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Circular economy strategies for adaptive reuse of cultural heritage buildings to reduce environmental impacts

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ABSTRACT

Circular economy strategies seek to reduce the total resources extracted from the environment and reduce the wastes that human activities generate in pursuit of human wellbeing. Circular Economy concepts are well suited to the building and construction sector in cities. For example, refurbishing and adaptively reusing underutilized or abandoned buildings can revitalize neighborhoods whilst achieving environmental benefits. Cultural heritage buildings hold a unique niche in the urban landscape. In addition to shelter, they embody the local cultural and historic characteristics that define communities. Therefore, extending their useful lifespan has multiple benefits that extend beyond the project itself to the surrounding area, contributing to economic and social development. To explore this complex issue, the research applies systematic literature review and synthesis methods. Decision makers lack knowledge of the environmental benefits of adaptive reuse of cultural heritage buildings and lack tools to implement these projects. A new comprehensive circular economy framework for the adaptive reuse of cultural heritage buildings to reduce environmental impacts intends to meet these needs. The framework integrates methods and techniques from the building and construction literature that aim to reduce lifecycle environmental impact of buildings with a circular product supply chain approach.

1. Introduction

Today's city planners and city dwellers desire environmentally sustainable and vibrant communities. Resourceful and innovative approaches for the built environment in general and existing buildings in particular are key to accomplishing future sustainability. Urban cultural heritage buildings are of particular interest because they may be underutilized or abandoned; nevertheless, are important for the heritage of local, and possibly international, communities. The unique historic and cultural characteristics of the building(s) are their “heritage”. Heritage extends beyond the project itself to the surrounding area, is often a public or common good, and is recognized for contributions to the economic and social development of the area (Guzmán et al., 2017; Hosagrahar et al., 2016; Rypkema and Cheong, 2011; Throsby, 2009; Vileniske, 2008; Zhang, 2010). Cultural heritage[1] buildings can be former places of religious worship, aristocratic/royal residences, community meeting places, industrial production sites, early modern office buildings, or military objects. It is important to seek sustainable solutions for these buildings in urban development.

A solution proposed by this paper is a comprehensive circular economy (CE) framework for the adaptive reuse of cultural heritage buildings based on a synthesis of the literature. The proposal integrates methods and techniques from the building and construction literature that reduce environmental impact of buildings over their lifecycle with the goals of adaptive reuse of cultural heritage buildings. An adaptive reuse of a cultural heritage project is the retrofit, rehabilitation and redevelopment of one or more buildings that reflects the changing needs of communities. Cultural heritage projects include both legally protected (listed) and unprotected buildings. Although the original purpose of a building is no longer continued, the goal of the project is to maintain the building's distinct historic and cultural character (Binder, 2003). Experts may judge if cultural heritage values are sufficiently preserved (Forsyth, 2013). These projects are often the keystones of unique urban neighborhoods worldwide (Boeri et al., 2016; Girard, 2014; Yung et al., 2017).

This research is motivated by four drivers found in the literature: 1) The CE is a new and compelling strategy to achieve a sustainable economy; 2) The building and construction industry's crucial role in

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[1] “Cultural heritage is an expression of the ways of living, developed by a community and passed on from generation to generation, including customs, practices, places, objects, artistic expressions and values. Cultural heritage is often expressed as either intangible or tangible cultural heritage.” ICOMOS, I.I.C.o.C.T. (2002). ICOMOS international cultural tourism charter: principles and guidelines for managing tourism at places of cultural and heritage significance. International Council on Monuments and Sites, ICOMOS International Cultural Tourism Committee.

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human well-being and high environmental impact; 3) Urbanization trends worldwide underscore sustainable urban planning research; and 4) The existence of significant cultural heritage resources embodied in buildings in urban centers and their potential role in sustainability. The confluence of these drivers for adaptive reuse of cultural heritage sites is an opportunity recognized by the EU Horizon 2020 funded project "Circular models Leveraging Investments in Cultural heritage adaptive reuse" (CLIC),[2] under which this study was undertaken. CLIC's foundation is the thinking of Luigi Fusco Girard and Antonia Gravagnuolo (Girard, 2014; Girard and Gravagnuolo, 2018). Similar themes are acknowledged in the EU Horizon 2020 funded project, "Buildings as Material Banks".[3] The four drivers are briefly described as follows.

1.1. Circular economy

The realization that human activities have caused environmental degradation, destruction of habitats and alterations to ecosystems that endanger human wellbeing, has led to the pursuit of more sustainable strategies, such as the CE (Bruce et al., 1996; EMF, 2013; Korhonen et al., 2018). The common understanding of a product supply chain in economics is linear. A linear supply chain processes natural resources into products that support human wellbeing. Consumers use these products and subsequently dispose them as waste. A CE supply chain model stands in contrast to a linear economy model. There are many definitions of CE in use with different theoretical underpinnings (Kirchherr et al., 2017; Reike et al., 2017). There is no single best option for CE strategies. Many circularity strategies are complimentary and also fit to varying industrial and societal contexts (Moreau et al., 2017) To avoid ambiguity, the current work defines CE and CE strategies as follows.

Circular Economy is a production and consumption processes that require 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 are 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, nontoxic, 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.

1.2. Environmental impacts of buildings

The need for shelter is irrefutably critical to human well-being. The subsequent manufacture, use, and disposal of buildings for shelter is conducted on a massive scale, causing significant consumption of natural resources extracted from the environment and wastes returned to the environment. This demand makes the construction industry the largest consumer of resources and raw materials globally (WEF, 2016). Furthermore, the building industry's greenhouse gas emissions tied to global climate change have risen steadily. The International Energy Agency recently noted that there was a 45% increase in building related emissions since 1990 (IEA 2017). These facts make managing the environmental impacts of buildings, particularly greenhouse gas emissions, critical to achieving a sustainable economy and limiting global warming. In October 2018, the International Panel on Climate Change (IPCC) reviewed options for limiting global warming to 1.5 °C above pre-industrial levels. The IPCC noted that rapid changes to the building sector would be necessary to meet this goal (Rogelj et al., 2018). In 2017, the International Energy Agency unequivocally stressed the daunting sustainability challenge and opportunity of the building sector by stating, "More efficient buildings support the whole energy system transformation." (OECD/IEA, 2017)

1.3. Sustainable urban development

How to sustainably build and manage cities with expanding populations is a vibrant area of research that crosses several academic disciplines such as architecture, economic policy, planning and economics (Andersson, 2006; Hassan and Lee, 2015; Hoornweg and Freire, 2013; Lehmann, 2010, 2011; Lehmann, 2013; Lewin and Goodman, 2013; Quintero, 2013; Rodwell, 2011; Wolch et al., 2014). According to the United Nations' 2018 estimates, fifty-five percent of humans now live in cities (United Nations, 2018). This is an upward trend in many countries (Habitat, 2016). The United Nations' *Urbanization and Development: Emerging Futures* report sets out the following principle "Promoting environmental sustainability… [that] can lead to transformative change when a critical connection is established between environment, urban planning and governance…" (Habitat, 2016) The sustainable urbanization discussion broadly includes culture at the international and regional governmental levels. For example, UNESCO started the "Culture for Sustainable Urban Development Initiative" in 2015. The United Nations Sustainable Development Goal 11, "Make cities and human settlements inclusive, safe, resilient and sustainable", includes the target "Strengthen efforts to protect and safeguard the world's cultural and natural heritage".[4] Likewise, the Urban Agenda for the European Union (Pact of Amsterdam) established in 2016 incorporates cultural heritage as a major aspect of urban development.

Although not all cultural heritage buildings are located in urban areas, the majority of buildings that adaptively reused in future are concentrated in cities. They are critical to sustainable urban development.

1.4. Cultural heritage builds cities

Cultural heritage is a resource for economic development and placemaking movements in urban areas worldwide (Montgomery, 2003; Richards, 2011). For example, major cities, e.g. Paris, Vienna, New York and Dubai, have historic districts that preserve cultural history, anchor functioning commercial districts and attract tourists. "Historic cities possess assets of both cultural and economic values, with high potential for growth in a sustainable perspective." (Girard, 2014) Additionally, cultural heritage sites may or may not be ancient. For example, modern skyscrapers are cultural hallmarks in Malaysia and Hong Kong. Increasingly, culture, cultural heritage and cultural heritage sites and their contributions to sustainable development are the focus of investigation (Dessein et al., 2015; Guzmán et al., 2017; Hill, 2016; Melo, 2012; Soini and Dessein, 2016; Throsby, 2017; Vélez et al., 2016; Wright and Eppink, 2016). Barthel-Bouchier's book Cultural Heritage and the Challenge of Sustainability is a cogent synopsis of the is emerging field (Barthel-Bouchier, 2016). The 2011 UNESCO report, "Recommendation on Historic Urban Landscape" describes the historic urban landscape as follows:

[2] https://www.clicproject.eu/#

[3] https://www.bamb2020.eu/

[4] Available at https://sustainabledevelopment.un.org/sdg11

> "The historic urban landscape is the urban area understood as the result of a historic layering of cultural and natural values and attributes, extending beyond the notion of "historic centre" or "ensemble" to include the broader urban context and its geographical setting. This wider context includes notably the site's topography, geomorphology, hydrology and natural features, its built environment, both historic and contemporary, its infrastructures above and below ground, its open spaces and gardens, its land use patterns and spatial organization, perceptions and visual relationships, as well as all other elements of the urban structure."
>
> UNESCO, Recommendation on the Historic Urban Landscape, including a glossary of definitions, United Nations Educational, Scientific and Cultural Organization Paris, 2011.

The UNESCO recommendation demonstrates that the international community is framing the culture and urbanity debate as complex and intertwined.

1.5. The adaptive reuse nexus

Adaptive reuse of cultural heritage buildings stands at the nexus of the major trends described above and is inherently complex. The significance of the topic is increasingly recognized (Alikhani, 2009; Aytac et al., 2016; Boeri et al., 2016; Bullen and Love, 2011a,b; Camocini and Nosova, 2017; Hein and Houck, 2008; Ijla and Broström, 2015; Rodrigues and Freire, 2017; Wong, 2016). As a nexus issue, adaptive reuse of buildings (with or without cultural heritage values) in urban settings requires transdisciplinary thinking. The transdisciplinary approach taken here draws upon knowledge across disciplines to solve a common multi-faceted problem (a nexus issue).

Current research establishes the environmental benefits from adaptive reuse of buildings, albeit the benefits are not widely espoused in practice. Studies on individual buildings and meta-analyses find significant reductions in energy consumption and related carbon dioxide and other greenhouse gas emissions, fossil fuel consumption, fresh water consumption, and materials use. Multiple analyses concur that adaptive reuse of existing buildings are beneficial for the environment (Assefa and Ambler, 2017; Baker et al., 2017; Bullen and Love, 2010; Elefante, 2007; Kubbinga et al., 2017; Munarim and Ghisi, 2016; Thornton, 2011). The main driver of environmental benefits in the literature is "embodied energy", which is the cumulative energy inputs that were required to construct the building initially (Hammond and Jones, 2008) and process/operational energy consumed during the building's use (Cabeza et al., 2013). Embodied energy calculated as carbon dioxide avoided by reuse, or the carbon dioxide equivalent of the energy and materials used to construct the existing building, takes advantage of a buildings' longevity. The life of buildings in cities can span hundreds of years. Even modern concrete and steel buildings may have considerable lifespans, depending upon maintenance. An important caveat is that although studies show environmental benefits, realizing these benefits is not guaranteed. First, reuse of existing buildings may not completely reduce the need and desire for new construction. For example, spillover effects may result in more buildings being built overall rather than less (Cooper and Gutowski, 2017). Second, the adaptively reused cultural heritage building could fall short of today's expected standards (Bullen and Love, 2011a), for example in comparison to zero-emission buildings. Third, circular strategies and adaptive reuse strategies are perceived as more expensive alternatives to demolition and new construction regardless of environmental and sustainability benefits (Bullen and Love, 2011a; Debacker and Manshoven, 2016) Despite these caveats, the conclusion stands that adaptive reuse of cultural heritage buildings is a win for the environment.

The comprehensive CE framework for the adaptive reuse of cultural heritage buildings proposed herein is original because it aggregates and synthesizes key learnings from disparate sources. In doing so, a new tool is created that may be used for setting strategy, assessment of projects, assessment of government policies, and awareness raising. It is an appropriate strategy for a nexus issue. Building users, project managers, architects, city planners, etc. may also use this framework for collaborative brainstorming. The framework explicitly targets construction industry practitioners of cultural heritage adaptive reuse in addition to academics with the purpose of encouraging more implementation of adaptive reuse strategies across the supply chain. Although the paper addresses a niche, it is relevant to the wider research fields of CE and the general buildings sector.

To understand the importance of the proposed framework and its applications it is important to place it in the context of an ongoing discussion about adaptive reuse of buildings. Section 2 describes the methodology used to bring together diverse fields of research. Section 3 discusses the relevant literature. Section 4 discusses the framework that resulted from this research. Section 5 concludes with thoughts on future research directions.

2. Research methodology

The research methodology consisted of four steps as illustrated in the conceptual framework (Fig. 1): 1) conducting a literature review; 2) selecting a CE framework appropriate to the topic; 3) defining the phases of the buildings life-cycle that best reflects the elements of the industry and possible interventions to realize a CE model; and 4) synthesizing discreet interventions from the literature according to the new model with the goal of achieving fewer material resources consumed and positive environmental outcomes at each phase.

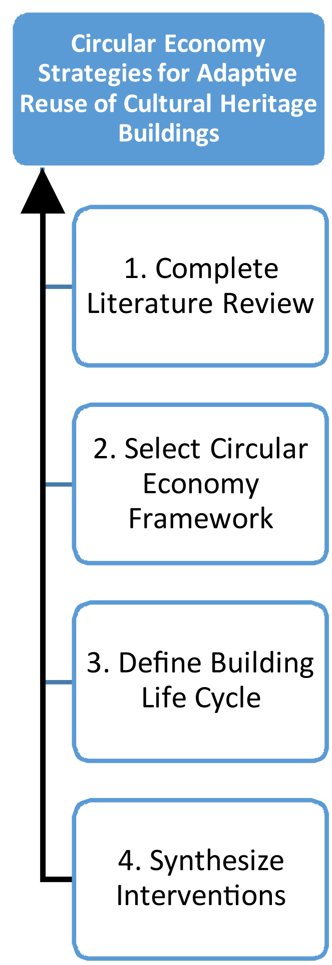

Fig. 1. Conceptual framework of the study.

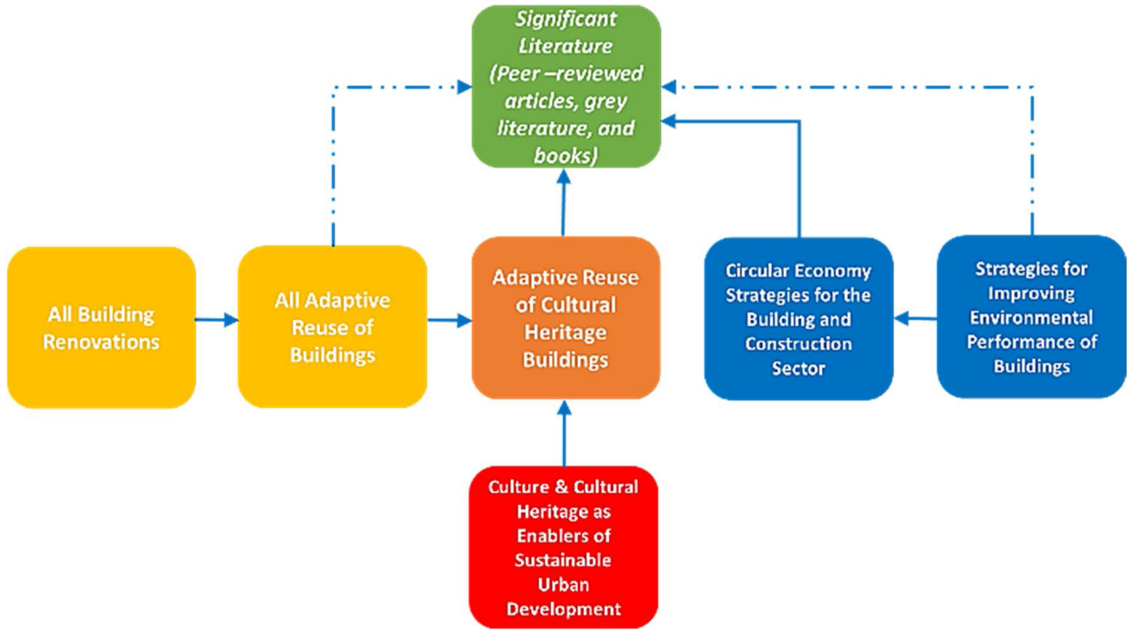

Fig. 2. The literature review process identified the niche of significant literature (green rectangle) (for interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

1) A structured and iterative literature review process was necessary because the topic is new and a niche within a large field of published works. This study relies on secondary sources of evidence; therefore, a rigorous and extensive literature review was crucial. The search for significant and relevant literature lasted from March to September 2018. The literature search of peer-reviewed journal papers and published books utilized several databases (Science Direct, Google Scholar, and Web of Science). In addition, a Web of Science Search Alert was employed between March and August 2018. The key words used to conduct the searches were: “adaptive reuse”, “circular economy”, “adaptive reuse of cultural heritage”, “buildings and construction”, “environmental impact assessment”, “sustainability assessment”, “urban renewal”, “construction”, “built environment”, and “green building”. Reference lists from the original set identified additional papers. Moreover, internet searches with Google and Bing identified supplementary grey literature.

The main goal of the literature review process, presented in Fig. 2 was to unearth the most relevant publications whilst excluding the general publications. As Fig. 2 illustrates, the process began with a review of several broad genres and ended with a relatively small body of relevant and significant literature comprised of peer-reviewed journal articles, grey literature and books (shown by the green box). The graph also shows the genres that are beyond the scope of this study. The general building retrofitting/rehabilitation genre is extensive and outside the scope of this study (first yellow box on the left-hand side). The general publications on adaptive reuse of buildings and strategies for improving environmental outcomes of buildings contribute to this niche. However, this genre goes beyond the study’s purpose so a dashed line represents this genre’s contribution. Likewise, the literature on strategies to improve the environmental performance of buildings (blue box on the right with dashed blue line to green box) contributes, but is generally beyond the scope of this study. The categories with direct relevance to this study are: 1) Adaptive reuse of cultural heritage buildings; 2) Circular economy strategies for the building and construction sector; and 3) Culture and cultural heritage as enablers of sustainable urban development.

The publications identified by the literature review were segregated into two groups according to their use in the study. The first group is relevant papers that serve as the corpus to which this paper contributes. Section 3.2 describes these individually in the literature review. Second, the literature review identified a group of documents, which serve as source material for the strategies in the framework. Several documents served both purposes.

Most important, how to determine the cultural heritage values attached to a building is outside the scope of the framework. There are many competing doctrines in the field. Determining cultural heritage values is an art and science that is inherently site-specific. The first assumption is that users of the framework for cultural heritage buildings will have already independently assigned cultural heritage values to their unique projects. Second, because there are many definitions and frameworks for CE in use today, it was important to write a clear definition for CE (See Section 1) and select a framework with a scope and scale suitable to the topic. Several CE frameworks and definitions use variations of the well-known Reduce, Reuse, Recycle rubric often referred to as “Rs” (Kirchherr et al., 2017; Sauvé et al., 2016). Some apply the Rs, but do not include longevity in their scope, instead focusing on manufacturing level efficiencies. Other frameworks do not include end-of-life wastes within their scope. Kirchner et al. concluded that only a third of [one hundred and fourteen CE] definitions explain a waste hierarchy (Kirchherr et al., 2017). Building longevity and overall waste reduction are critical for the buildings and construction industry. Furthermore, it was important to hone in on the scale as regards adaptive reuse of urban buildings (regardless of cultural heritage). The scale of a CE conceptualization can target the micro level, the meso level or the macro level. For example Qian and Wang’s explication of the “circular economy city” concept is a meso-level approach (Qian and Wang, 2016). This report takes a micro level approach focusing on a project (which may include more than one building) as the desired scale. The micro level scale is commensurable with the perspective that a given building is a *product* that supplies services to humans, namely shelter and health. Therefore, a product supply chain perspective is necessary. The paper “Circular Economy: Measuring Innovation in the Product Chain” (Potting et al., 2017), a publication of the Netherlands Environmental Assessment Agency (PBL), was chosen as the circularity framework for this research because it is in-depth, well-researched, and credible. See Fig. 3. CE framework for the topic. The analysis was framed and guided by the PBL paper. The paper introduces circularity strategies (R0-R9) that apply to product supply chains as part of an

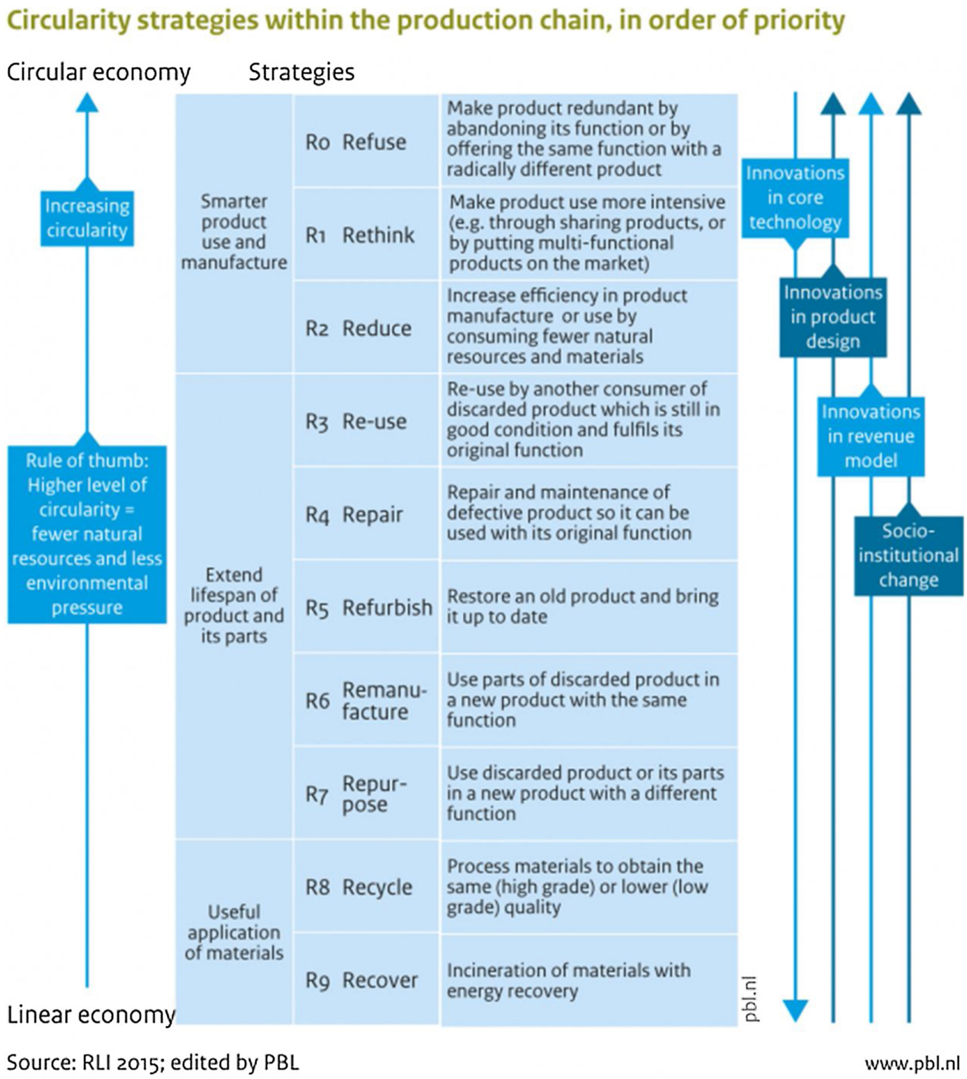

Fig. 3. Circularity strategies Employed for Adaptive Reuse of Cultural Heritage Buildings (reproduced with permission).

overall transition from a linear economy to a CE. The PBL graphic from (Potting et al., 2017), is reproduced here with permission under its Creative Commons License.[5]

Third, based on the literature and the principals of life cycle analysis, phases of a buildings' lifespan were defined to facilitate mapping CE strategies as interventions/ practices at each phase. The outcomes of Steps 2 and 3 resulted in Step 4 (Synthesis of the literature), which is presented in Section 4.

3. Literature review

The literature review provided understanding of the nuances of the field to identify research needs and relevant literature. This section provides the main results of the literature review. The research needs that this analysis aims to address are described in Section 3.1. The relevant papers, grey literature, and books that are considered the state-of-the-art (collectively) are compared to the present study in Table 1 of Section 3.2.

3.1. Research needs

Overall, the literature demonstrates that adaptive reuse of buildings aligns with CE goals and new research is needed in the field. In particular, research that explains the alignment between reuse of buildings and CE would be useful to practitioners in the industry. Three clear research gaps were discerned from the literature as follows.

1) Although the CE discourse is rapidly expanding, implementing CE is hampered by a lack of knowledge about what CE is and how to implement it, in general, and in the buildings sector. Recent analyses of the state of the art have found that "methodologies for delivering a CE are even more blurred and uncertain." (De Jesus and Mendonça, 2018) and that barriers include "Inadequate awareness, understanding and insight into CE in [construction and demolition] C&D waste management."(Mahpour, 2018) The results of Adams et al.'s survey make a compelling argument that adopting CE in the construction industry is challenged by a lack of awareness, "clients, designers and subcontractors" are the least informed (Adams et al., 2017). The proposed framework is intended as an intervention to raise awareness and skills at the micro-level. Ghiselini et al. 2016 defines fields of intervention at the micro-level in CE as firms and customers, the meso-level as industrial parks, and macro-level as cities, regions or nation (Ghisellini et al., 2016). Here, buildings

[5] The graphic is available at http://www.pbl.nl/en/infographic/circularity-strategies-within-the-production-chain-in-order-of-priority.

represent the micro-level and the intervention is providing useful knowledge to actors (cultural heritage managers, architects, civil engineers, building owners, contractors, city planners, etc.) engaging in adaptive reuse of cultural heritage buildings.

2) The literature on CE in construction tends to be fragmented, focusing on one phase of the supply chain, usually end-of-life. At this phase, the main focus is often reducing construction and demolition waste to landfill through recycling and reuse (Adams et al., 2017). Ghisellini's thorough literature review paper identified 70 academic papers on C&D wastes (Ghisellini et al., 2017). The papers that take a lifespan approach tend to narrow down environmental impact to embodied energy and greenhouse gas emissions (Pomponi, 2016). In contrast, the current work addresses this gap by proposing a coherent and comprehensive framework that identifies circularity strategies at each phase of the building supply chain for a range of environmental outcomes including, energy efficiency, climate change adaptability, water efficiency, for example. This is a unique approach.
3) The academic CE literature is focused on barriers, general methods of measurement such as Life Cycle Analysis, and technological proposals for closing material loops such as block chain applications. The academic CE literature avoids specific actions and activities that project managers can take to implement CE. Meanwhile, "Design tools and guidance" were identified as one of the "most significant enablers for implementing [CE in construction] industrywide" (Adams et al., 2017) Further, De Jesus and Mendonça found that "On the whole, the academic literature still seems focused on the role of technological innovation in the transition towards a CE." (De Jesus and Mendonça, 2018) This is a critical gap because the role of managing and applying technological innovation at the micro level is often neglected. CE needs to be "brought down" from the macro to the micro level. CE literature rarely focuses on the strategies and actions at the micro level. For the buildings and construction sector, the micro-level strategies are found in the architectural, retrofitting, rehabilitation and design literature, not in the CE literature. This study weaves these threads together by highlighting specific strategies that implement CE.

The three research gaps defined above confirm the need for the proposed explicitly circular strategies aimed at reducing the environmental impacts of cultural heritage buildings.

3.2. Overview of relevant literature

Table 1 describes several publications that collectively represent today's state-of-the-art and lay the groundwork for the current study. Eight papers, three reports (grey literature), and two books are included.

4. Results: circular economy strategies for adaptive reuse of cultural heritage buildings

This section presents and the main findings of the analysis. Section 4.1, describes the building life cycle defined herein. Section 4.2 highlights participants at each phase that use the framework. Section 4.3 presents and discusses the components of the framework and demonstrates how each strategy promotes circularity. Section 4.4 discusses the study's challenges and limitations.

4.1. Defining the building life cycle

As discussed in the methodology section, the framework intends to transform a linear product supply chain to a circular product supply chain for buildings in order to capture the environmental benefits of adaptive reuse discussed in the Introduction. Step 3 of the methodology, "Defining the Building Life Cycle" as a linear product supply chain is not trivial. No uniform method for defining a product supply chain for buildings exists, even when applying LCA methodologies. Moreover, defining the building life cycle in question defines the opportunities and constraints of the interventions/actions that implement the CE framework (the R0-R9 strategies).

The framework goes beyond many life cycle analyses in the buildings and construction sector, which are cradle to gate, meaning that they begin with the resource extraction and end with construction. Another way to organize a life cycle analysis is cradle to cradle, which means considering the environmental impacts at the very beginning and the very end of a product's useful life. This research (although not an LCA) takes a cradle-to-cradle perspective. This point is important because Pomponi and Moncaster's analysis of LCA's on embodied carbon mitigation in the built environment demonstrated that many LCA's were incomplete. They state, "Impacts during the occupancy stage and at the end of life of a building are often totally overlooked." (Pomponi and Moncaster, 2016) This framework avoids this mishap. Munarim et al. decided that rehabilitation was a "new stage" in existing buildings life cycle" (Munarim and Ghisi, 2016). The framework does not take this approach, instead establishing rehabilitation as a CE strategy analogous to refurbishing (R5). Similar to other research in the field, the framework includes Design as a distinct phase of the building life cycle (Debacker and Manshoven, 2016; Ghisellini et al., 2017). This is important because Design is critical to how buildings are ultimately realized, used, adapted, reused and demolished. Owing to the large scale of building projects, the design directly drives the materials and resources extracted from nature because major layers of buildings, such as the façade and windows, are bespoke. Nevertheless, the Design phase is frequently left out of a building's supply chain in LCAs, being conflated with Building Materials Sourcing. For these reasons, the proposed framework designates Design and Building Materials Sourcing as separate phases. The building life cycle defined in this study is familiar. Its phases are based on common understandings of LCA analysis; though it strives to be more inclusive than is usual to assimilate a broader range of environmental impacts and circularity strategies. Fig. 4 explains the building life cycle phases for this study as a linear product supply chain to illustrate and emphasize the traditional (non-circular perspective).

4.2. Participants in the building life cycle

The principles of stakeholder engagement and inclusiveness are critical to theories of sustainable development, modern architecture, and urban planning. Therefore, potential users of the framework at each stage of the building cycle are an important audience for this work. Potential framework users are direct and indirect participants in the adaptive reuse project. Participants at each phase may use the framework as a reference or as a blue print. Therefore, "participant" and "user" are inclusive concepts that comports with stakeholder categories commonly noted in the literature (Aapaoja and Haapasalo, 2014; Adams et al., 2017; Debacker and Manshoven, 2016; Hobbs and Adams, 2017; Kubbinga et al., 2017). They include those participants with a financial stake in the project's costs and revenues as well as participants who may or may not contribute to the revenue of the property in its Use and Operate phase. Table 2 couples the description of each phase with its participants. The list of participants provided in Table 2 is descriptive and generalized, not exhaustive because each project's stakeholder identification process is unique.

4.3. Circular economy strategies for adaptive reuse of cultural heritage buildings to reduce environmental impacts

This section presents the central result of this research study, the framework of CE strategies for adaptive reuse of cultural heritage buildings to reduce environmental impacts. The framework is intentionally deep and narrow in scope with the aim of addressing the

Table 1
Relevant Literature Regarding CE Strategies for Adaptive Reuse of Cultural Heritage Buildings.

Citation Data	Main contribution to the literature	Main relevant results	Methods used	Limitations relevant to the present study	Strategy Source?
Papers					
Conejos, Sheila. "Designing for future building adaptive reuse." (2013).	This important publication provides criteria for future adaptive reuses of new buildings from the point-of-view of design and develops the rating tool adaptSTAR. Describes Sustainability Assessment Methods and highlights that the majority of these are for new buildings.	The paper highlights two main goals of a CE approach, long life and the ecological footprint.	Survey, Literature review, case studies, Empirical analysis	Conejos highlights environmental impacts that are linked to the design phase, e.g., design for "ecological sustainability objectives and helps minimize ongoing habitat disturbance." However, it is not the task of the paper to provide strategies at every stage of the lifecycle as the proposal does.	Yes
Heidrich, Oliver, et al. "A critical review of the developments in building adaptability." *International Journal of Building Pathology and Adaptation* 35.4 (2017): 284–303.	Conveys the "state-of-the-art". The paper is not about circularity, but distils the theory and models behind building adaptability to the layers social, space, stuff, plan, services, skin, structure, site, surroundings.	It clarifies the dimensions and strategies of adaptability and notes the most cited adaptability characteristics.	Literature review	The paper highlighted the interactions between building layers. The adaptability strategies for layers were useful in developing the framework.	Yes
Ghisellini, Patrizia, Maddalena Ripa, and Sergio Ulgiati. "Exploring environmental and economic costs and benefits of a circular economy approach to the construction and demolition sector. A literature review." Journal of Cleaner Production 178 (2018): 618–643.	This in depth discussion of C&D wastes applies the CE framework to C&D wastes using the 3 Rs, Reduce, Reuse, and Recycle. The article also reviews methods used in the literature to determine environmental impacts and environmental and economic costs.	This article applies a product life cycle approach to waste, an important measurement of the CE approach. The authors confirm that "refurbishing seems to provide lower environmental impacts than demolition and new construction", but is "less competitive in economic terms than new construction" (Ghisellini et al., 2017).	Literature Review	Although waste, at the end of life phase is an important measure of environmental impact relevant to CE for example carbon and energy. Also, the 3Rs, is a narrow interpretation of CE principles; whereas the R0 to R9 strategies described by Potting et al. as adapted herein is a more structured, detailed, and useful approach for understanding CE in construction in general, and adaptive reuse in particular.	Yes
Adams, Katherine, et al. "Circular Economy in Construction: Current Awareness, Challenges and Enablers." (2017).	The authors survey industry participants to gauge their awareness, challenges and enablers regarding CE strategies.	In addition to their main research results, which establish a significant gap in knowledge in the field, the authors published a concise table of CE aspects across a building's life cycle stages.	Survey and analysis of the literature.	The table of circular economy that Adams, et al. derives from the literature is the closest example to the current proposal identified. However, it does not apply or interpret the strategies using the R0-R9 concept.	Yes.
Pomponi, Francesco, and Alice Moncaster. "Circular Economy for the Built Environment: A Research Framework." Journal of cleaner production 143 (2017): 710–18.	This article proposes a framework for CE research for the built environment. However, it does not discern the conditions and strategies for CE in the construction sector in a framework.	The framework assigns manufactured components to the micro level, buildings to the meso level and cities to the macro level.	Literature review	In contrast, the present study agrees with (Ghisellini et al., 2016) that the micro level is products and in this case buildings are the micro level in a transition to a sustainable built environment. In contrast, the current study places the strategies in a CE framework.	No
Pomponi, Francesco and Moncaster, Alice. "Embodied Carbon Mitigation and Reduction in the Built Environment–What Does the Evidence Say?" Journal of Environmental Management 181 (2016): 687–700.	The authors discuss seventeen diverse embodied CO_2 mitigation strategies that they gleaned from the literature.	Their study showed that a range of strategies is needed, as no one strategy was effective in embodied CO_2 reduction.	Literature review and meta-analysis	The article presents a deep analysis of embodied CO_2 across all life cycles. However, it is not combined with other potential environmental impacts, focusing only on low-carbon impacts.	Yes
Aytac, D. O., T. V. Arslan, and S. Durak. "Adaptive Reuse as a Strategy toward Urban Resilience." European Journal of Sustainable Development 5.4 (2016): 523–32.	Proposes design considerations for the adaptive reuse potential of existing buildings incorporating the theories of resilience from ecology and building layers from architecture.	The main relevant results are mapping the layers to the adaptSTAR criteria. The theoretical development proposed for the "resilient adaptive reuse strategies" is interesting and fits well with CE concepts.	Theoretical study	As the article notes, detailed criteria are needed for the building layers "based on building life and product life cycles". The current proposal fulfills this need to some extent as it fits detailed strategies into a product life cycle frame.	No

(*continued on next page*)

Table 1 (*continued*)

Citation Data	Main contribution to the literature	Main relevant results	Methods used	Limitations relevant to the present study	Strategy Source?
Munarim, Ulisses, and Enedir Ghisi. "Environmental Feasibility of Heritage Buildings Rehabilitation." Renewable and Sustainable Energy Reviews 58 (2016): 235–49.	This study discusses environmental impacts avoided by reuse of existing buildings using the lens of life cycle analyses (LCA). The foci are mainly energy consumption and embodied CO2.	The paper confirms the environmental benefits of adaptive reuse of buildings. The authors find that LCA is a reliable indicator of environmental impact.	Literature Review	Discrete strategies are not the paper's focus, instead it reviews existing LCA methodologies and regulations. The extended building life cycle concept described is different from the framework's life cycle approach. Munarim et al.'s approach is not fully circular, although it targets the end-of-life as the phase for recycling, reuse, and rehabilitation as a new phase. However, the authors share the same research motivations and observations about the field as the present study.	No
Berthold, Étienne, Juste Rajaonson, and Georges A Tanguay. "Using Sustainability Indicators for Urban Heritage Management: A Review of 25 Case Studies." (2014).	Identifies the most frequently used indicators including CO2 emissions, recycling materials, reducing resource and materials consumption, environmental and ecological awareness, implement low pollution, energy efficient infrastructure, and environmental quality of area.	Culls the longer list of most frequently used indicators to 20 key indicators of sustainable urban heritage conservation, such as "Viability of recycling existing materials"	Reviewed 25 case studies.	This review does not apply a circularity perspective or identify strategies to carry out the indicators.	Yes
Grey Literature					
Frey, Patrice, et al. "The greenest building: Quantifying the environmental value of building reuse." Preservation Green Lab, National Trust for Historic Preservation (2011).	This is the most complete report to date on the topic. It is cited frequently in the literature because it sets out a clear rationale for environmental benefits of building reuse.	Defines the phase of a buildings life cycle with the highest environmental impacts. Quantifies the environmental impacts of renovation as a percentage of new construction.	Compares Demolish vs Reuse case studies using Life Cycle Assessment	Although the analysis is not specifically circular it provides an overview of the life cycle stages and identifies the operating phase as the most important. This is particularly important as the environmental impacts of the operating phase; beyond energy efficiency is often neglected in adaptive reuse studies. Therefore, this paper leads to the use and operate phase should being emphasized here. The focus of this article is empirical analysis of potential environmental benefits such as CO_2 savings from reuse projects not *how* to achieve the benefits.	No
Kubbinga, Ben, et al. A Future Proof Built Environment. Netherlands: Circle Economy and ABN AMRO, 2017.	The Dutch bank ABN AMRO and social enterprise Circle Economy review the implications of the CE approach for the construction industry with a Dutch perspective emphasizing the construction of the CIRCL ABN AMRO building in particular.	Excellent overview of the issue that identifies new value chains in adaptive reuse.	Business report	The framework incorporates the new value chain models as strategies.	Yes
Debacker, Wim, and Saskia Manshoven. "D1 Synthesis of the State-of-the-Art." Key barriers and opportunities for Materials Passports and Reversible Design in the current system. 2016	The report poses the important question, "Why are Design/Build for Change and Circular Economy not yet (fully) integrated in the current building practice and related policy?" The research determines that circularity in the building sector requires strong interactions between all main phases. Also, the authors observe that the industry is conservative, slow to change, and circular solutions are considered too expensive.	Based on their observations, the authors characterize the building life cycle phases as "design, build, use and repurpose" and describes the sub-phases of each phase. Provides an in-depth description of actors and their roles at each phase.	European Union Project report for the Buildings as Material Banks Project	This report provides ample evidence that the proposed framework would be useful to multiple actors in the sector. The proposed framework agrees with this report that the design phase is critical. In contrast, the proposed framework includes the phase of raw material extraction.	Yes

(*continued on next page*)

Table 1 (*continued*)

Citation Data	Main contribution to the literature	Main relevant results	Methods used	Limitations relevant to the present study	Strategy Source?
MacArthur, E., K. Zumwinkel, and M. R. Stuchtey. "Growth within: a circular economy vision for a competitive Europe." Ellen MacArthur Foundation (2015).	This report explores future development scenarios for major industries including the building sector in Europe. Each scenario's output is measured in total consumer output (TCO). The report promotes the RESOLVE framework (Regenerate, Share, Optimize, Loop, Virtualise, Exchange).	According to this report, a circular scenario for the building sector might reduce TCO by 50%. Articulates a circular city/built environment vision.	Scenario analysis with economic modeling	The present work is narrower in scope, does not use benefit calculations, and offers readers many more practical strategies.	Yes
Books					
Description of book					
Wilkinson, Sara J., Hilde Remøy, and Craig Langston. Sustainable building adaptation: innovations in decision-making. John Wiley & Sons, 2014.	This book concentrates on commercial buildings adaptive reuse case studies. It clearly explains and links between theories for building adaptive reuse and sustainability. It is essential reading for architects and design experts interested in the topic.				Yes
Carroon, J. (2010). *Sustainable preservation: Greening existing buildings*. John Wiley & Sons.	This book covers all theoretical and technical aspects of the topic including energy, resource optimization, and waste reduction. It is an essential resource for a more technical audience.				Yes

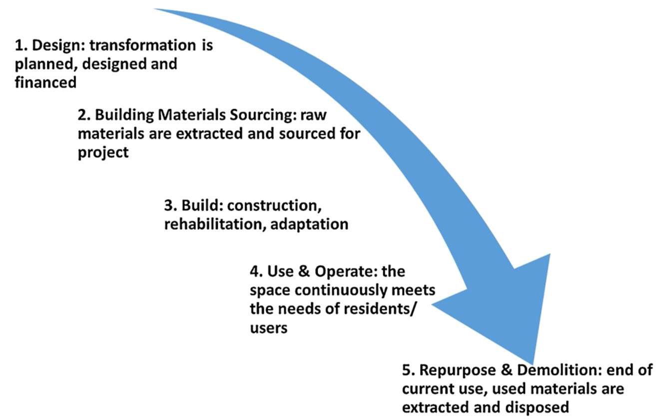

Fig. 4. Building Life Cycle Phases as a Linear Supply Chain.

research needs discussed in Section 3.1. It provides a heretofore-missing tool for stakeholders at all phases of an adaptive reuse building's lifecycle. The framework builds on the schema devised by Potting et al. summarized in Fig. 5. A higher level of circularity implies that materials remain in the product value chain longer, are more intensively used, and, in the case of refusing materials, never enter the value chain at all. The main goal of circularity is to reduce new extraction of materials from the environment. Strategies that achieve a higher level of circularity should receive a higher priority in project planning. This means that, strategies in the green zone "Smart building use and manufacture" impart more circularity than those strategies in the orange zone, "Useful application of materials". This is relevant because most practical circularity approaches in the construction industry are for recycling and recovery.

The analysis applies the schema differently than the authors originally devised as follows.

- Although, Potting et al. mention circularity for the building sector and the circular city concept, they identify only R1 to R9 as possible strategies. Because the current framework inspires reusing existing buildings and includes the Design phase, it explores R0 "Refusing materials" as well. R0 strategies, in this work, are powerful engines of circularity and are in fact its overarching achievements. R0 strategies represent transformative progress towards circularity, likewise sustainability.
- The current work broadens the scope of the green zone "Smart building use and manufacture", R0 to R3, to emphasize opportunities for direct environmental benefits/reducing environmental impacts such as eliminating fossil fuels, addressing climate change, recovering water and energy, and increasing green space and habitat. Further, the green zone now includes using materials from biomass rather than fossil fuel intensive materials for building materials. This is a high-level circularity strategy because biomass may be returned to natural resource stocks over time. In addition, the sustainability focus of the framework and the inclusive definition of participants leads to including strategies aimed at human interaction with the project in the blue zone "Extend lifespan of building and its parts", which are R3 to R7. For example the strategies: enhancing public access to the site; reviving traditional construction techniques; improving access to low-carbon mobility options; and realizing cultural heritage benefits do not necessarily concern the construction, instead the project's influence on the people who use it. These influences make the project valuable to all participants, thereby enhancing its lifespan. These changes in scope are due to the current application, existing buildings, which are fundamentally different from Potting et al.'s case study products (plastic packaging and large household appliances). This research demonstrates that Potting et al.'s, circularity strategies within the production chain are

Table 2
Building Life Cycle Phase Participants and Framework Users.

Phases	Participants/Framework Users (in no particular order)
Design: transformation is planned, designed and financed	Project lead team-responsible for project, may include the owners and combination of the following participants. Owners Project financers/Bankers Head Architects Historic Preservation Architects Local cultural heritage experts Architectural conservation experts Experts in traditional building techniques (wood framing, stone and lime mortars, plasterwork, etc.) Contractors and Subcontractors Local & regional government planning officials Local & regional government regulators Residents, tenants, and users (if accessible to the general public, people who use the space for recreation, etc. e.g., public park) Neighborhood & regional residents
Building Materials Sourcing: raw materials are extracted and sourced for project	Architects Contractors Procurement experts Regional materials suppliers (foresters, saw mills, quarries, thatch materials dealers, recovered construction materials dealers) Local manufacturers of components, glass, doors, windows, tiles, carpets, metalwork, etc. Companies for waste and materials recovery including collection, sorting, and selling and reselling
Build: construction, rehabilitation, adaptation	Regional/Traditional Artisans (masons, carpenters, joiners, millwrights, weavers, plasterwork, plaster decorations for facades, metalwork, shinglers, etc.) Architects Contractors and Subcontractors Suppliers Owners Local cultural heritage experts Architectural conservation experts
Use & Operate: the space continuously meets the needs of residents/users	Residents Commercial renters Owners Neighbors Users Visitors (for example museum, library, exhibit, aquarium, etc.) Utility operators that provide energy, water, and waste disposal, for example
Repurpose & Demolition: end of current use, used materials are extracted and disposed	Project lead team- responsible for project, may include the owners and combination of the following participants. Owners Architects Companies for waste and materials recovery including collection, sorting, selling and reselling Energy firms Landfills Local & regional government planning officials Local & regional government regulators

useful and flexible enough to apply in a broad range of sectors and products.

Fig. 6 illustrates the components together in the Circular Economy Strategies for Adaptive Reuse of Cultural Heritage Buildings to Reduce Environmental Benefits. Each of the individual strategies creates feedback loops between individual phases of the building life cycle. Closing material loops is a common technique for circularizing a production process or product supply chain. In this case, as explained above, circularization starts with material and extends to people. The circle in Fig. 6 is the building life cycle envisioned as a circular product supply chain (the solid blue boxes). Each phase in the circle is connected continuously. Individual strategies are color-coded according to the ascending principles of circularity proposed by Potting et al., adapted herein. For example, "Plan for long term climate change by choosing flexible heating and cooling" is an action undertaken in the Design phase and color-coded green because it addresses climate change. Similarly, the strategy "Design for energy efficiency including passive methods" is green because it exemplifies R2 "Cutting raw materials". Finally, orange zone strategies, R8 and R9, capture "Useful application of materials" for recycling and recovery for process inputs (e.g., recycled plastic bottles) or heat energy (incineration). In total, the framework lists forty-seven strategies organized by building life cycle phase and circularity zone indicating the degree to which the strategy implements circular economy goals.

4.4. Implementing the framework

The envisioned implementation of the framework has two central goals. First, the framework allows participants in a cultural heritage adaptive reuse project to gauge the level of circularity that a project achieves. The participants may evaluate if their current plans cluster in "Useful Application of Materials" or achieve a higher level of circularity, such as "Smart building use and manufacture". Second, following this assessment, projects may choose to include additional strategies from the framework to raise the level of circularity. In this way, the framework provides straightforward guidance to both technical and non-technical participants. This guidance is necessary because, as the literature review concluded that knowledge about *how* to implement CE is lacking (De Jesus and Mendonça, 2018; Mahpour, 2018). This framework provides a methodology for assessing a project's level of circularity *and* provides guidance to realize CE for cultural heritage adaptive reuse projects.

Flexibility is an important feature of the framework. Participants

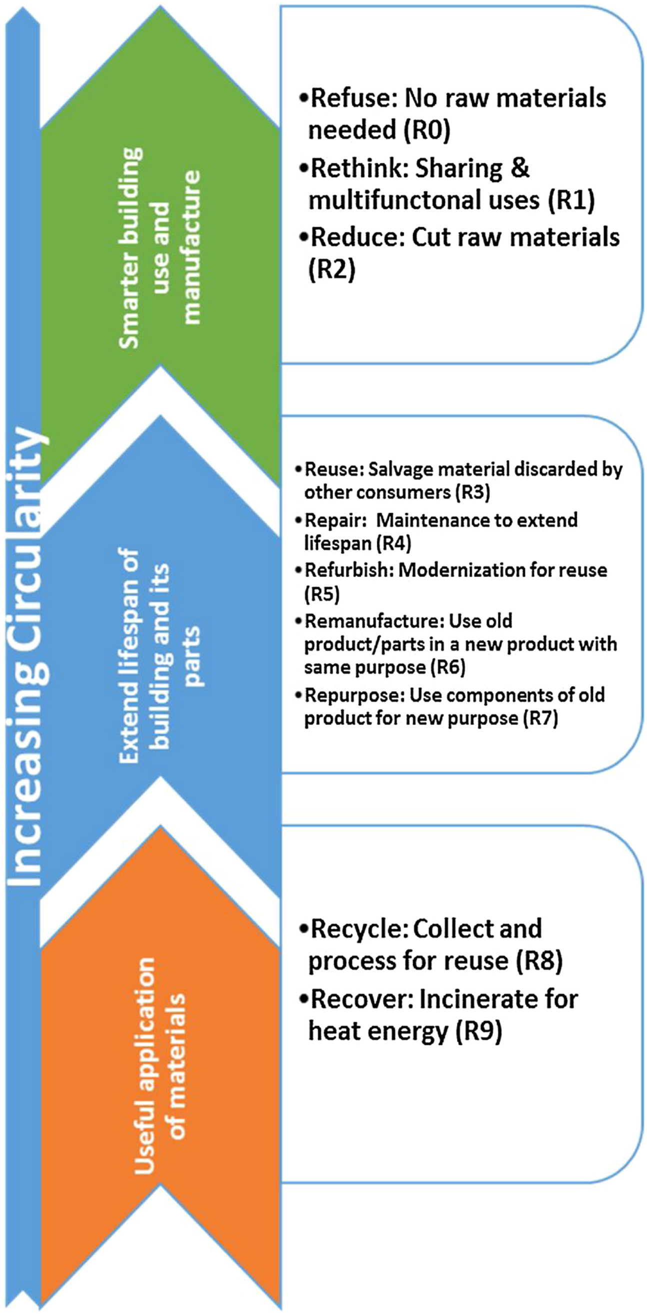

Fig. 5. Ascending circularity strategies indicating order of priority.

may use the framework at any phase of the building life cycle education, assessment, and improvement. For example, a project team that is already at the Use & Operate phase can start with the strategies listed, noting how these connect with other phases. In addition, the team can use Table 2 to identify relevant participants at other phases. For example, the strategy "Provide facilities for easy collection of recyclable materials and biomass for compost" of the Use & Operate phase links to four other phases and involves residents, the municipality, and materials recovery firms. Fig. 7 depicts three examples with arrows connecting a strategy to several phases. The Annex I provides a tabular list of strategies with corresponding links to each phase.

5. Discussion and conclusions

This research establishes a new and comprehensive framework for circularity strategies for existing buildings, addressing cultural heritage preservation and environmental impacts. The findings derive from a structured review and synthesis of the relevant literature. The framework's design is straightforward and easily understood. It is intended as a practical tool for project teams made up of participants and non-participants at every stage of a building's life cycle. Project teams should use it as: 1) a planning and evaluation tool at the start of project development; 2) an exploratory scoping exercise in combination with other participatory methods; and 3) for post project review of circularity as well. Non-participants may use the framework for education and policy development. For example, it can inform public procurement experts about the level of circularity that a building project achieves.

The next steps of this research are hypothetical and practical. Hypothetically, the framework's scope may be expanded to additional topics that are needed to realize circularity, such as circular environmental impact indicators. The current use of the R0-R9 scheme suits environmental impacts well, but may not fit other topics (finance, governance, etc.). A new ranking scheme to express relative levels of circularity for additional topics is necessary in future. Practical research applies the framework in actual projects with participatory planning. The research results will evolve and improve through use. Incorporating feedback from users is critical because implementing circularity is fundamentally a social process that will need to go beyond niche initiatives to social acceptance at the macro level.

The main challenges of this study were to triage a large body of literature, distill important strategies, and present them in a comprehensive way intended for a diverse audience. The tactic taken to overcome these challenges was to deliberately narrow the scope. The trade-offs for this decision are limitations of the study. The results are comprehensive, however are not exhaustive. Moreover, each strategy has a history of experimentation and context not discussed in this paper. It is a deliberate choice to present the information in an article format and graphics instead of a book in order to best disseminate solutions for mitigating environmental impacts including curtailing carbon emissions to decision makers. The article format presumes that most readers have adequate technical knowledge (architects, engineers, planners) to apply the strategies in practice, whilst meeting the needs of a diverse audience.

Another challenge of the research is that all cultural heritage buildings and their adaptive reuses are unique, place-based and community-based, meaning that a universal solution is impossible. This challenge may be obvious; nevertheless, it is significant. A consequence is that the strategies serve conflicting goals. For example, increasing green space conflicts with maximizing space utilization (increasing density). It will be up to the users to carefully consider conflicts and tradeoffs resulting from the circularity strategies.

In conclusion, the goal of circular economy is macro-level transformation to a sustainable economy. This goal cannot be reached without the micro level transformations supported by this research. It is not enough to focus on closing material loops to create new products from today's waste streams without care for the overall scale of resources used. Reducing the throughput and total amount of resources used in the construction industry is the ultimate goal of the research; therefore, the emphasis on promoting higher-level strategies.

Declaration of Competing Interest

None.

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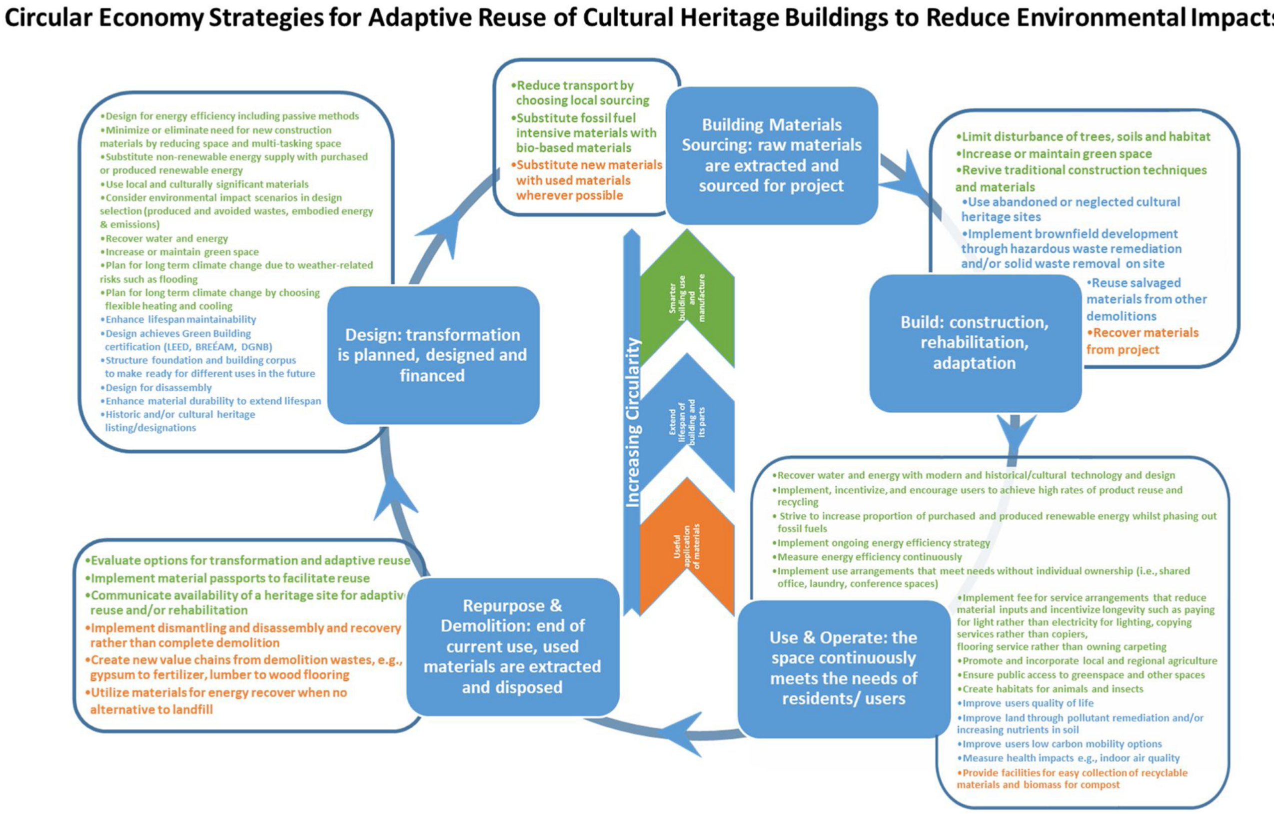

Fig. 6. Circular Economy Strategies for Adaptive Reuse of Cultural Heritage Buildings to Reduce Environmental Impacts.

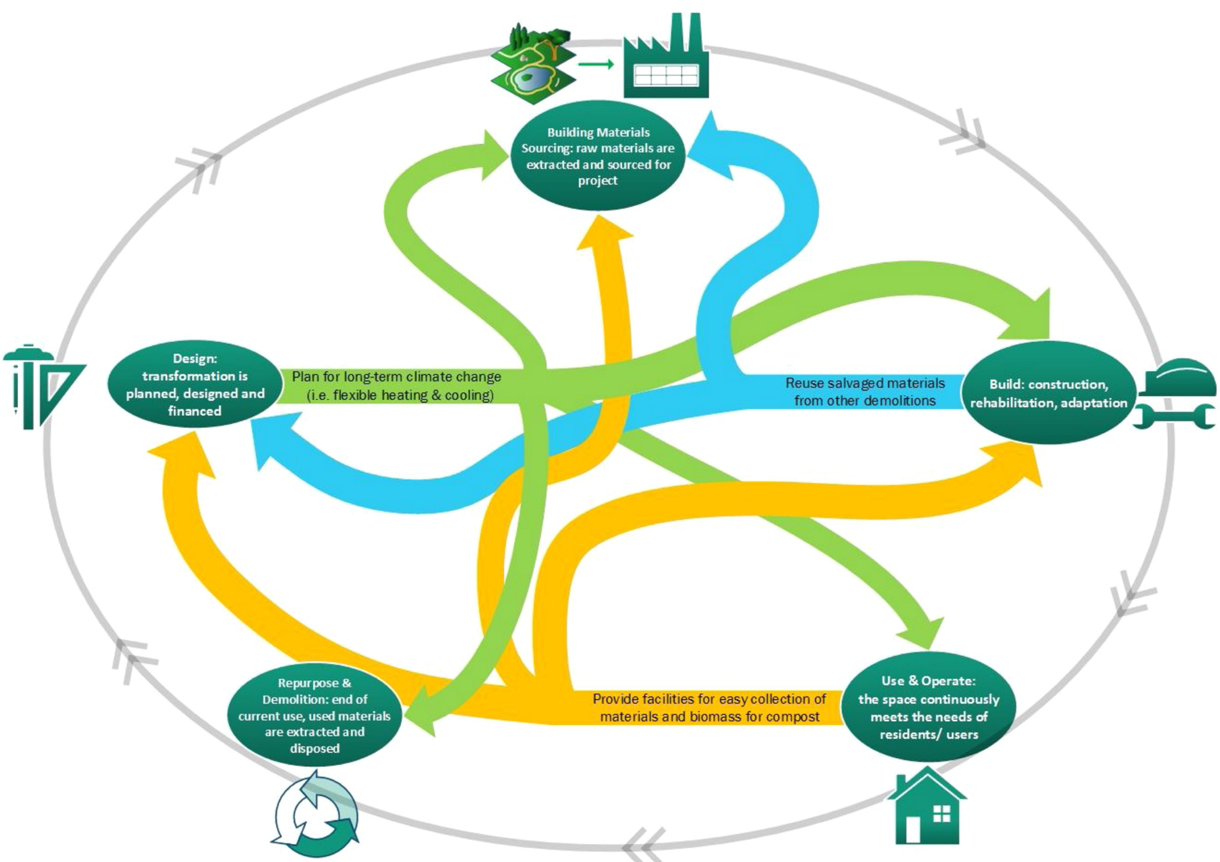

Fig. 7. Three strategies connecting building life-cycle phases highlighted.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.resconrec.2019.104507.

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