural heritage buildings and cultural heritage zones in urban areas in its indicators and tools, because the EU intends Level(s) as a regulatory rather than voluntary regime. The long lifespan of cultural heritage buildings should be credited, for example, in the calculation of global warming potential. The findings also highlight the omission of public consultation elements in the emerging CE regimes (Level(s) and BREEAM), which is routinely included in EIA processes. Public consultation is particularly important for ARCH as communities determine cultural heritage values, and projects that do not address community concerns are often contested. Focusing on cultural heritage with the participation of neighbours, residents, and users during the planning and review of ARCH buildings should be required by future CE practices.

The analysis of the Framework's indicators correspondence to the Resource Efficiency Scoreboard, CE, and Energy Union indicators found notable differences and omissions:

- The Resource Efficiency Scoreboard is more in line with CE for buildings and ARCH than the EU's current CE indicators. For example, renewable energy, water quality, and land use change are all included in the Resource Efficiency Scoreboard, but not included in the CE indicators.
- Cultural heritage building preservation through designation and natural heritage conservation designation are relevant to achieving a CE. Legal protection of buildings and landscapes meet several CE goals (as shown in Table 2). Natural heritage conservation provides habitat for endangered or culturally relevant species in addition to green and blue space. However, indicators for these designations are under-represented or non-existent in the macro CE policies.
- ARCH often employs traditional, biomass and/or local sustainable materials (often linked to local heritage). These materials tend to be low-carbon alternatives, yet these types of building materials are not highlighted as preferable materials.
- The Resource Efficiency and CE indicators convert environmental indicators into financial proxies by measuring them as a percentage of GDP. Efficiency and impact are defined as intensity of wealth/capital deployed. The authors recommend per capita or per area (e.g., hectares) indicators to measure efficiency or intensity for environmental aspects. The financial measures at the macro-level are not down-scalable to the micro-level.
- The regenerative capacity of ARCH projects, such as water collection, renewable energy generation, and habitat conservation are currently not captured at the EU level. A common understanding of regenerative capacity for CE would be helpful for practitioners.

In summary, this study finds that the current EU CE indicators are too narrow at the macro-level to effectively guide the micro-level indicators for ARCH. This is a warning for policy-makers that a deleterious gap in CE policy exists. A bottom-up approach is necessary—as realized in the ARCH Circular Environmental Indicator Framework.

Conclusions and recommendations

The resource intensity of the European building and construction sector is not sustainable. CE, as the current focal point of EU sustainability policy, offers a good framework for integrating environmental concerns into the building and construction sector. An overall reduction of materials and energy employed by the economy for human provisioning to sustainable levels is the central goal of CE. However, reaching this vision of sustainable consumption and production, requires better indicators, measurement and monitoring at the building project level. This article tackles this issue by analysing best practices, voluntary and regulatory regimes in Europe to develop the ARCH Circular Environmental Indicator Framework.

Although ARCH buildings are germane to achieving CE in Europe, several relevant indicators are missing from the reviewed EU CE regimes. For example, reducing air pollution, utilizing traditional/regional materials from biomass, and implementing cultural and natural heritage designations due to adaptive reuse. The results of this study clarify that it is imperative to harmonize, to the extent possible, the multiple EU directives and guidance documents under a common CE umbrella.

The findings of this analysis and the ARCH Circular Environmental Indicator Framework may be used to define CE for ARCH and may assist CE policymakers to harmonize CE indicators for existing buildings. The Framework is proposed as a "bridging device" to connect the micro and macro environmental management levels and connect policymakers to practitioners. A bridging device is particularly valuable when several policy initiatives exist in the same area, as with CE, ARCH, and buildings in Europe.

As a bridging device, the Framework is not intended to replace existing methods of measuring environmental impact such as LCA or EIA. It is a new tool that

targets an important and distinct topic, cultural heritage buildings in Europe. It has several potential uses, for example:

- If an ARCH project does not require a full EIA or LCA, then a project team may use the Framework. It is an accessible and implementable alternative.
- The Framework may be applied to assess the completeness of new CE policy instruments, such as procurement or grant rules for funding ARCH at the municipal or regional level.
- Builders and planners may refer to the Framework in their planning and design efforts, with the caveat that the Framework and this article are limited to environmental impacts. The broader role of ARCH in a sustainable economy, although vital for builders and planners, is beyond the present scope.

In conclusion, the rapid expansion of CE in Europe for buildings will drive new policy and new indicator sets. ARCH should not be left behind. In this light, the following policy recommendations are suggested. EU CE policy for the construction and buildings sector needs to better clarify the concept of "regenerative capacity", specifically, building projects should maintain or increase ecosystem health and biodiversity. More research on this topic is needed to illustrate the regenerative capacity of ARCH. To expand support for renovating cultural heritage buildings for new purposes, EU procurement guidance for office buildings should also be expanded to include mixed-use and residential ARCH. Likewise, municipal procurement policies should explicitly advantage ARCH as the keystone of a circular economy and circular cities in Europe.

Abbreviations

ARCH: Adaptive reuse of cultural heritage; BREEAM: Building Research Establishment Environmental Assessment Method; CE: Circular economy; DMC: Domestic material consumption; EIA: Environmental Impact Assessment; EU: European Union; GBC: Green building certifications; LCA: Life Cycle Analysis; LEED: Leadership in Energy and Environmental Design.

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Authors' contributions

Gillian Foster made substantial contributions to the conception and design of the work, data acquisition, analysis and interpretation of the data, and drafted and revised the work. Halliki Kreinin made substantial contributions to the data acquisition, analysis and interpretation of the data, and revised the work. Sigrid Stagl made substantial contributions to the conception and design of the work and revised it. All authors read and approved the final manuscript.

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