Chapter

Circular Economy in Buildings

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Abstract

This chapter is centred on waste management in buildings. It discusses the principles of applying circular economy in buildings toward resource efficiency with regard to the building sector. The study investigates a series of building assessments and reviews different aspects of energy efficiency as it relates to circular economy in buildings. It recommends the best practices to ensure the reuse and recycling of building components during and after the life of a building. The world is experiencing huge resource depletion and it is eminent to research the waste management practices in the building industry, Circular Economy offers major interventions in buildings which are explored in this chapter, another aspect of the discussion in this chapter is the design for disassembly and design for recycling under the concepts of circular economy.

Keywords: building, waste, recycle, reuse, circular economy, sustainability

1. Introduction

Building construction and demolition industries are the largest contributors to overall waste among the other industries globally [1]. Due to the non-recyclability of building materials, almost 50% of the entire waste is generated by the construction industries [2]. In 2016, European member countries have generated 2.54 billion tons of waste which are expected to rise to 3.4 billion tons per year by 2050 [3]. The journal of the European Union [4] suggested a waste hierarchy to deal with materials in the following order: prevention, preparing for re-use, recycling, recovery and, finally, disposal. Moreover, European Commission (2018) prepared a protocol and guideline for waste management to implement circular economy.

Globally, the construction sector has been developing environmental burdens by consuming primary resources, and energy and producing a significant amount of waste [5]. This industry is accountable for 36% of CO_2 emissions and 40% of total energy consumption in Europe [4]. As this sector is consuming a huge amount of primary resources, especially minerals, wood and ferrous metals, it is of utmost importance to figure out ways to minimize the consumption rate and impact on climate change [5]. Using recyclable materials and utilizing the building waste after demolition can help to reduce this burden and impact on our climate [5]. To increase the material values and use available resources in a circular material flow by recycling process, [6] proposed the concept of the circular economy (CE). Moreover, European Commission [4] prepared a protocol and guideline for waste management to

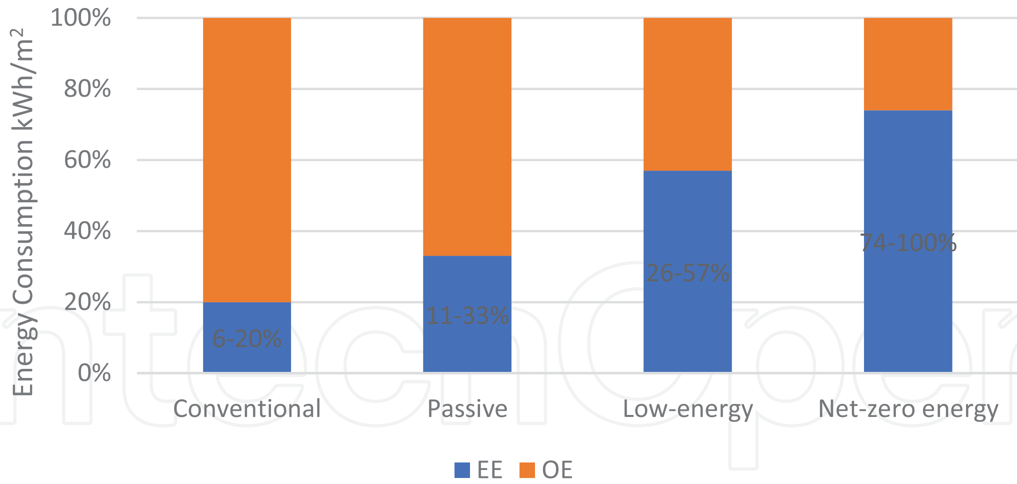


Figure 1.
Energy use accountability of EE and OE [11].

implement circular economy. Utilizing recovered building materials directly is more beneficial than recycling options as the reusing of building materials requires minimal energy usage than the recycling process [7]. Building deconstruction is preferable to the demolition process because of the economic and environmental benefits [8].

The alarming increase rate of building energy use and carbon emission has raised the issue to create new policies and strategies for sustainable and zero-energy building design and construction [9]. Energy-efficient buildings and constructions can change the energy use prospects in the coming decades and ensure the sustainability of the built environment [10]. Consequently, low-energy buildings can be one of the solutions to achieve the carbon reduction targets for the coming decades. But low energy buildings often use strategies like plastic insulation, energy-efficient service systems, and shading devices which reduce their operating energy demand at the expense of increasing the rate of embodied energy emission [11] (**Figure 1**).

Due to the high embodied carbon emission of low-energy buildings, the concept of reusing, and recycling building materials have been developed globally by many researchers to increase the resilience and durability of building materials. Building designers can contribute to minimizing the number of resources and materials used in construction by following the principles of circular economy [12]. Therefore, there are many scopes for researchers and designers to figure out the possibilities of designing low-energy buildings with lower embodied carbon emissions by reusing or recycling the same building materials or waste.

To address this issue, developing a material matrix will help to quantify the circularity of materials and enable the designers to be informed to prevent the harmful impact of the buildings on our environments [13]. Although the feasibility of circular economy may face several barriers like cost-effectiveness, quality, legislation and required time, this can contribute to protecting our natural resources and preventing global climate change.

2. Circular economy in buildings

The consumption rate of natural resources is at twice the rate they are produced, and it would be three times by 2050 [14]. To minimize the rising demand for natural resources, pressure is increasing on the built environment. Ellen MacArthur foundation generated a circular approach to building materials to reuse the resources and reduce the carbon footprint. According to the Eurostat waste statistics (2011) [6], 60% of the total waste is not recycled, composted, or reused. A continuous loop of material use, repair and recycling can retain their optimum intrinsic value and this circular process of using materials can reduce waste and carbon emission [15]. The aim of the circular economy strategy is to maximize the potentialities of the materials and utilization of available resources through the circular flow of building materials, decreasing waste, reduction of primary resource consumption, and environmental burden [6]. To ensure material sustainability and reduce embodied energy, the circular economy is significant to consider in any building design phase [16].

High-rise buildings are often associated with higher initial embodied energy [11]. Embodied energy (EE) is defined as the total energy used for the production, transportation, and installation of building material [11]. Ellen Macarthur Foundation [6, 14] proposed eco-effectiveness of building materials which will create metabolism to use the material repeatedly at a high level of quality. Using the material repeatedly can increase the quality of environmental quality, economic prosperity, and social equity at different levels like cities and nations [17].

2.1 Circularity of building materials

Building components should be selected with their potentialities of circularity by following the 3Rs (reduce, reuse, recycle) hierarchy of circular economy [15]. An extensively clean life cycle strategy of circulating building materials in society, excluding contaminants and adulteration, is required to reduce the consumption of primary

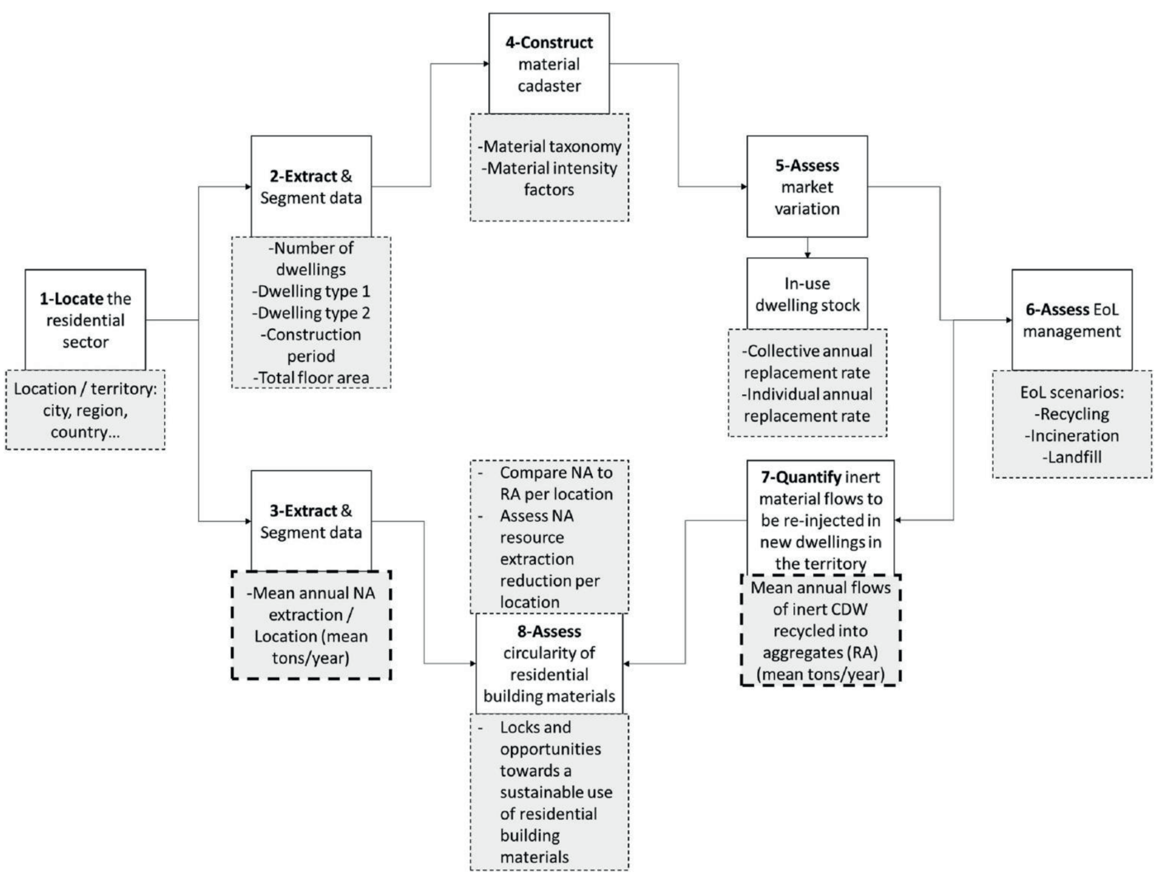


Figure 2.
Model framework to assess circularity of the building materials [16].

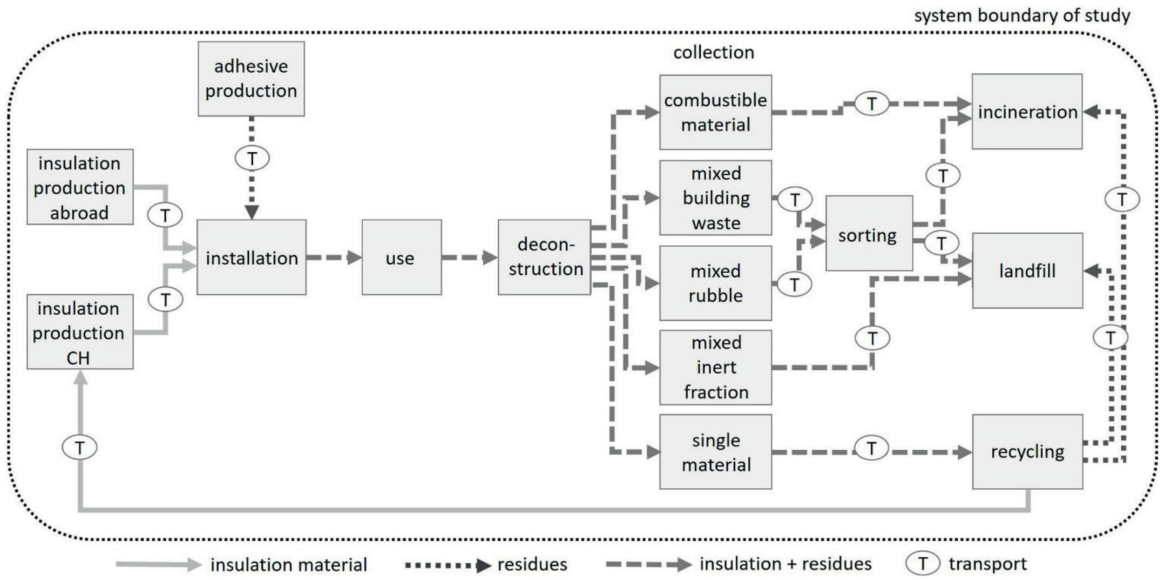


Figure 3.
Representation of processes, material flows, transport and system boundary of the thermal insulation material case study.

resources [18]. Tazi [16] used a replicable methodology to locate, extract, construct and assess the end-of-life (EOL) and circularity of the building material (**Figure 2**).

He also created a model map flow, based on a material flow analysis (MFA) and a STAN (State-of-the-art platform) software run for uncertainty assessment, which can thus be used by decision-makers in cities in order to yield an outlook of material stock and flows which were contained in French residential buildings over a time period extending from 1919 until late 2013 [16] (**Figure 3**).

Wiprachtiger M. et al. [19] suggested the sustainable circular system design (SCSD) method in three structured phases to provide an extensive assessment of material flow, impact and circular economy strategies. One-third of the 60 metals studied by Eurostate (2011) [20], showed a global end-of-life recycling rate of 25% or more. Taking a closer look at various ferrous and non-ferrous metals reveals that even for metals that already have high recycling rates, it was found that significant value has been already lost [6].

2.2 Evaluation of circular economy of building materials

From a circular economy perspective, the major criteria to consider in the selection of construction materials for all types of buildings should include local availability, embodied energy, recyclability potential, recycled content, renewability potential, potential to reduce construction waste, life span and durability, and maintenance needs [11]. According to Potting et al. [21], the circular economy (CE) principle is based on the assessment of 10 circularity strategies which are refuse, rethink, reduce, re-use, repair, refurbish, re-manufacture, repurpose, recycle, and recover.

Recyclability- Generally, recyclability means converting waste materials into new products, materials or ingredients [22]. Recyclability is one of the prime strategies to establish the design of a circular economy through a closed loop [20]. From the analysis by [22, 23], the thermal recycling process was identified as one of the best processes and the mechanical recycling process was found as the least energy-consuming process.

Reusability- The concept of reusing materials is one of the most sustainable and established methods to reduce the waste and use of primary resources [24]. Reusing contraction materials can reduce not only the building materials but also the overall cost of the project [24].

Toxicity- Toxicity of the material is defined as the behavior to release sufficient harmful chemicals or ingredients during the production or end of life which can directly or indirectly impact the environment negatively [25]. Incinerated wastes, slags, dust, sludges and other hazardous products are considered toxic waste [22].

Assembly and disassembly- Assembly refers to the installation or construction of individual parts and disassembly refers to the detachment of individual parts of building fabric including wall cladding, non-structural wall panels, flooring, kitchens and internal finishes [26]. Disconnecting of different materials may take place at any time in the whole life cycle of the building, including renovation or the end of the building's life.

Wastage- The number of materials that cannot be used or recycled or reused in the construction process is counted as wastages. Analyzing the construction and demolition waste, Noor et al. [26] have identified the major construction wastes which are plastic, wood, steel, surplus mortar, surplus concrete, broken bricks, green waste and excavated soil.

Finishing- Finishing refers to the additional layer of materials over the real materials which is generally used to enhance the durability and esthetic aspects of the materials.

From the analysis of [2], the highest reusability ratio was found in the buildings with the structural components largely made of steel structure. Other building structural components like timber structure have 0.65 reusabilities and 0.35 recyclability, and concrete structure has 0.42 reusability and 0.58 recyclability (**Figure 4**). The concrete structures are difficult and unsuitable to reuse as it has the least reusability of 0.42 [26]. By comparing the recyclability and reusability quality of different materials, designers will have a clear understanding of the building materials which can increase the circularity of the building materials.

The whole life performance of the buildings and required adjustment opportunities can be analyzed with a BIM-based whole life performance estimator (BWPE) model which also leads to an efficient material recovery system for the circular economy [2]. Akanbi et al. [2] prepared a table to establish the recyclability, reusability, toxicity, finishing and connection typology of the building materials for the building structure, floor, roof, frame, wall, doors, windows and ceiling systems (**Table 1**).

End-of-life scenarios can demonstrate the possibility of reusing or recycling existing building materials which help to select the materials in line with circular economy strategies. But due to the lack of sufficient research on the end-of-life treatment of each building material, it is not possible to decide on the end-of-life scenarios of all the materials of the building precisely. Tazi [16] investigated end-of-life treatment on some of the building materials which are listed in **Table 2**.

Based on the design science approach of Hever et al. [31], the Circularity Assessment Tool (CAT2022) was prepared by Tokazhanov et al. [32]. The circular economy in the construction industry was the focal point of this assessment tool which was a process and practitioner-based assessment tool. The third-party assessment was also involved to include the responses from the construction industry at different positions and levels. This proposed tool can also complement the existing certification method circular economy by providing specific and required information.

However, the 3DR method can be different due to the local recycling and reuse regulations and facilities. Northern European countries can recover almost 80%

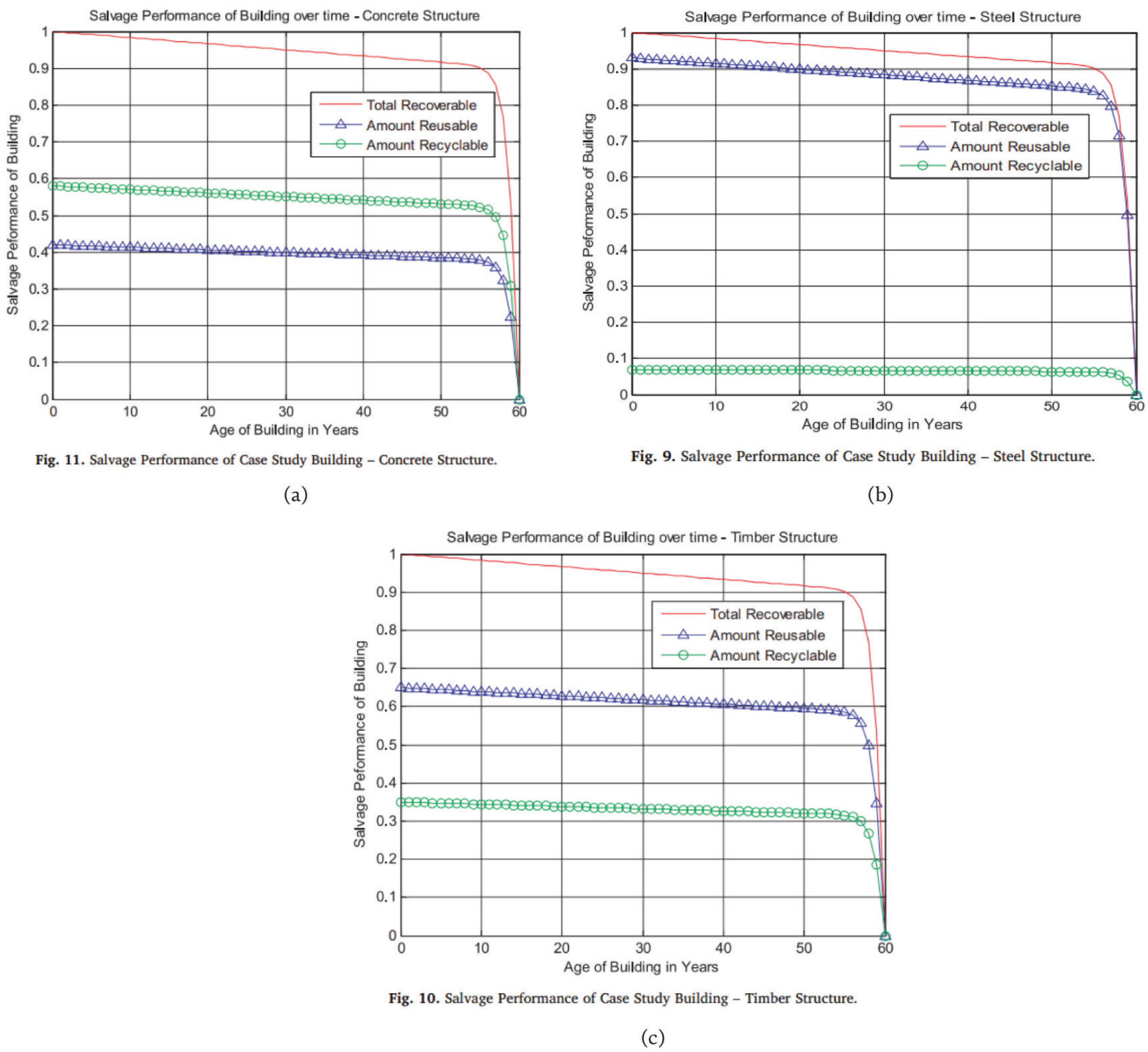


Figure 4.
Salvage performance of materials (a) concrete (b) steel (c) timber [2].

Systems and options	Recyclable (r_1)	Reusable (r_2)	Toxic (x)	Sec. Finish (s)	Connection type
1. Structural Foundations H-Pile foundation	✓	✓	×	×	*cb*
Concrete ground beam	✓	×	×	×	*cf*
Concrete with mastic tanking	✓	×	×	×	*cf*
2. Floor system Insitu Concrete floor with ceramic tiles	✓	×	×	×	*cf*
Precast Concrete slab with carpet	✓	×	×	×	*cd*
Timber floor with ceramic tiles	✓	✓	×	×	*cn*
3. Structural frame system Exposed Steel with fixed connections Concrete Encased Steel	✓	✓	×	×	*cf*
Exposed Steel with bolted connections	✓	×	×	×	*cf*
Concrete Encased Steel with bolted	✓	✓	×	×	*cb*
Timber with bolted connections	✓	✓	×	×	*cd*

Systems and options	Recyclable (r_1)	Reusable (r_2)	Toxic (x)	Sec. Finish (s)	Connection type
Timber with nailed connections	✓	×	×	×	*cb*
Reinforced Concrete with bolt	✓	✓	×	✓	*cf*
4. Wall system Demountable dry internal wall – Steel Curtain wall	✓	✓	✓	✓	*cb*
Brick/block cavity wall	✓	✓	×	×	*cb*
Cladded timber cavity wall	✓	×	×	✓	*cb*
Steel framed wall	✓	×	×	✓	*cn*
5. Doors and windows Glass with aluminum frame Timber with timber frame – Softwood	✓	✓	×	×	*cb*
Timber with timber frame – Hardwood	✓	✓	×	✓	*cn*
6. Ceiling system Aluminum strips with steel frame	✓	×	×	✓	*cf*
Soffit plaster and paint	✓	✓	×	×	*cf*
Timber planks with timber frame	✓	✓	×	✓	*cn*
Ceiling tiles with metal frame	✓	✓	×	✓	*cn*
7. Roof system Flat galvanized steel on Z profile beams	✓	✓	×	×	*cn*
Reinforced concrete roof	✓	✓	×	×	*cn*
Pitched roof timber structure	✓	×	×	✓	*cf*
Tiles covering on a pitched roof	✓	✓	×	×	*cn*

Table 1.
Material selection options for building [2].

Materials	Treatment	Materials	Treatment
Stone [27]	88% recycled þ 12% landfilled	Concrete and block concrete [27]	88% recycled þ 12% landfilled
Solid and hollow bricks from baked clay [27]	88% recycled þ 12% landfilled	Tiles from baked clay	100% recycled
Gypsum [28]	100% recycled	Mortar and mineral plaster	100% recycled
Glass [29] Wood and conglomerated wood	85% recycled þ 15% landfilled 61% recycledfilled þ 28% incinerated þ 11% land	Mineral wool [30] Metals (steel, aluminum and zinc)	100% recycled 98% recycled þ 2% landfilled
Polymers (PVC þ PS þ PU) [29]	70% recycled þ 30% incinerated	Asphalt þ Sand [29]	100% recycled

Table 2.
End of life scenarios for construction and demolition waste [16].

Description	Mass (kg)	Tools needed	*DIt*	Transport tools	*DIm*	Resilience	*Ri*
Structural materials							
Steel chassis and load-bearing structure	16,138.9	Gas/ pneumatic tool	0.5	Forklift	0.4	Infinitely reusable	1
Stairway steel structure	422.8	Gas/ pneumatic tool	0.5	Forklift	0.4	Recyclable	0.6
Lightweight steel structure, internal walls	3590.3	Power tool	0.8	Two people	0.9	Infinitely reusable	1
Bolts and nuts	97.7	Power tool	0.8	One person	1	Recyclable	0.6
Pressed fiber particle board used as floor structure	4102.6	Power tool	0.8	Two people	0.9	Downcyclable	0.2
Glass wool used in all external walls and ceiling	2325.6	No tool	1	One person	1	Recyclable	0.6
Glass wool used in the roof	190.4	No tool	1	One person	1	Recyclable	0.6
Screw pile lightweight steel foundations	735	Hydraulic plant	0.2	One person	1	Recyclable	0.6
Finishes							
Carpet covering 193 m^2 of internal floors	183.4	No tool	1	One person	1	Reusable 3 times	0.9
Vinyl covering floors in wet areas	714	Hand tool	0.9	One person	1	Reusable once	0.7
Salvaged timber composing the stairway steps	164	Power tool	0.8	Forklift	0.4	Reusable 3 times	0.9
Plywood covering internal walls and first-floor ceiling	3328.0	Power tool	0.8	Two people	0.9	Reusable 3 times	0.9
Magnetic felt ceiling	333.7	No tool	1	One person	1	Reusable 3 times	0.9
Plasterboard cladding used in kitchen/bathroom and ground-floor ceiling	140.2	Power tool	0.8	One person	1	Disposable	0
Pressed timber for ground-floor external cladding	1811.7	Power tool	0.8	One person	1	Reusable 3 times	0.9
Steel sheets for first-floor external cladding	652.1	Power tool	0.8	Two people	0.9	Infinitely reusable	1

Description	Mass (kg)	Tools needed	*DIt*	Transport tools	*DIm*	Resilience	*Ri*
Steel sheets used for roof covering	531.3	Power tool	0.8	Two people	0.9	Infinitely reusable	1
Aluminum windows and glazed doors	744.0	Hand tool	0.9	Two people	0.9	Reusable 3 times	0.9
Internal timber doors	138.0	Power tool	0.8	One person	1	Infinitely reusable	1

Note: DIt = the tool(s) required to disassemble components; DIm = equipment required to move components; Ri = resilience of components.

Table 3.
Building material analysis [33].

of construction materials, but Brazil can recover only 6% of the construction waste [26] (**Table 3**).

For oil-based materials, the most emission-intensive process is production, followed by the incineration of the material itself and then the incineration of the attached glue and plaster. For mineral insulation materials, the environmental impact of production surpasses the impacts caused by the oil-based materials (inert material landfill) [19] (**Figure 5**).

The main drawback of the circular economy process is the disassembly or demolishing process, material size, and further installation process may require

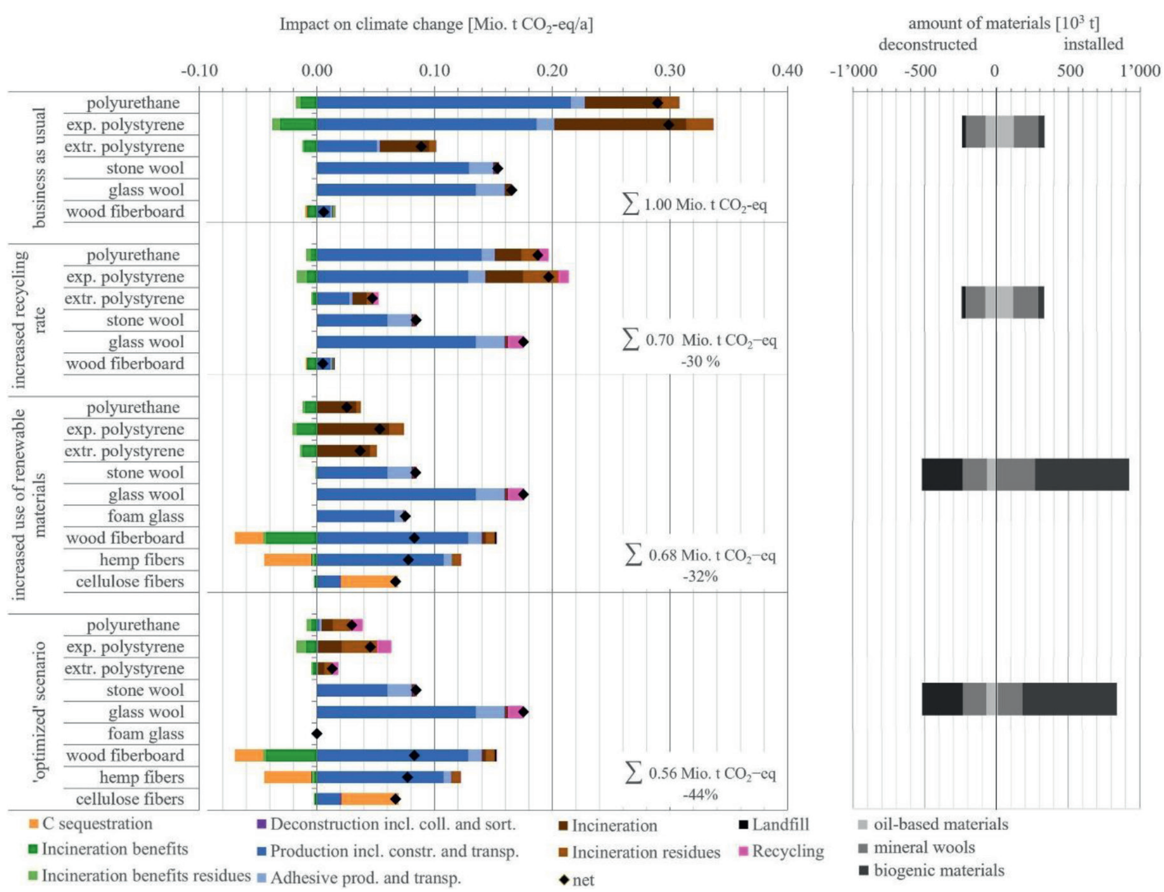


Figure 5.
Impact of different insulating materials [19].

Author	Research name	Research design	Study purpose	Key insights
Hopkinson et al. [34]	Recovery and reuse of structural products from end-of-life buildings.	Comprehensive literature review approach.	CE application to materials and building components.	• Recycling process can contribute to the environmental benefits • Research on environmental wellbeing and material reusability is not sufficient
Honic et al. [35]	Improving the recycling potential of buildings through material passports (MP): an Austrian case study	Creating a methodology to compile the Material Passport of the building, through the use of BIM.	Material matrix or passport for building materials. The authors tested the method with a case study of timber vs. concrete.	• Although concrete is recyclable, it produces more waste than timber. • Integration of a circular economy can be beneficial for the environment if it is started from the early design phase.
Jimenez-Rivero and Garcia-Navarro [36]	Best practices for the management of end-of-life gypsum in a circular economy.	Survey and literature review.	To collect sufficient information on recycling gypsum waste.	Many countries still do not have any proper regulations or policies for the recycling of gypsum. The following issues are also limiting the process- • On-site segregation. • Skilled workers • Lacking knowledge on disassembly
Verbinnen et al. [37]	Recycling of MSWI bottom ash: a review of chemical barriers, engineering applications and treatment technologies	General review.	Investigating the probabilities and limitations of using MSWI fly-ashes.	The combination of by-products with other materials can cause secondary consequences like heavy metal concentration.
Parron-Rubio et al. [38]	Concrete properties comparison when substituting a 25% cement with slag from different provenances.	Testing different types of slag as by-products To substitute concrete.	Reusability of concrete by integrating bioproducts.	• Reusing waste (Cross-Industry) is a new opportunity to develop a circular economy, • Combination of slag and concrete can be double beneficial.
Rose et al. [39]	Cross-Laminated secondary timber: experimental testing and modeling the effect of defects and reduced feedstock properties.	Research on used timber in cross-laminated secondary timber (CLST).	Comparison of the different structures of CLT with similar types of products.	• Conventionally, used-timber or similar products have the tendency to down-cycled before disposal. • In the EU, reusability of timber is not allowed. CLST is proven to have similar characteristics to CLT.

Table 4.
Focus on circular economy practices.

some additional time and cost in some cases [24]. However, when a good number of material and construction companies will start the recycling unit and maintain the supply chain regularly then the recycling products will be regular products which will reduce the demand for using materials from primary resources. Due to a lack of research on the circular economy, there are no proper databases or building material matrixes that can be followed by professionals to select the building materials with circular economy potentialities. There are few studies that were based on specific types of materials or properties, but they are not precise enough to take decisions when compared with other materials. As a consequence, a building material matrix is necessary where a wide range of building materials will be present and identified with their circular economy potentialities like recyclability, reusability, toxicity, wastages, assembly and disassembly.

The main drawback of the circular economy process is the disassembly or demolishing process, and further installation process may increase the required time to complete the project and cost in some cases Atkins [24]. Because the material recycling plant will need the time to recycle the materials after the demolishing of the building and prepare them to use or reuse in the new building. However, when a good number of material and construction companies will start the recycling unit and maintain the supply chain regularly then the recycling products will be a regular products which will reduce the demand for using materials from primary resources.

2.3 Summary of state of art of circular economy

This subsection summarizes the studies which are focused on circular economy in **Table 4**.

3. Embodied energy of tall buildings

This subsection presents the embodied energy of different building materials which can be reused in the process of circular economy and their relationship with the operational energy consumption of the building (**Table 5**).

3.1 Embodied energy of building materials

The embodied energy of building materials means all the energy which were expended during the production of that material, from the extraction of resources to the final manufacturing processes, transportation, and construction. Embodied energy (EE) difference among the different tall buildings is significant not only for the thermal performance or specific construction types but also for the material selection process. Maintaining the circularity principles of building materials is also responsible for the difference in EE in tall buildings. The combination of a conscious material selection process and durable design decisions can also help to achieve 50% embodied energy saving in the building.

3.1.1 Building structure, floor and walls

The embodied energy of the building rises according to the floor level of the building as the tall building requires more structural materials. Azari and

Author	Research name	Research design	Study purpose	Key insights
Eberhardt et al. [40]	Life cycle assessment of a Danish office building designed for disassembly.	LCA of a building designed for disassembly, a case study in Denmark. Four different structural materials are compared to traditional buildings.	To identify the potentialities of environmental savings, the authors investigated the LCA and reusability of concrete, steel, and timber structure.	• Components of building service systems are very significant and • influence the LCA of buildings. • By reusing the building components three times, Up to 60% of savings can be achieved.
Brambilla et al. [41]	Environmental benefits arising from demountable steel-concrete composite floor systems in buildings	LCA of different concrete/steel floor structure technologies designed for disassembling (case studies).	Evaluating the impact of structural components and technologies on the environment.	Reusing the structural components multiple times can reduce the negative impacts on the environment.
Tingley et al. [42]	Understanding and overcoming the barriers to structural steel reuse, a UK perspective.	Semi-structured interviews and literature study.	Identify the limitations and barriers of steel components in the UK and prepare a framework to overcome them overcome these barriers.	• Demand for reused steel components is not still popular in the market and their reintegration in the market is unachievable. • Disassembling and reusing steel the structure can be more expensive • Government can create pressure to reuse and recycle building materials by implementing new regulations.
Akanbi et al. [2]	Salvaging building materials in a circular economy: a BIM-based whole-life performance estimator.	BIM and case study evaluation.	Use of BIM and calculate the reusability and recyclability of building materials accurately.	Buildings designed with the BIM tools have the potentialities to provide 93% reusable components.

Table 5.
Focus on design for disassembly.

Abbasabadi [11, 34] compared embodied energy of building materials on different floor levels in **Table 6**.

3.1.2 Windows and window frames

Giordano [44] investigated the operational energy (OE) and embodied energy (EE) of different types of façades in 5 climatic zones. Although, in terms of OE,

Source	Method	Number	Structural System & Material	EE of Structure	Total	CED
		of floors		(GJ/m^2)	EE(GJ/m^2)	(GJ/m^2)
Treloar, et al. [26]	Economic Input–output	3	Precast concrete walls, floors and columns	—	10.7	—
		7	Reinforced concrete	—	11.9	—
		15	Reinforced concrete frame	—	16.1	—
		42	Reinforced concrete core with composite columns	—	18	—
		52	Steel frame with reinforced concrete core and floor slabs	—	18.4	—
Foraboschi et al. [2]	Process-based	20	Steel frames and steel-concrete floor	3.3	—	—
		30		3.3	—	—
		70		5.6	—	—
		20	Reinforced concrete frames and slabs	2.2	—	—
		30		2.3	—	—
		20	Reinforced concrete frames and floors with the 3rd lightweight floor system	2.9	—	—
		30		3	—	—
		60		3.8	—	—
		70		3.8	—	—
Bawden and Williams [38]	Hybrid	3	Wood siding and wood frame	—	—	30
		3	Stucco on concrete block/wood joists	—	—	29.9
		4	Precast concrete panels/reinforced concrete	—	—	33.6
		4	Precast concrete panels/steel	—	—	33.7
		7	Precast concrete panels/reinforced concrete	—	—	33.8
		7	Precast concrete panels/steel	—	—	34
		11	Ribbed precast concrete/ reinforced concrete	—	—	39

Source	Method	Number	Structural System & Material	EE of Structure	Total	CED
		11	Ribbed precast concrete/steel	—	—	39.9
		21	Ribbed precast concrete/ reinforced concrete	—	—	38.6
		21	Ribbed precast concrete/steel	—	—	39.5

Table 6.
Embodied energy as a function of the number of the floors [44].

double skin systems involve lower operational energy requirements in all the climate zones, but consume higher embodied energy (**Figure 6**).

They have also experimented with the double-skin façade (U-1.10 W/m^{2}K) of "The Shard" in the UK and found that the embodied energy has increased almost double than the typical single-skin façades. Azari and Abbasabadi [11, 43] experimented with the embodied energy of different window systems from cradle to grave and found that wood has the lowest embodied carbon emission. The performance of PVC is completely opposite to the wooden window systems and Aluminum has a high operational and embodied carbon emission rate (**Figure 7**, **Table 7**).

3.1.3 Fabric insulation

In Europe, inorganic fibrous insulations like glass wool and stone wool are dominating the market of insulation materials (almost 60% of the market), and organic foamy materials like polystyrene and polyurethane account are almost 27% of the market. Different glass types, window-to-wall ratio, size, number of glass panes, and frame types are responsible for the embodied carbon emission of windows (**Table 8**).

Therefore, EE studies of tall buildings should be facilitated by comparing available materials and developing inventory databases of building materials and tools that represent tall building construction practices [43] Designer's choice made on all

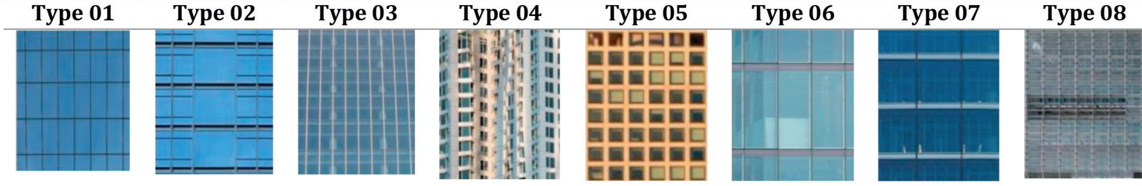
Type 01	Type 02	Type 03	Type 04	Type 05	Type 06	Type 07	Type 08
							
Single Skin	Single Skin	Single Skin	Single Skin	Double Skin	Double Skin	Double Skin	Double Skin
Insulated Glass, Curtain wall	Insulated Glass, Spandrel panel, Curtain wall	Triple insulated Glass, Curtain wall	Insulated Glass, Spandrel panel, Curtain wall	Insulated Glass, window wall	Insulated Glass, stratified glass, natural ventilation	Insulated Glass, stratified glass, mechanical ventilation	Insulated Glass, stratified glass, operable louver
U_{cw}= 1.52 W/m^{2}K	U_{cw}= 1.59 W/m^{2}K	U_{cw}= 1.14 W/m^{2}K	U_{cw}= 1.66 W/m^{2}K	U_{cw}= 1.45 W/m^{2}K	U_{cw}= 1.10 W/m^{2}K	U_{cw}= 1.12 W/m^{2}K	U_{cw}= 1.23 W/m^{2}K
g-value= 33%	g-value= 38%	g-value= 33%	g-value= 40%	g-value= 42%	g-value= 12%	g-value= 32%	g-value= 33%

Figure 6.
Embodied energy analysis of glazed façade typologies [44].

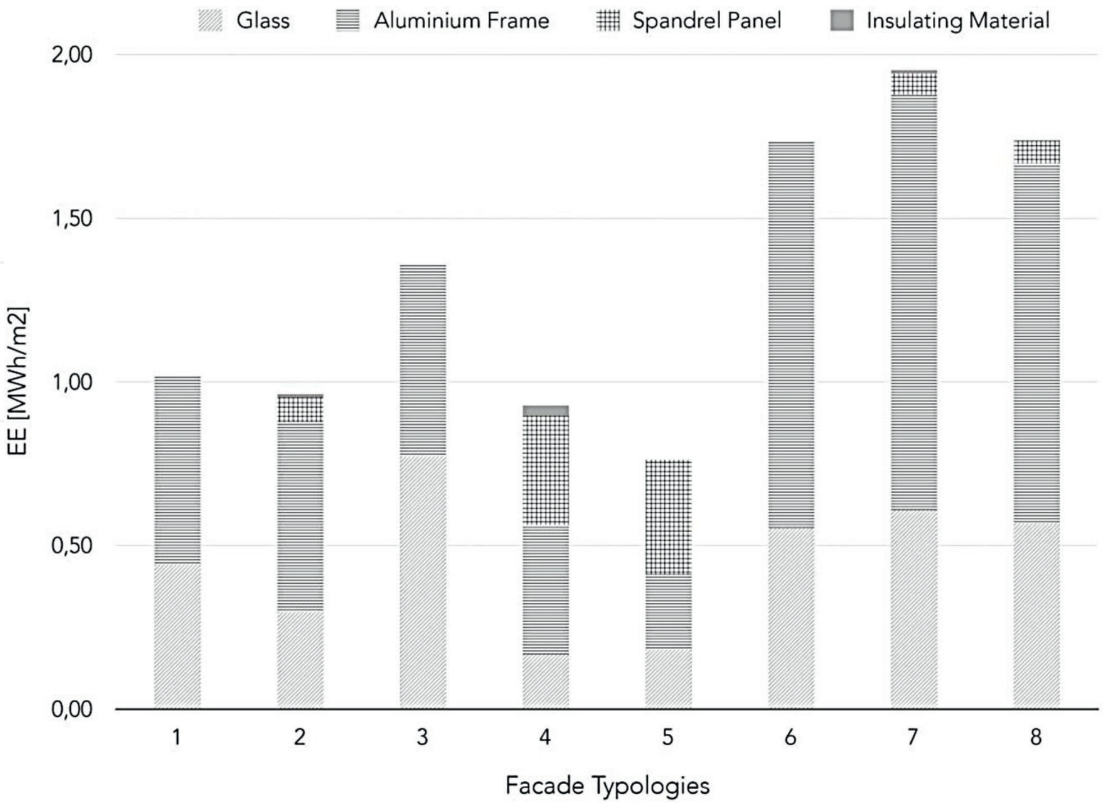


Figure 7.
Embodied energy analysis of glazed façade typologies chart [44].

Frame		Glazing	Conductivity of window ($W/m^2/°C$)	EE of window (kWh)	OE ∗ 50 yrs. (kWh)
Material	Recycled content				
PVC	0	double	0.65	352.6	1427.4
PVC	30%	double	0.65	312.6	1427.4
Aluminum without thermal break	0	double	0.89	2218.5	2194.5
Aluminum without thermal break	30%	double	0.89	1643.5	2194.5
Aluminum with thermal break	0	double	0.77	2219	1600
Aluminum with thermal break	30%	double	0.77	1644	1600
wood	—	double	0.68	138.2	1906.8
wood	—	single	1.14	84.1	2548.9

Table 7.
Cradle-to-grave embodied energy and operational energy of different windows [43].

the materials in the building construction can introduce reductions of 50% of non-renewable life cycle EE in the buildings (Himpe E et al. 2013). Comparing the embodied energy emission of steel, concrete, and wood, the following results were found.

For the non-zero-energy buildings, the impact of the building services was about 5% of the life cycle EE which is negligible but the impact of the building services

	Density	Embodied Energy	Conductivity	Embodied Energy
	(kg/m^3)	MJ/kg	(W/m/K)	(MJ/m^2/RSI)
Cellulose	40–70	0.9	0.045	1.6–2.8
Fiberboard (Enginering Wood)	190–240	11.2–11.8	0.053–0.45	113–127
Polystyrene	15–30	127	0.032–0.30	61–113
Polyurethane	30–35	137	0.035–0.020	144–96
Mineral Wool	20–140	18	0.045–0.035	16–88
Fiberglass	35	22.2	0.04	31.1

Table 8.
Embodied energy of insulation panels [43].

of zero-energy tall buildings rose to 18 and 48%. The area of research on building embodied energy is still a largely unexplored area. Many of the existing studies on EE are subject to inconsistently reported methodologies, poor data quality, lack of technological and geographical representativeness, limitations in the generalizability of results and repeatability of research, etc. [11]. While there exist strong quantitative methodologies for EE estimation in the built environment, the lack of standardized protocols is still a major problem. To reduce the embodied energy of tall buildings and increase material circularity, BIM can assist construction and demolition by providing an accurate number of materials. So that contractors are aware of valuable components which can be used in the process of circular economy.

The embodied energy of building materials is an essential component for calculating the potentialities of the circular economy of building materials. Building materials that have higher embodied energy can be recycled or reused more than materials with lower embodied energy. As a consequence, it is important to investigate and select the building materials which have lower embodied energy and high potential to reuse or recycle several times.

4. Circular economy building materials matrix

O'Grady [33] introduced the 3DR method (design, disassemblability and deconstructability) which was used to prepare a circular economy index by considering the design stage, disassembly, deconstruction, resilience of the buildings' structural fabric and finishing components. The potential second life of building materials, reuse, recycling, downcycling or disposal and the difficulty of separating materials from each other was the main influence in preparing the index [33].

The necessity of circular economy building material matrix is significantly rising as there is no specific matrix yet which can be followed by the designers to select the potential building materials. Designers and users are being more conscious of the need for recyclability and reusability of different materials to ensure holistic sustainability. But this is very challenging for them when they want to select materials for construction due to the lack of material database and tables. They need to study and research the materials to figure out the most potential materials which have the maximum value of reusability and recyclability. Due to this reason, many designers often ignore the considerations of the circular economy of building materials.

Consequently, the building construction and demolition industries are contributing the largest portion of wastage globally.

To prepare that matrix, building materials need to be selected by assessing their quality to follow the principles of circular economy. Extensive literature reviews will be studied to identify the potentialities of recyclability, reusability, toxicity, tolerance of assembly and disassembly, amount of wastage and finishing requirements of the building materials which have been being used in different types of buildings. Collected data will be used to prepare the circular economy building matrix which can be used to select the building materials that satisfy the principles of circular economy.

5. Circular economy barriers and mitigations

According to the study by [43, 45], there are 16 barriers if the circular economy in developing countries' supply chains. Among them, "lack of sufficient environmental regulations" and "lack of policies for promoting circular economy" were the main barriers. Their survey also found that only 65.33% of professionals were aware of the circular economy.

Out of 25 barriers identified from the literature, 12 barriers were shortlisted by building sector experts [45]. The MICMAC technique and CE barriers-indicator matrix were used by Bilal et al. [46] to identify key barriers to CE. According to their study, the key barriers were "lack of environmental laws and regulations", "lack of customer/public awareness", "lack of support/public awareness" and "inadequate financial resources". They also recommended further CE assessment by collecting

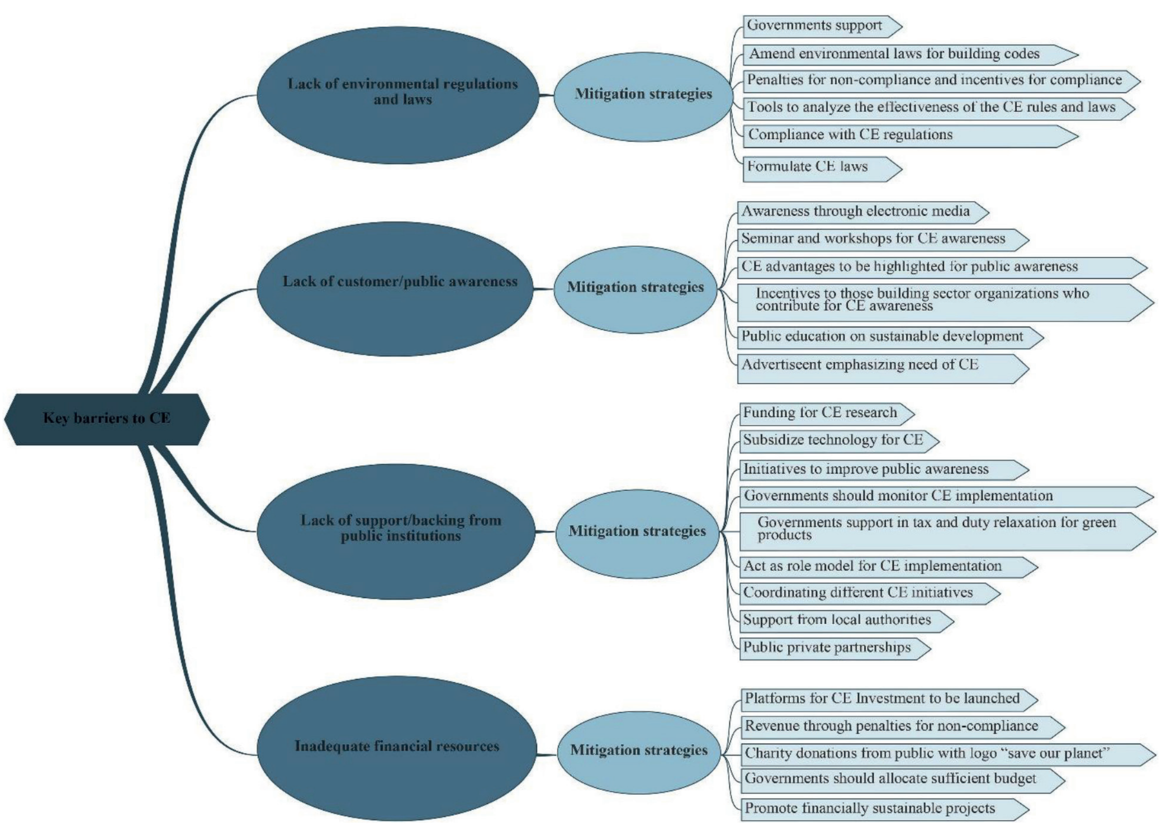


Figure 8.
Circular economy barriers mitigation framework [46].

quantitative data, the round of expert's opinions, testing building materials, and preparing database (**Figure 8**).

Inadequate knowledge and certified professionals on circular economy strategies are also significant construction problems of circular economy for a new generation and refurbished buildings. In many cases, the designers are selecting the building materials without being aware of the whole life cycle scenario of the materials. Sometimes the strategies are based on so many assumptions which may lead the strategy to failure which.

Additional detailed information should be included in the "Circular Economy Statement" which is prepared to submit to the Greater London Authority (GLA). So that, the strengths and weaknesses of the proposed strategies can be identified properly to ensure the presence of adequate measures.

6. Conclusion

Circular economy of building materials can significantly preserve the embodied carbon which is not properly defined in building regulations yet. Therefore, further improvements to the building regulations are recommended to achieve the reduction target of building energy consumption. The relationship between operational carbon and embodied carbon should be considered from the early design stage as there is always a possibility of higher embodied energy during the optimization process of the operational energy. The properties of the building materials play a vital part in resource and energy efficiency in buildings. Hence, building material matrices are also recommended to develop continuously with new materials and follow regularly to select the building materials. This process will help to enhance the potentialities of circular economy in our building construction industries and reduce the consumption of primary resources and overall project cost as well.

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