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Use of circular economy practices during the renovation of old buildings in developing countries

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ABSTRACT

The construction industry is responsible for over 30% of global natural resource extraction and 25% of solid waste production, primarily due to its prevalent "take, make, dispose" economic model. Shifting toward a circular economy within the construction sector has become a pressing need, especially in countries like Sri Lanka, to transition from linear material consumption patterns. This study aims to assess the current state of the construction industry in Sri Lanka by presenting findings from two case studies. To establish a foundation, a concise review of pertinent literature is conducted to outline key circular economy principles and their potential integration into the Sri Lankan construction processes. To evaluate material circularity within building construction, the study employs the One-Click LCA software. The analysis is focused on various construction materials used in building projects, with a particular emphasis on concrete frame buildings. The circularity assessment considers concrete, steel, and brick elements in terms of their end-of-life or serviceable period scenarios. Results indicate that maximizing building retention through adaptable design and incorporating disassembly strategies in end-of-life processes significantly enhances circularity, particularly in the case of concrete elements. Based on these findings, a comprehensive framework is proposed for the effective implementation of circular economy concepts during building renovation initiatives, particularly in developing nations. In conclusion, this study underscores the urgency of adopting circular economy principles in the Sri Lankan construction industry, highlighting the potential benefits of sustainable material management and providing a practical framework for their incorporation in building renovation practices.

1. Introduction

Population growth is causing many problems, particularly in developing countries. For example, Sri Lankan cities face a scarcity of land, resulting in significant price increments for land and materials. Industries are trying to increase their outputs efficiently to satisfy the demands of the population. The construction industry significantly extracts and consumes virgin materials contributing to the depletion of natural resources and the generation of waste ([1]. Furthermore, a recent study [2] underscores the growing importance of assessing a building's complete life cycle, encompassing design considerations, functionalities, and material compositions. This emphasis has intensified due to the heightened focus on enhancing circularity and minimizing environmental impact.

The circular economy is a new concept, even for developed countries. It can be defined as a regenerative system, in which resource input and waste, emission, and energy leakage are minimized [3]. Long-term design, maintenance, repair, reuse, remanufacturing, refurbishment, and recycling can all help to achieve this. Pomponi and Moncaster [4] discussed the circular economy concept in the construction industry from six different perspectives: governmental, economic, environmental, behavioral, social, and technical. The current "take--make-consume-dispose" practice of the linear economy should be transformed into a circular economy which is denoted by "Cradle to cradle". In the linear economy, virgin materials are extracted, manufactured into new products, assembled on-site, producing waste, and, eventually, disposed of, as they become obsolete [5]. As a result, accessible virgin resources are being depleted, and the cost of materials is skyrocketing. However, it is vital to implement circular economy concepts in developing countries like Sri Lanka, especially in the construction industry [1]. The circular economy helps keep the value of products and materials in the economy for as long as possible,

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eliminating waste generation and preventing the extraction of new resources. Sustainable development goals can be achieved by implementing circular economy concepts. Wijewansha et al. [6] have pointed out the lack of adequate guidance for construction professionals in implementing circular economy concepts, at the pre-construction stage. The need to expand the knowledge of circular economy concepts within the Sri Lankan construction sector has been recognized.

Transferring linear economy practices to circulative practices is an essential concern in the current situation. To shift from a linear economy and to implement circular economy concepts, a variety of strategies have been proposed. One type of strategy is defined within the three-R's waste hierarchy (reduce-reuse-recycle, sometimes expanded to 11 different R-strategies) [7]. Reduce, reuse and recycle are the main concepts of managing waste and are defined as R concepts. Different researchers have defined different numbers of 'R's for circular economy implementation. The elements of reimagining and redesign should be explored, to ensure the process and the design of construction activities become more innovative by prioritizing the environmental aspect. However, according to Esty and Winston [8], the 3R principles are not enough to mitigate the environmental impacts of waste generation. Waste reduction is compiled only in the construction stage. But the 'R' concept: reduce, recover and recycle helps toward the circular economy in every stage of construction.

Waste reduction [9], Design for Disassembly (DfD) [10], Design for Adaptability (DfA) [11], selecting proper materials and the use of building layers [12,13] are vital to implement the circular economy concept in the construction industry. Waste can be produced at any point of the building construction process, including planning, design, procurement, transportation, worksite, service stage, and end-of-life [9]. Moreover, construction demolition accounts for 40% of all waste, globally [14]. Even though it may be reusable, downcycled building demolition trash is frequently disposed of in landfill locations. Therefore, it is important to identify the potential solutions to reuse or recycle the construction and demolition waste. Moreover, when buildings are designed for disassembly, the building components are not fixed permanently. When the building is at the end-of-lifespan or end-of-service period, its components can be recovered. The recovered parts are directly reused in a new building or during modifications of an existing building [10]. Similarly, the DfA concept is that a building that serves its current purpose may readily be modified to future generations' changing needs, situations, and demands, whereas it would otherwise be totally or substantially dismantled. In this way, energy and material can be saved. The reuse dimension of DfA is almost totally focused on the building as a whole, on extending its lifespan, by making it adaptable and, as a result, improving its multi-functionality. The components of the building allow it to be convertible at the end of its lifespan [11]. In addition, during the material selection process for buildings, it is important to select materials with low embodied energy and carbon, enabling circular economy principles, combined with being reusable and recyclable. Preference must be given to the materials that can be reused in the construction industry or natural environment [10]. However, the reuse of available materials in each structural element can be challenging.

The use of building in layers helps distinguish between the various components of structural elements and their lifespans. The layers are defined by the lifespan of a particular component [6]. To be recycled and replaced, each structural component must offer capabilities that are not dependent on the others. Layers allow for quick identification and repair of something that has been damaged, without changing the adjacent layers. All of the layers make the structure more adaptable and flexible than a structure without them. They also make it easier to rapidly retrieve shattered components [12,13].

The implementation of different 'R, strategies has been discussed in the literature. However, discussions remain on how to implement 'R' strategies during the renovation of existing buildings. Moreover, to implement circular economy concepts, most of the frameworks have been developed based on the experiences from developed nations. The applicability of such frameworks to developing countries like Sri Lanka is questionable. Therefore, this research study discusses the current circular economy practices in Sri Lanka and proposes a framework to implement circular economy practices in the Sri Lankan construction industry, using two case studies.

2. Challenge of implementing circular economy concepts in the construction industry in Sri Lanka: literature review

The effects of the construction industry on the environment are widely established. These effects include high energy consumption, significant waste creation, excessive greenhouse gas emissions, and resource depletion (Oluleye et al. [15]. The construction and building industry use a lot of resources and releases a lot of trash into the environment. Sustainable management of construction waste is paramount important in order to minimize resource consumption, increase recycling, and reduce the related environmental impacts [16].

However, the construction industry in Sri Lanka faces several challenges in implementing circular economy concepts. One of the biggest challenges is changing from the traditional linear model of "take-make-use-dispose" to a circular model of "reduce-reuse-recycle". Although the circular economic concept is popular to some extent in the world, in Sri Lanka there is a lack of awareness about the circular economic concept in the construction industry. Based on the findings from Wijewansha et al. [6], Wanaguru et al. [17], Gunarathne et al. [1], and Gunarathne et al. [18], the following challenges were identified as the key parameters for implementing circular economic concepts in Sri Lanka.

2.1. Lack of awareness and understanding of circular economic concepts

Many people in the construction industry may not be aware of circular economy concepts or the benefits they offer. Educating stakeholders about the benefits of circular economy concepts is crucial for creating a mindset shift towards adopting them. Currently, the construction industry in Sri Lanka has adopted the linear model of "take-make-use-dispose". Providing a guide for construction professionals in implementing the circular economic concept at the pre-construction stage and expanding knowledge on circular economic concepts within the Sri Lankan construction sector is important. Special emphasis should be given to raising the awareness of construction professionals engaged in the pre-construction phase, since most aspects of a construction project are determined during the pre-construction stage.

2.2. Cost and financial viability

Implementing circular economy concepts can be more expensive in the short term, and there is a perception that they may not be financially viable [19]. Because they should be implemented throughout the planning stage, circular economic principles, such as design for disassembly and design for adaptability, should be used. Therefore, special construction techniques are used, such as precast structural elements, using bolts for joints, etc. These will cost more than the traditional construction methods. However, circular economy concepts can lead to long-term cost savings and create new business opportunities.

2.3. Lack of regulation and standardization

There is currently a lack of regulation and standardized practices around circular economy concepts in the construction industry in Sri Lanka. There is also a lack of incentives for businesses to adopt circular business models [18]. This makes it difficult to implement these concepts in the construction industry. If the Sri Lankan government can regulate regulations for pushing the construction industry towards the circular economy, it will be helpful to construction companies to switch to the modern circular economic model.

2.4. Technical challenges

There are technical challenges to implementing circular economy concepts, such as designing buildings for disassembly, implementing closed-loop supply chains, finding new ways to utilize the waste materials, lack of awareness of value of the waste materials, etc. [6]. In Sri Lanka, compared to the developed countries, low levels of modern construction technologies are adopted. New construction techniques, such as using precast structural elements and connecting joints of structural elements with bolts, are not very popular in the construction industry. A very recent study conducted by Prince et al. (2023) revealed that instead of relying entirely on expert opinion or judgment, artificial intelligence models could be used to improve the expected recyclability of the materials. Therefore to recycle the waste materials, modern recycling techniques and artificial intelligence models are required to achieve maximum optimized value for the product.

2.5. Fragmentation of the industry

The construction industry is highly fragmented, with many different stakeholders and subcontractors involved in various stages of the construction process [20]. This fragmentation can make it difficult to implement circular economy concepts and coordinating links between the stakeholders. All the stakeholders should be aware of the circular economy concept. Designers should design the structures with the purpose of reusing or recycling the building materials and the structural elements. Constructors must have proper construction knowledge and technologies to build the structure. Also, manufacturers of building materials must have the technical capability and willingness to produce materials by utilizing recycled waste materials or their byproducts. In addition, the client and the project management team should be able to correlate all the stakeholders and push towards a circular economy in the construction practices adopted in Sri Lanka.

3. Material and methods

The main objective of this manuscript is to develop a framework to adopt the circular economy during the renovation of buildings in developing countries. To develop the framework, the case study research method is used to gain concrete, contextual, in-depth knowledge about the renovation of buildings and the possibilities for using circular economy concepts during rehabilitation. The overall methodology is shown in Fig. 1. Initially, the case study buildings and the region of study are described in Section 3.1. Section 3.2 discusses the software which was used to estimate the level of circularity in each case study.

3.1. Case study buildings

In this study, two buildings located in Matara and Galle, districts in Sri Lanka, have been selected. One of the buildings belongs to the Faculty of Graduate Studies, University of Ruhuna, Matara, Sri Lanka (i.e., Building A). The second building belongs to the Ocean University, Boossa, Galle, Sri Lanka (i.e., Building B). Matara and Galle are cities in the Southern part of Sri Lanka, with high population densities of around 694.3 km^2 and 680.4 km^2, respectively. Therefore, it is vital to study the possibilities of renovation of the existing buildings in the areas with high population and less availability of land for new constructions. Moreover, the renovation of buildings will help to reduce linear material consumption [21]. The analysis considered the two stages of a particular building as:

(i) Final building after the completion of construction (existing and new structural/non-structural components)
(ii) New building parts that were added to the existing building (new structural/non-structural components)

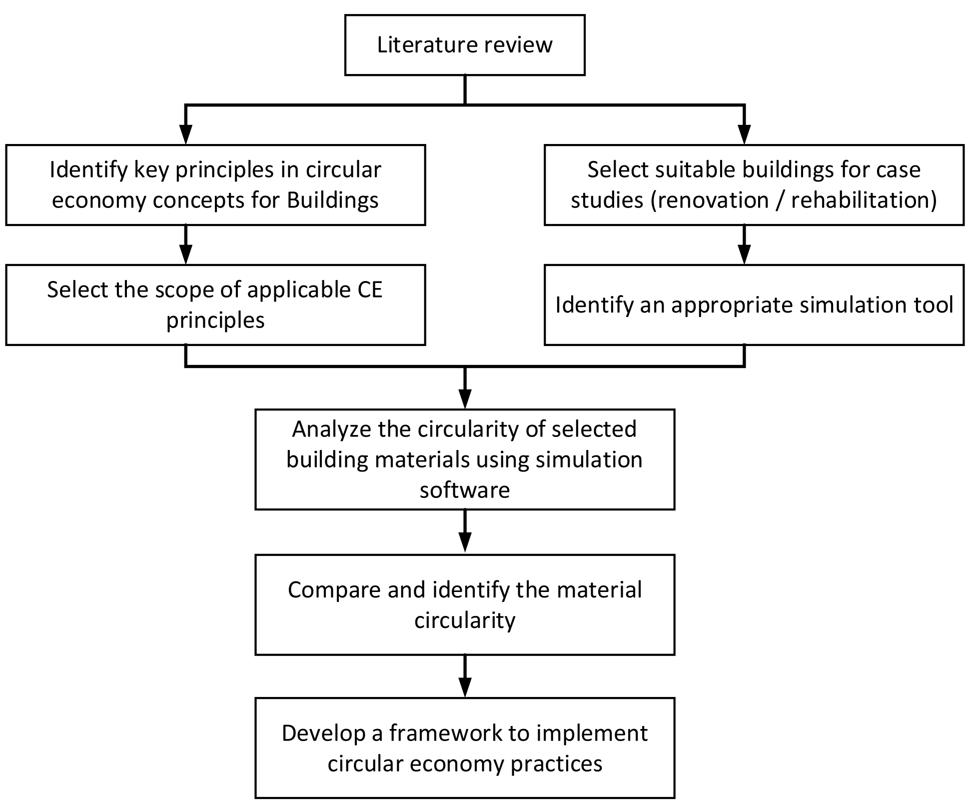

Fig. 1. Overall methodology.

3.1.1. Condition assessment of buildings

Prior to the renovation of the existing buildings, a thorough visual inspection was conducted to assess their condition. A summary of the findings from the visual inspection evaluations and the corrective activities done as part of the renovation strategies used in both buildings are shown in Table 1. The visual inspection evaluations were utilized to gauge the quality of materials at the current service life of the buildings. This assessment aided in the identification of reusable components. For a comprehensive understanding of the potential material reuse in the existing buildings, it is advisable to estimate both the overall circularity and material circularity. Furthermore, employing non-destructive and destructive testing (NDT/DT) methods would offer valuable insights into the structural capacities of individual components. Unfortunately, due to the buildings' renovation being carried out by a private contractor and certain archaeological concerns, acquiring samples for NDT/DT was restricted. Consequently, the recommendations from the visual inspection evaluations were partially employed to track, quantify, and optimize the material circularity in both buildings.

3.1.2. Building A

The existing Building A was built with reinforced concrete columns and beams, brick walls, steel trusses and asbestos sheets for the roof, as shown in Fig. 2. The building was single-story and nearly 100 years old. The existing floor area in the building was nearly 420 m^2. The administration of the University of Ruhuna, Matara, Sri Lanka, decided to build a two-story building with total floor area of 630 m^2 at the same location, by including more structural elements. The design and construction were carried out without disturbing the archeological concerns. Based on the inspection and re-analysis of the structure, it was confirmed that outer walls, beams, and columns had sufficient capacity to withstand the load as a single-story building.

3.1.3. Building B

This single-story building was used as a warehouse, with nearly 590 m^2 of floor area. It was decided to adapt it to become an academic building with two stories. The proposed building is a concrete-framed structure, with a steel roof and burnt clay bricks in the walls. Fig. 3 shows the construction stages of the building. The existing building consisted of reinforced concrete columns, beams, and walls. The columns, beams, and external walls were retained, and new structural and non-structural components were added for the final building.

3.2. Circular assessment tool

OneClick LCA software was used to assess the building's circularity. The software is a standardized web-based platform, specifically designed for the Life Cycle Assessment (LCA) of construction projects [22] and building circularity assessment. In addition, OneClick LCA can be used to obtain building certifications such as the Building Research Establishment Environmental Assessment Method (BREEAM), the Leadership in Energy and Environmental Design (LEED), and Environmental Product Declarations (EPD) [23]. Moreover, the tool has been third-party verified against ISO and EN standards and is widely used around the world. In this study, OneClick LCA was used for the building circularity assessment.

Fig. 2. Building A: Faculty of Graduate Studies, University of Ruhuna, Matara, Sri Lanka.

The basic inputs for One-Click LCA software are materials used in the buildings, acceptable circularity weighting factors, and the lifespan of the buildings. The Building Circularity tool in One-Click LCA software helps in the tracking, quantifying, and optimizing of the circularity of materials which have been used during the building's life cycle, as well as the circularity at the end of life. In this analysis, input data were extracted from AutoCAD drawings and Bill of Quantities (BOQ). All the values and proper references were used from the library of the simulation tool (i.e., One-Click LCA).

The results can be obtained from two different categories:

(i) With overall material/total material
(ii) With each material category (e.g., concrete, steel).

The categories of input data for circularity in the software are:

(i) Building material
(ii) Circularity weighting factor
(iii) Calculation period.

Here, only structural elements were considered as input data. Those are:

Table 1
Visual Inspection Evaluations and Renovation strategies adopted during the rehabilitation.

Type of Defect/issues	Element/s issues identified	Level of Issue based on the visual inspection/evaluation	Applicability of reusable level of the component during renovations/ rehabilitations
Cracks	Wall, Column, Beam, Timber Sections	Minor and major cracks were observed.	Depending on the crack width, length, element type and location. applicable repairing method was adopted.
De-laminating	Plaster mortar in Wall, Column and Beam	Major portions of the wall plaster interior and outside, Certain levels of de-laminating of the existing plaster in columns and beams	Common issue identified in both buildings. Non-bonded areas were removed. New plaster mortar was applied with a bonding agent.
Defects and Failures	Solid Timber Sections in the roof frame, Door and Window Frames & Panels	Insect attacks, holes and fungi, staining were observed in the exposed timber sections; Knots, and Fissures were other common defects identified in door and window frames & panels.	Necessary cleaning and applying wood preservatives, Identify reusable sections.
Corrosion	Steel Sections, Steel reinforcement bars.	Severe corrosion in exposed steel sections due to sea breeze; Major cracks in reinforced concrete caused corrosion in reinforcement steel.	Identify the level of corrosion; Replace severe corrosion steel sections/bars; Application of corrosion protection paints.

Fig. 3. Building B: Ocean University, Boossa, Galle.

Table 2
Circularity weighting factors.

Material	End of life usage	Circularity weighting factor
Concrete	Land filling for concrete	0
	Concrete crushed to aggregate	0.5
Metal	Steel recycling	0.85
	Reuse as material	0.85
Bricks and ceramics	Landfilling/backfilling	0
	Reuse as material	0.85
	Brick/stone crushed to aggregate	0.5

(i) Foundation
(ii) Beam
(iii) Column
(iv) Slab.

The highest circularity weighting factor scenario was selected for each material from the available end-of-life process of the tool. Circularity weighting factors denote the circularity of a specific process or scenario, indicating how much recycling of the material can be carried out at the end of its lifespan or beyond its service period. The weighting factors for the scenarios other than from the software are taken by considering the wastage percentages in Sri Lanka, according to the research carried out by Wanaguru et al. [17], as given in Table 2. End-of-life scenarios, such as concrete crushed to aggregate, metal for reuse as material, and bricks and ceramics for reuse as materials, were considered in this analysis. These scenarios give the highest circularity weighting factor in the end-of-lifespan. During the analysis, it has been assumed that efficiency for reuse as material and recycling is 85%, and downcycling and use as energy is 50%. The calculation period is selected as 60 years because the retained concrete lifespan is in the range of another additional 50–60 years.

Wuni et al. [24] have revealed that existing design for excellence techniques such as Design for Manufacturing and Assembly (DfMA), Design for Adaptability (DfA), and Design for Disassembly (DfD) have been proposed in relation to eco-designs of products to promote systemic circularity. DfMA proved effective in ensuring the project's timely and secure completion while preserving its value and reducing project costs. Additionally, a study conducted by Antwi-Afari et al. [2] demonstrates that the adoption of DfA in certain case buildings contributes to the advancement of circularity in the building industry. This study suggests that considering the End-of-Life (EoL) scenario of building materials during the design stage could enhance their potential for reuse in subsequent cycles.

During the analysis, the percentage of material recovered, and the percentage of material returned in each building were found. Finally, the overall circularity (OC) has been estimated as a percentage, where the average from the materials recovered adds up to the materials returned using Eq. (1). OC indicates the amount of material that is reused from the old building before adding new structural/nonstructural components. Moreover, it is vital to identify the key material groups that contribute significantly to OC. This will help in the decision-making process to understand the exact amount of construction materials that contribute to the virgin, renewable, recycled, or reused categories. Therefore, material circularity was estimated as given in Eq. (2). Moreover, DfD and DfA principles have been integrated into One-Click LCA software. For the DfD scenario, a weighting factor of 0.85 was used only for the new structural/nonstructural components, where the existing structural/nonstructural components were not designed for dissembling.

$$Overall\ Circularity = \frac{Renovated\ building - New\ structural/non\_structural\ components}{\text{Renovated } building} \times 100\% \quad (1)$$

$$Material\ circularity = \frac{Renovated\ building_M - New\ structural/non\_structural\ components_M}{Renovated\ building_M} \times 100 \quad (2)$$

where

Renovated building$_M$: Total amount of material (concrete/steel/bricks/timber) in the renovated building

New structural/non_structural components$_M$: Total amount of material (concrete/steel/bricks/timber) in the new structural/non-structural components

4. Results of the analysis

This study revealed how to estimate the circularity of Buildings A and B, considering overall material consumption and reuse and the consumption and reuse of individual materials. Overall circularity, material circularity of the existing building, circularity with end-of-life scenario for new components, and circularity with a DfD option for concrete are the main parameters considered in the decision-making. Retained parts of the existing building give the initial circularity as the DfA option. The retained percentage is illustrated compared to the final building. The end-of-life process is only compatible with new parts; due to the older age of the buildings, it was not possible to reuse or recycle. The high circularity weighting factor was selected from the available scenarios in the One-click LCA software. The DfD option is applicable for the concrete element with mechanical joints only for new parts, since the old building cannot be disassembled and assembled because it already has rigid joints.

The following circularity scenarios are considered for the assessment of both Buildings A and B;

1 Circularity DfA + crushed aggerate (end-of-life) scenario:
  - DfA: This focuses on designing new building components for easy disassembly and reuse.
  - Materials Crushed as Aggregate (End of Life): At the end of its life, the building is disassembled, and materials are crushed and repurposed as aggregate for new building components.

2 Circularity DfA + DfD scenario:
  - DfA: Building components are designed for easy disassembly and reuse.
  - DfD: New building components are designed to be easily disassembled and reused when necessary.
  - DfD: New building components are designed to be easily disassembled and reused in the future.

3 Crushed for aggregate (end of life) scenario:
  - Building materials from the old structure are disassembled and crushed to be used as aggregate for new building components when the building reaches the end of its life.

4 Retain / DfA scenario:
  - The existing building components are retained and refurbished.
  - Design for Assembly (DfA) principles are applied to make it easier to disassemble and reuse old parts when necessary.

4.1. Circularity assessment: Building A

The total material consumption for the new structural/non-structural components and the wastage of material at the construction site have been found, as given in Table 3. In Table 3, "Renovated building" means the total material used at the end of the construction, and "new structural/nonstructural components" indicate the materials which are newly added to the existing retained building. The overall circularity was calculated using Eq. (1) and presented in Table 2. The old building's structural components were retained as much as possible, and new structural/nonstructural components were added, and it was identified as a renovated building. The two-story section of the new building is a concrete frame building; the roof structure was made of timber and burnt clay brick was used for the walls. It could be seen that about 43 % of the total weight in the renovated building consists of material reused from the old building.

Construction material in Building A includes concrete, steel, bricks, and timber. Considering the different construction materials used for Building A, the circularity of each material (i.e., concrete, steel and timber) has been calculated in tons, using Eq. (2). The result of the calculations is given in Table 4. The circularity of each material indicates the percentage of material that can be saved if a building is renovated, rather than constructing a new building. According to Table 4, the percentage circularity of bricks is about 62 %, which is higher than that of other materials in the building.

In this study, the building circularity has been estimated using One Click LCA software scenarios for new structural/non-structural components, by considering the end-of-life scenarios for the period of 60 years. In this analysis, concrete crushed to aggregate, steel recycling, reuse as material, and incineration have been used as the end-of-life scenarios. The weighting factors for the end-of-life scenarios are given in Table 5. The circularity weighting factor for new components of steel is high, resulting in a high circularity percentage. For the material in old components, it has been assumed that the end-of-life scenario is landfilling. Therefore, the percentage circularity of material in the old components became zero. However, there is a possibility to reuse aggregates in concrete with a lower weighting factor.

The concrete elements can be reused as the same element with the DfD option, by introducing mechanical joints in between two elements, with the circularity weighting factor of 0.85. Of the circularity increment, 55.92% can be achieved with the DfD option for steel elements. This option can be applied only for new steel parts, considering the age of the building. Since the selected case study was concrete frame structures, the circularity of concrete is an important parameter to analyze. This building can be included with different circularity scenarios, as given in Fig. 4. Based on Fig. 4, the DfA+DfD scenario gives the highest circularity percentage. Therefore, DfA with DfD shows the highest circularity.

This building is already nearly 60 years old. Concrete has a lifespan of about 100–120 years. At the end of the renovated building's lifespan, the old building's retained parts cannot be used. Therefore, the circularity of the old retained parts is zero. However, the new parts can be used in the end-of-life-span of the building, assuming the building's lifespan is about 60 years. With the mechanical joints or from other end conditions, the concrete members (e.g., beams and columns) can be reused for another building, with the disassembly of those members. This gives a 0.85 weighting factor with high circularity. The old building parts are already constructed and cannot be used for DfD. Therefore, the Dfd option is only applied to new parts of the building. The circularity weighting factor of 0.85 is assumed for steel.

Table 3
Building A: Overall material consumption and wastage.

	New structural/non-structural components (tons)	Renovated building (tons)	Overall circularity (%)
Construction materials	559.95	980.57	42.9
Material wastage at construction site	23.72	41.8	

Table 4
Material circularity: Building A.

Material (M)	New structural/non-structural components (tons)	Renovated building. (tons)	Material circularity (%)
Concrete	421	640	34
Steel	18	21	14
Bricks	120	319	62
Timber	1	1	0

Table 5
Circularity for materials with end-of-life scenario with a weighting factor.

Material	End-of-life scenario and weighting factor	Circularity (%) of new structural/non-structural components in renovated building
Concrete	Concrete crushed to aggregate – 0.5	33
Steel	Steel recycling – 0.85	73
Clay bricks	Reuse as material – 0.85	32
Wood	Incineration – 0.5	50

Table 6 shows the possible scenarios identified and listed with their circularity percentage. The considered building can be included with different circularity scenarios, as discussed in the Section 4 Results and Analysis. Other materials used to make the structure in addition to concrete include brick, steel, and timber. The circularity cannot be increased using those materials. This is mainly because bricks can be reused (highest circularity), steel can be recycled (highest circularity) but cannot be reused due to corrosion, and timber is incinerated and decayed. Therefore, concrete is circulatable, with a higher circularity weighting factor, and can be considered as a DfD option, with a circularity percentage of 55.9%. In addition, DfD is only applied to new parts of the building, since old parts are already constructed.

4.2. Circularity assessment: Building B

The columns, beams and external walls of the existing building were retained, and new structural/non-structural components were added for the final building. A similar analysis has been carried out for Building B. The reuse of materials or components was not significant, compared with that of Building A. The overall material consumption and wastage of construction material at the site have been given in Table 7. Using Eq. (1), overall circularity has been estimated. The overall circularity of Building B (i.e., 15%) is lower than that of Building A.

The circularity of the material has been calculated using Eq. (2), using the data given in Table 8. The results indicate that the material circularity is lower for concrete and steel than for bricks (33%). When comparing with Building A, there is great potential to reuse clay bricks in both buildings.

The building circularity has been estimated using One Click LCA software scenarios for new structural/non-structural components, by considering the end-of-life scenarios for the period of 60 years. For

Table 6
Possible scenarios identified and listed with their circularity percentages.

Scenario	Circularity (%)
DfA + crushed aggerate (end of life)	67.1
DfA + DfD	90.1
DfD	55.9
Crushed for aggregate (end of life)	32.9
Retain / DfA	34.2

Table 7
Building B: Overall material consumption and wastage.

	New structural/non-structural components (tons)	Renovated building. (tons)	Overall circularity (%)
Construction materials	512.97	600.31	15
Material wastage at construction site	22.15	26.41	

Table 8
Material circularity: Building B.

Material	New structural/non-structural components (tons)	Renovated building. (tons)	Material circularity (%)
Concrete	349	359	3
Steel	7	7	0
Clay bricks	157	234	33

Building B, concrete crushed to aggregate, steel recycling and reuse as material have been used as the end-of-life scenarios, as given in Table 9. According to Table 9, 85% of steel in new structural/non-structural components can be recycled. Moreover, 49% of concrete in new structural/non-structural components can be crushed into aggregates.

The influence of DfA and DfD has been analyzed, using One Click LCA software for concrete, and the results are presented in Fig. 5. The analysis was carried out for concrete because the highest amount of material that is used in the renovated building is concrete. Building B

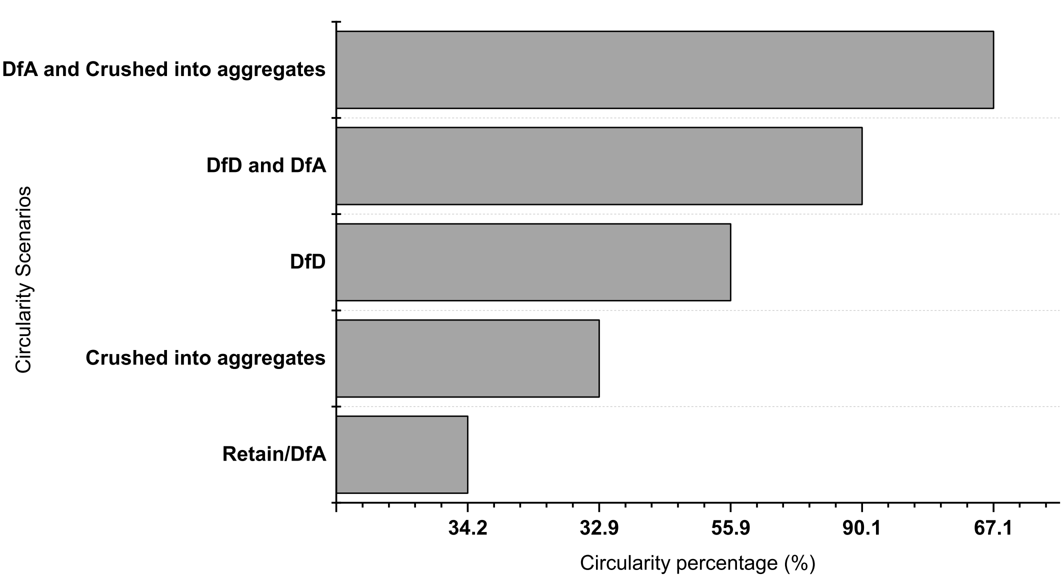

Fig. 4. Circularity percentage vs. circularity scenarios: Building A.

Table 9
Circularity for materials with end-of-life scenario with weighting factor.

Material	End-of-life scenario and weighting factor	Circularity (%) of new structural/non-structural components in renovated building
Concrete	Concrete crushed to aggregate – 0.5	49
Steel	Steel recycling – 0.85	85
Bricks	Reuse as material – 0.85	57

was built with reinforced concrete columns and beams, brick walls, steel trusses and sheets for the roof. Only concrete is considered for this analysis, since the other materials were analyzed with a high circularity weighting factor. Similar to Building A, the concrete can be circulated with different options with different circular economy principles. DfA (retaining/refuse), Crushed to Aggregate (recycle) and DfD (reuse) were used as different combinations, and the concrete gives the highest circularity. Fig. 5 shows that DfA, combined with DfD principles, gives the highest circularity of 85.4% for Building B.

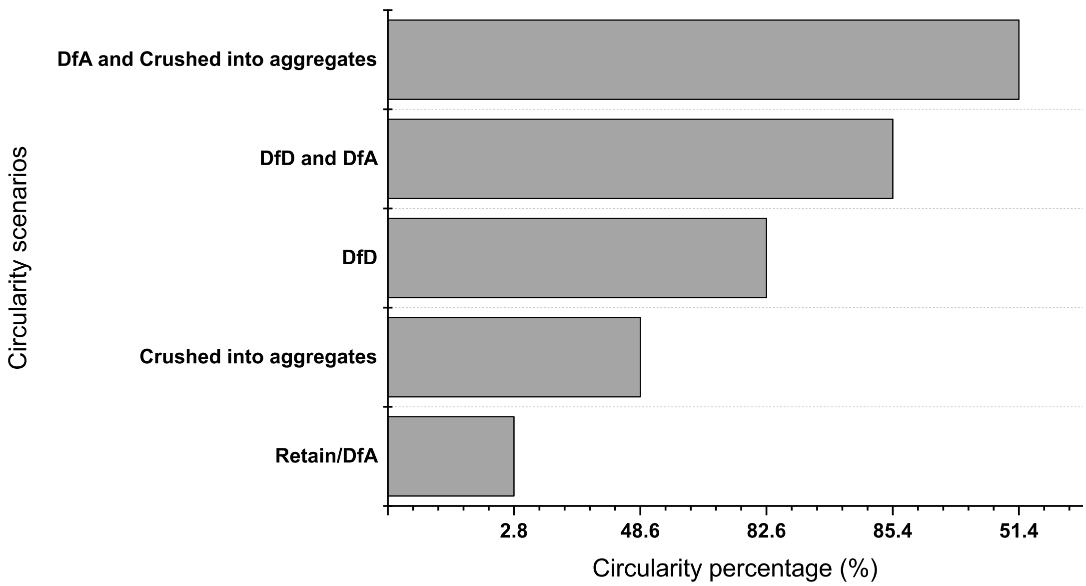

Fig. 5. Circularity percentage vs. circularity scenarios: Building B.

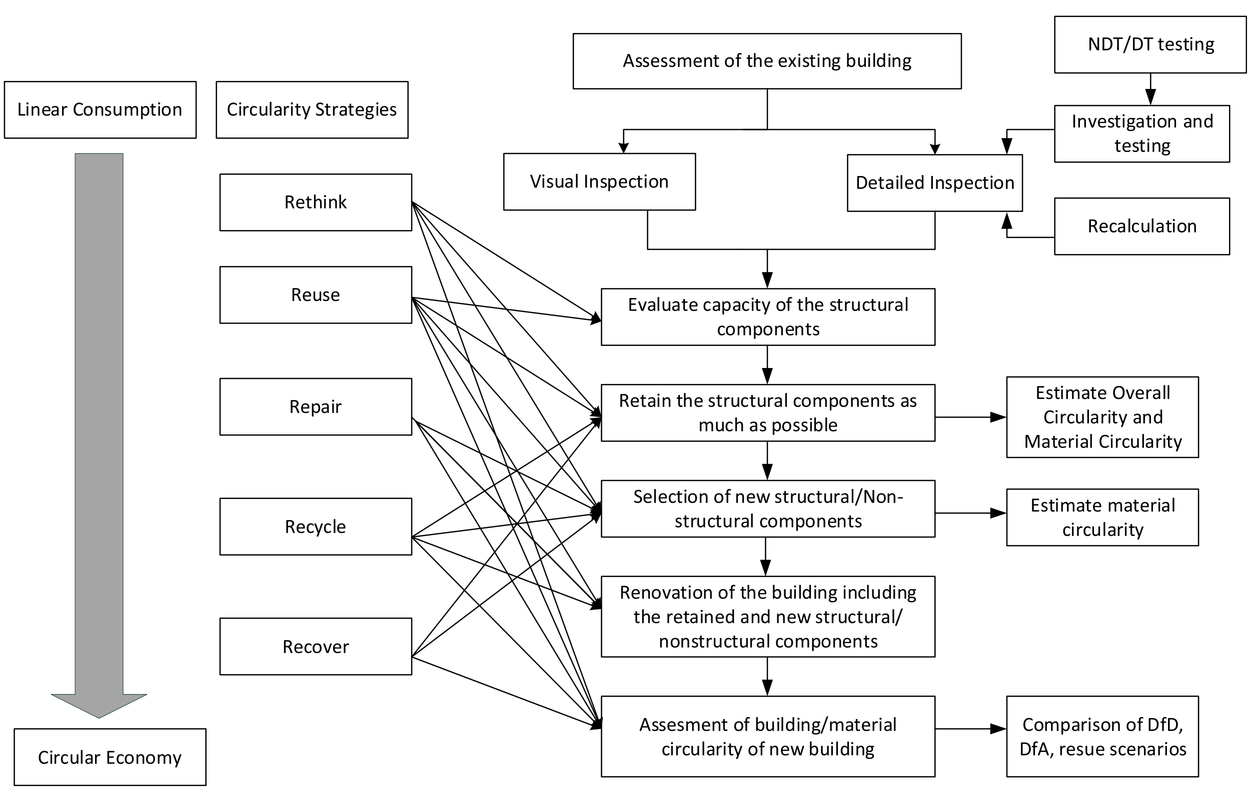

Fig. 6. A framework to implement circular economy concepts during renovation of buildings.

5. Proposed framework for including circular economy concepts during building renovation

The study by [25] revealed that there are two main objectives for the framework's anticipated implementation. Firstly the participants can assess whether their existing strategies compatible within the "Useful Application of Materials" cluster or achieve a higher degree of circularity, such as "Smart building use and manufacture", and secondly framework offers participants on clear direction of both technical and non-technical how circular economy concepts adopted the renovating of an existing building. Another challenge identified in the study that all cultural heritage buildings and their adaptive reuses are unique, place-based, and community-based, meaning that a universal solution is impossible. Therefore, the current study faces the same challenges to implement circular economy concepts for the renovation of existing buildings.

Based on the findings from two case studies and literature reviews, the following framework is proposed to implement circular economy concepts during the renovation of an existing building in a developing country. Fig. 6 shows the proposed framework, which gives guidance throughout construction, from the planning stage to the end of the service life period. Initially, the existing building is assessed using the visual inspection method and detailed inspection, to understand the deterioration levels at the end of the service life of the building. Non-destructive and destructive testing (NDT/DT) methods can be useful during the evaluation of the capacities of the existing structural components. Moreover, it is vital to recalculate the new capacities of the existing structural components that can be reused in the renovated building. Based on this evaluation, the reusable components can be identified. The estimation of overall circularity and material circularity is recommended, to get a clear overview of the potential reuse of material in the existing building. If an existing building is to be adapted as a new building, retaining the existing building as much as possible will circulate the building material at a low cost and highly sustainably. As a result of that, the usage of new materials and the material cost of the construction will be reduced. The demolished components can be reused for new element construction. For this purpose, bricks and steel elements show better results, according to circularity analysis. Based on the results in Section 4, 90% of bricks and 85% of steel can be reused as material in the end-of-lifespan of the old building.

The framework has indicated what circularity strategies can be involved, while moving from linear material consumption to the implementation of circular economy concepts. Reuse, Rethink, Repair, Recycle and Recover strategies can be implemented in different stages of the process, as shown in Fig. 6. One Click LCA can be a useful tool for implementing some of these strategies. Moreover, it is crucial to consider DfD and DfA concepts when selecting new structural/non-structural components during the rehabilitation of the building. The concrete can be crushed to aggregate with 50% desirability, according to One Click LCA. But when designing new concrete elements, it can be included as a DfD option with mechanical joints in between concrete elements. That gives a high circularity when DfA (retaining) and DFD (reuse) are implemented. It achieves high circularity above 85% compared to the final building.

6. Conclusions

There is a lack of methodologies on the implementation of circular economy concepts during the renovation of buildings in developing countries. This manuscript focuses on the development of a framework to implement circular economy concepts during the renovation of buildings. Two case studies have been briefly studied, to understand the possible circularity strategies that can be implemented. To adapt an existing building, retaining as much of the existing building as possible will circulate the building material for the new building. As a circularity aspect, this principle is often applied in Sri Lanka. Components that have been demolished can be utilized in the building of new structural/non-structural components. According to circularity studies, bricks and steel elements perform well for this purpose. After demolition or as part of the end-of-life process, bricks with a content of more than 90% and steel with a content of more than 85% can be reused as material or recycled in the end-of-lifespan of the old building.

Because the connections between columns and beams are permanent, concrete cannot be utilized as a material in the end-of-life process of an existing building. As a result, according to One Click LCA, 50% of concrete in new structural/non-structural components can be crushed to aggregate. However, when designing new concrete elements, the DfD option with mechanical joints in between concrete elements can be included. This results in a high circularity for fresh concrete usage, and when DfA (retaining) and DfD (reuse) are combined, they can attain a high circularity of more than 85%.

In this study, the main consideration is to evaluate and analyze the circularity of material through the possible construction stages. When including circularity for a building, the cost can differ with circularity applications. In certain cases, the circularity concept will not be economical when compared to the usual construction process. Therefore, analyzing the economic benefits of circular economy thinking in the construction process should be considered a future concern.

Other than concrete, structural materials like steel and timber should also be evaluated and compared through the Life Cycle Assessment software, to identify preferable materials for high circularity in the construction industry. Also, material passport analysis is most appropriate for this comparison.

The proposed framework for circular economy implementation is gained through the literature review and local case studies completed in this study. The practicality of this methodology should be evaluated by local experts at the top of the management-level hierarchy in the construction industry.

Future research

The proposed framework for circular economy implementation, informed by thorough literature review and localized case studies, offers a promising path forward. However, its real-world efficacy requires validation and refinement through evaluation by local industry experts occupying senior positions within the management hierarchy. Future studies should undertake a comprehensive assessment of economic, environmental, and social factors to holistically gauge the viability of circular economy approaches within the construction industry. In this case, use of tools like life cycle assessment [16] and life cycle costing would be beneficial. Moreover, the applicability of the proposed framework may vary across different regions due to varying cultural practices and local market conditions.

Collaborative efforts with governmental and regulatory bodies are essential to foster an enabling policy environment that incentivizes and supports circular economy practices in the construction industry. Policymakers should consider integrating circular economy principles into building codes and regulations to encourage sustainable renovation practices. Investing in training and capacity building for industry professionals can facilitate the effective adoption of circular economy practices. Develop financial and non-financial incentives to promote circular economy adoption, thereby aligning economic interests with sustainable practices in building renovation.

This study lays a significant foundation for the implementation of circular economy concepts within the context of building renovation in developing countries. By addressing these recommendations, acknowledging limitations, and embracing policy implications, stakeholders can collectively contribute to the advancement of circularity in the construction industry, fostering a more sustainable and resilient built environment for the future.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: **S. M Samindi M.K. Samarakoon** reports financial support was provided by University of Stavanger. **S.M Samindi M.K. Samarakoon** reports a relationship with University of Stavanger that includes: employment.

Data availability

Data will be made available on request.

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