

OPEN ACCESS

Volume: 5

Issue: Special 2

Month: October

Year: 2026

ISSN: 2583-7117

Published: 15.10.2026

Citation:

Saniya Nitin Jadhav “ Carbon Reduction Through 4Rs: Adaptive Reuse of an Existing Building(s) on Site” International Journal of Innovations in Science Engineering and Management, vol.5, no.S2, 2026, pp. 15-25

DOI:

10.69968/ijisem.2026v5iS215-25



This work is licensed under a Creative Commons Attribution-Share Alike 4.0 International License

Carbon Reduction Through 4Rs: Adaptive Reuse of an Existing Building(s) on Site

Saniya Nitin Jadhav¹¹VESCOA

Abstract

This research proposes a module to assess carbon reduction through the 4Rs (Reduce, Reuse, Recycle, Recover) within the framework of adaptive reuse of existing buildings. The study proposes retrofit as a potential solution in response to increasing demolition practices and resource-intensive construction, to reduce material consumption, embodied emissions, and construction waste, while retaining architectural identity and continuity.

The methodology is based on on-site documentation, material inventory mapping, and condition assessment to quantify existing material systems. Two scenarios are considered: a baseline case that considers the building as it is, and a proposed case that utilizes the 4R framework by selective retention, repair, reuse, and replacement of materials. Embodied carbon is calculated using a spreadsheet-based carbon assessment tool from Solar Decathlon India (SDI), supported by standard emission factor datasets and material quantification.

The baseline scenario results in 19.4 tonnes CO₂e, while the proposed retrofit reduces emissions to 3.8 tonnes CO₂e, achieving a reduction of 15.6 tonnes CO₂e, equivalent to an 80.4% decrease in embodied carbon. The findings highlight the importance of material-level decision-making, particularly structural retention and debris reuse, in minimizing new material demand and associated environmental impacts.

The study establishes a quantifiable and replicable framework that integrates material evaluation, carbon quantification, and circular strategies, offering potential for application in similar retrofit contexts and informing future low-carbon architectural practice.

Keywords; Adaptive Reuse, Embodied Carbon, 4R Framework, Heritage Retrofit

INTRODUCTION

“The most sustainable building is the one that is already built”. The given principle becomes particularly topical as the construction sector worldwide is becoming larger thus putting the strain on the material resources, energy systems, and waste cycles. During the demolition of old buildings, an assessment of the material worth of the buildings, their service life, and the environmental impacts of total demolition are often not performed. This practice is a source of considerable embodied carbon emission, which represents an almost a third of overall building industry emissions.

In order to produce new construction materials, including steel, cement and bricks, intensive energy is needed and lots of greenhouse gases are produced. This increases the amount of new material inputs demanded as the urbanization process accelerates thus increasing the emissions and depleting the resources.

Conversely, recycling of existing constructed fabric conserves the energy already stored in foundations, walls, floors and structural systems. It also minimizes the amount of waste produced during the demolition process and lessens the environmental cost of production of new materials and their transportation.

Research highlights that the practice of prolonging the life of buildings is one of the most effective in alleviating environmental impact in the construction industry. Alternative to demolition and complete replacement, retrofit-oriented approaches encourage a critical evaluation of elements which can be maintained, those which require repair and those which can be improved through minimal intervention. This shift from replacement to retention enables more responsible use of materials and aligns architectural practice with broader sustainability goals. Retrofit strategies can be used to reduce the gap between environmental stewardship on the one hand and practical decision-making in design, because they conceptualize buildings as an asset that can be reused, rather than a structure that should be discarded.

The 4R framework, consisting of Reduce, Reuse, Recycle, and Recover, provides a systematic method to evaluate retrofit strategies and their environmental outcomes. By identifying materials that can be conserved, repurposed, or replaced, the framework enables a comparison between full material replacement and selective retrofit scenarios, allowing embodied carbon savings through material conservation to be quantified.

PROBLEM STATEMENT

The demolition of old buildings emits large quantities of embodied carbon due to the waste disposal, new material production and transportation. However, such environmental effects are seldom counted before taking the decision to destroy something, even in cases where an important part of the waste such as the stone masonry is still

structurally fit to be salvaged. Such negligence is causing unnecessary emissions and avoidable waste of resources. Moreover, the demolition also destroys the cultural memory and knowledge on the construction of traditional materials and techniques. No direct, quantifiable method of comparing the environmental advantages of retention, repair, or reuse of materials with the process of creating a new one is now forthcoming, regardless of such losses.

This study addresses this gap by creating a measurable 4R based (Reduce, Reuse, Recycle, Recover) framework to evaluate the embodied carbon implications of retrofit and demolition of a building.

Aim

To design a measurable 4R based assessment module that quantifies embodied carbon reduction by comparing the baseline condition of an existing building with a proposed selective retrofit scenario.

Objective

- To increase the focus on retrofitting of existing buildings as an alternative to demolition and re-development.
- To understand the role of material retention and debris reuse in reducing new material demand and overall carbon emissions.
- To demonstrate that low carbon outcomes can be achieved through simple, measurable retrofit decisions at the material scale.

Research Methodology

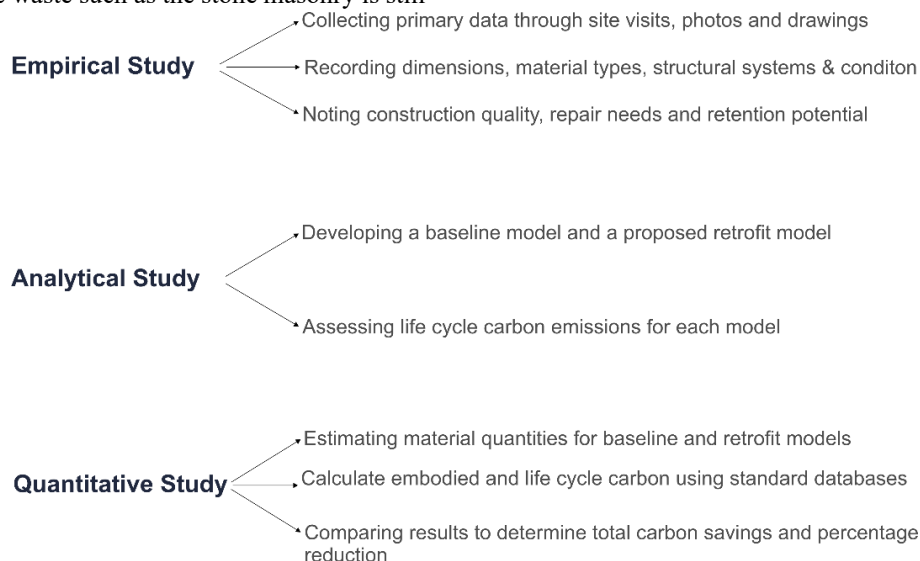


Figure 1 Methodology

Source: Author

- To calculate the embodied carbon of the baseline material using standard EF (emission factors).
- To identify materials that can be retained, repaired, reused or recycled through the 4R framework.
- To assess the embodied carbon impact of a proposed selective retrofit based on low carbon material inventions (proposed case).
- To compare baseline and proposed cases to find out the total carbon savings achieved through retrofit.
- To establish a replicable module that can be used as a guide for future retrofits of small traditional structures.
- Embodied carbon is calculated using carbon assessment tool by Solar Decathlon India (SDI),

supported by standard emission factor datasets and material quantification.

Research Focus

The focus is on understanding how much environmental value lies within existing materials and how retrofit strategies can meaningfully reduce carbon emissions at a building scale. The research aims to demonstrate that even small structures, when assessed through a clear and replicable method, can offer significant insights into sustainable construction practice and responsible resource use.

LITERATURE REVIEW: STRATEGIES

Circular Economy

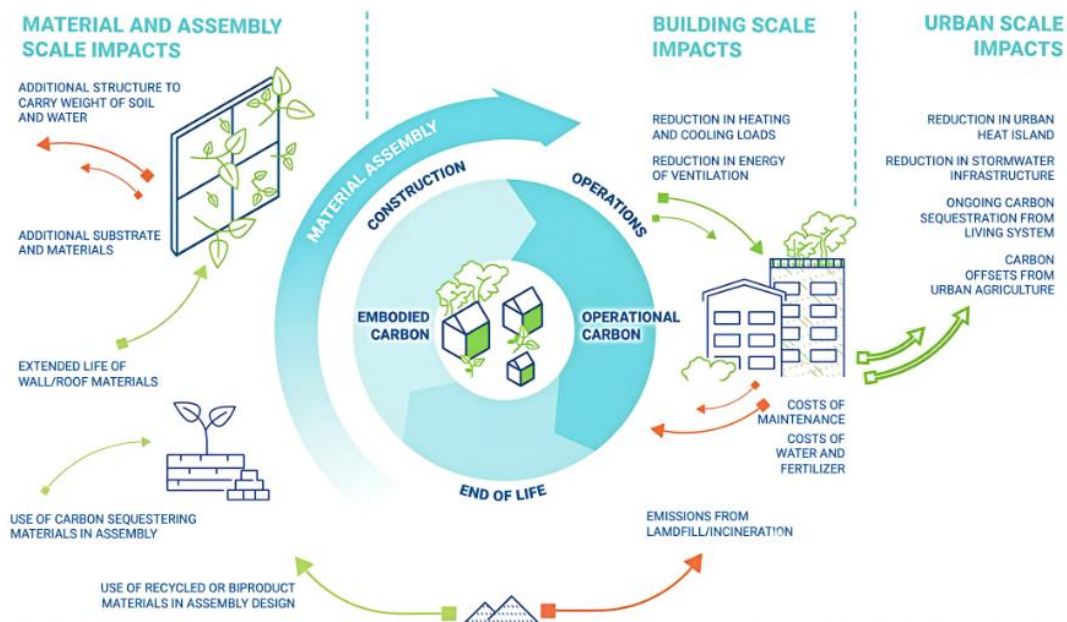


Figure 2 Circular Economy

Source: Yale University

Circular economy is an economic system that minimizes the use of raw materials and the generation of waste. Materials are reused and recycled to maximize their lifetime, and social and economic benefits, approximating a sustainable closed-loop system. (Ewijk, n.d.). In the construction industry, the circular economy focuses on minimization of waste of materials by increasing the life span of construction materials and components. By repairing, maintaining and retrofitting old buildings, the materials continue to be in use over a long period hence reducing the need to produce new materials. Long durability of quality and structural integrity of building elements and materials, with or without significant maintenance, requires reduction in embodied energy over time.

Increasing material lifespan effectively removes the necessity to make new materials, and therefore leads to significant carbon reductions in embodiment. The other notable aspect of the circular economy is the aggressive utilisation of the existing buildings by adding new programmes, multipurpose spaces and adaptive reuse.

The need to reduce the closure of the already established structures, by making them used in the best way, results in the reduction of the new construction demand bringing money to the economy, subsequently decreasing the environmental footprint of the extraction, production, and transportation of the raw materials.

**Carbon
Bank**

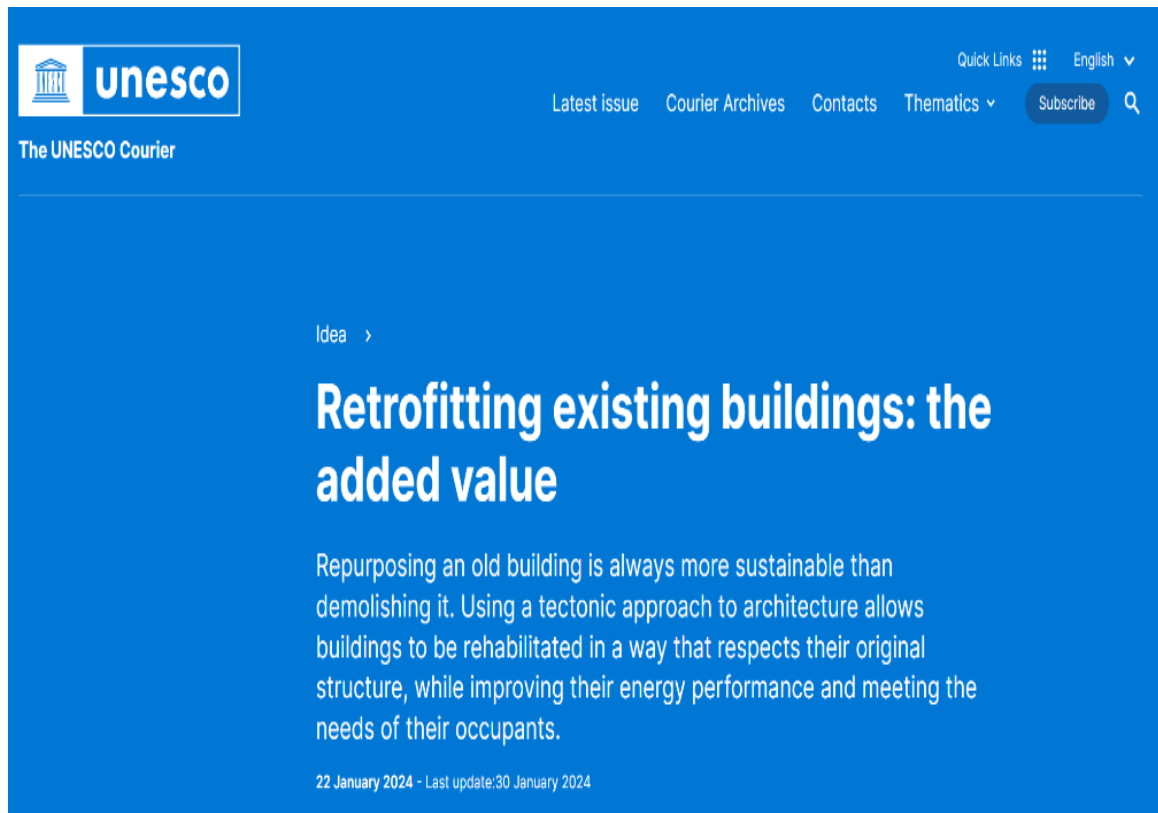


Figure 3: Retrofitting existing buildings

Source: UNESCO

UNESCO highlights that a tectonic, retrofit-oriented approach allows buildings to be upgraded while respecting the integrity of the original structure, ensuring that cultural and architectural value is not lost during the intervention.

Embodied Carbon Calculation



Image 1 Identified Structures (Underused/Dilapidated) on Site
Source: Author



Image 2: Structure Identified for analysis (Structure A)

Location Maheshwar, Madhya Pradesh, India
Building Typology (Currently underuse)
Local Karyalay
Level- G story (4.5 m)
Existing Built Up Area 125 sqm

Local Materials (Stone, Bricks, Timber), GI Sheets (Roof), Ceramic Materials Used Tiles (Interior)

MATERIAL QUANTIFICATION

The following table (Table 1) demonstrates how the quantification of various building elements such as the roof,

floor and wall systems. This step is the basis of carbon analysis because the volume and weight of material directly affect the lifecycle emissions. The building element classification enables a comparison of carbon contribution on individual components which can help identify high-impact materials. (Council, 2019)

Table 1 Material Quantification

Source: Author

Category	Material	Unit	Quantity
Roof	Air-dried sawn timber	kg	2250
	Corrugated Metal sheet	kg	1470
Floor	Tile adhesive for ceramic/concrete tiles	kg	800
	Cement floor screed (concrete screed)	kg	13125
	Glazed ceramic floor tiles	kg	2500
	PCC Bed	kg	30000
Wall	Stone (crushed)	kg	146025
	Cement based plaster	kg	6195
	Brick (common/facing)	kg	2390
	Cement mortar	kg	9765
	Brick (common/facing)	kg	7245

MATERIAL INVENTORY & CONDITION ASSESSMENT

A material inventory records every component of the existing building its type, quantity, and visible condition. Through systematic assessment, each material is evaluated for structural integrity, deterioration level, and potential for reuse, repair, recycling, or replacement. (Council, 2019)

Quantification then converts these observations into measurable units (kg or m²), forming the baseline dataset for calculating embodied carbon. This step ensures that retrofit decisions are evidence-based, environmentally informed, and aligned with the 4R framework. (Intergovernmental Panel on Climate Change, 2021)

Table 2 Material Inventory & Condition Assessment

Source: Author

System	Material	Existing Condition	Reuse Potential	Action (4R)	Quantity (in kg)
Wall System	Stone masonry	Strong, intact, no structural failure	Very high	Retain (Reduce)	171620
	Internal plaster	Cracks, moisture patches	Low	Replace / Repair	
	External plaster	Weathered, partial loss	Medium	Repair (Recover)	
	Cement mortar (joints)	Deteriorated in few bands	Medium	Repair (Recover)	
Roof System	Timber rafters	Partially aged, some reusable	Medium	Recover (Selective reuse)	3720
	GI sheets	Rusted, perforated	Very low	Replace	
Floor System	Ceramic tiles	Worn, old	Low	Replace	46425
	PCC bed	Intact	High	Retain	

Baseline Embodied Carbon Calculation

The baseline embodied carbon calculation (Table 3) establishes the total carbon emissions of the existing building in current condition, prior to any intervention. This is done to measure the environmental impact of materials already incorporated in the structure and which act as a benchmark in the comparative analysis of retrofit strategies.

It is calculated using a material-wise method, in which quantified material data is multiplied by the relevant data on emission factors (kg/CO₂e/kg) and standard life-cycle assessment practices are followed. (Royal Institution of Chartered Surveyors, 2017)

This facilitates specific decision-making towards carbon reduction, aligned with international frameworks for low-carbon construction. (Council, 2019)

Table 3 Baseline Embodied Carbon Calculation

Source: Author

Roof	Material	Unit	Material manufacturing emissions		
			Quantity	Emissions Factor	Material Emissions (kg -CO ₂ e)
	Electrogalvanized steel sheet ("corrugated zinc")	kg	120	3	360
	Air-dried sawn timber	kg	2250	-1.3	-2925
	Electrogalvanized steel sheet ("corrugated zinc")	kg	100	3	300
	Electrogalvanized steel sheet ("corrugated zinc")	kg	1250	3	3750
Floor	Material	Unit	Material manufacturing emissions		
			Quantity	Emissions Factor	Material Emissions (kg -CO ₂ e)
	Tile adhesive for ceramic/concrete tiles	kg	800	0.47	376
	Cement floor screed (concrete screed)	kg	13125	0.18	2363
	Glazed ceramic floor tiles	kg	2500	0.67	1675
	PCC Bed	kg	30,000	0.145	4350
Wall	Material	Unit	Material manufacturing emissions		
			Quantity	Emissions Factor	Material Emissions (kg -CO ₂ e)
	Stone (crushed)	kg	1,46,025	0.009	1314
	Cement based plaster	kg	6195	0.44	2726
	Brick (common/facing)	kg	2390	0.39	932
	Cement mortar	kg	9765	0.14	1367
	Brick (common/facing)	kg	7245	0.39	2826

$$\text{Embodied Carbon (kg CO}_2\text{e)} = \text{Quantity (kg)} \times \text{Emission Factor (kg CO}_2\text{e/kg)}$$

$$\text{Total Baseline CO}_2\text{e (Walls + Roof + Floor)}$$

$$\text{Baseline Total} = \text{Baseline Total (Walls + Roof + Floor)} = 9165 + 1485 + 8764 = 19,414 \text{ kg CO}_2\text{e} = 19.4 \text{ tonnes CO}_2\text{e}$$

*Embodied carbon was calculated using the standard life-cycle assessment approach in accordance with **ISO 14044** and **EN 15978**, where environmental impact is determined by multiplying material quantities (kg) with corresponding emission factors (kg CO₂e/kg)

The baseline case represents the embodied carbon stored in the existing stone-masonry building in its current condition. This model establishes a reference point against which the carbon savings of the proposed retrofit strategy can be measured.

Purpose of Baseline Model:

- A control case for comparison
- A quantifiable benchmark for evaluating retrofit efficiency

- A demonstration of the carbon cost of discarding existing built fabric

Calculating Salvageable Mass

Recovery Factors were estimated through my on-site assessment of material condition and supported by standard salvageability ranges reported in deconstruction literature. (Salvageability ranges published in deconstruction guidelines (DOE, CIWM), which report high recovery potential for stone and steel (70–95%) and low recovery for bonded materials)

Materials like stone and timber showed high recoverability, while plaster, mortar and tiles had low salvage potential. The final RF values reflect both observed site conditions and accepted industry guidelines.

Table 4 Calculating Salvageable Mass

Source: Author

Material	Baseline Mass (kg)	Recovery Factor (%)	Salvageable Mass (kg)
Stone (Basalt Stone wall)	146025	80%	116820
Timber Rafters	2250	90%	2025
GI Sheets	1470	50%	735
Cement plaster	6195	30%	1858
Floor Screed	13125	50%	6563
Brick patches (infill)	2390	70%	1673
Internal brick partition	7245	70%	5071
Timber Fenestration	219	90%	197

Avoided Manufacturing Emissions through Material Recovery

This table quantifies the emissions saved by reusing salvageable materials instead of manufacturing new ones.

For each material, the salvageable mass is multiplied by its emission factor to determine how much CO₂ would have been released if that same quantity were newly produced.

Table 5 Avoided Manufacturing Emissions through Material Recovery

Source: Author

Material	Salvageable Mass (kg)	EF (kgCO ₂)	Avoided Emissions (kgCO ₂)
Stone (Basalt Stone wall)	116820	0.009	1051.4
Timber Rafters	2025	-1.30	-2632.5
GI Sheets	735	3.00	2205.0
Cement plaster	1858	0.44	817.5
Floor Screed	6563	0.18	1181.3
Brick patches (infill)	1673	0.39	652.5
Internal brick partition	5071	0.39	1977.7
Timber Fenestration	197	-1.30	-256.1
TOTAL AVOIDED MANUFACTURING EMISSIONS			4996.8

Reuse Scenario: Avoided Emissions & Net Carbon Impact

This step evaluates the embodied carbon implications of material reuse in embodied carbon by determining avoided

emissions, as well as other effects of processing and transportation. The aim is to identify the net carbon advantage or cost of maintaining and reusing old materials in the building system.

Table 6 Calculating Net Reuse

Source: Author

Material	Avoided Emissions (kgCO ₂)	Processing (kgCO ₂)	Transport (kgCO ₂)	Net reuse (kgCO ₂)
Stone (Basalt Stone wall)	1051.4	2336.4	1543.02	-2828.03
Timber Rafters	-2632.5	20.25	13.39	-2666.14
GI Sheets	2205.0	36.75	4.85	2163.40
Cement plaster	817.5	18.59	12.29	786.66
Floor Screed	1181.3	65.63	43.48	1072.14
Brick patches (infill)	652.5	33.46	11.05	607.96
Internal brick partition	1977.7	101.43	33.56	1843.80
Timber Fenestration	-256.1	1.97	1.31	-258.10

Due to stone's high mass and very low material emission factor, dismantling basalt stone and transporting it for reuse results in higher carbon emissions than preserving the wall in-situ. Therefore, the project retains the stone walls and uses only minimal lime-based repair, making it the lowest-carbon strategy.

Timber elements yield significant carbon storage credit due to their negative embodied-carbon factor in the database. Reusing timber rafters and fenestration delivers considerable avoided emissions and aligns with circular economy principles.

$$\text{Processing emissions} = \text{Salvageable mass} \times \text{processing EF}$$

$$\text{Transport emissions} = \text{Salvageable mass} \times \text{distance (km)} \times \text{Transport EF}$$

$$\text{Distance Considered} = \text{Manufacturer} \rightarrow \text{Supplier} = 50\text{-}55\text{km}$$

$$\text{Supplier} \rightarrow \text{Site} = 3\text{-}5\text{km}$$

Debris Quantification (Leftover Material Assessment)

Debris is the unrecovered part of materials after the action of the recovery factor. Its carbon effect includes the emissions on residual mass besides the energy used in processing and moving which makes it an important pointer of the environmental cost involved with demolition.

The carbon effect of the debris includes, the embodied emissions that are attributed to the remaining mass as well as the emissions that are incurred in the course of processing and transport necessary to dispose the mass.

Table 7 Debris Quantification

Source: Author

Material	Baseline Mass (kg)	Reused Mass (kg)	Leftover Mass (kg)
Stone (Basalt Stone wall)	146025	116820	29205.00
Timber Rafters	2250	2025	225.00
GI Sheets	1470	735	735.00
Cement plaster	6195	1858	4337.00
Floor Screed	13125	6563	6562.00
Brick patches (infill)	2390	1673	717.00
Internal brick partition	7245	5071	2174.00
Timber Fenestration	219	197	21.64

Debris Management Strategy (Reuse- Recycle- Down-cycle Mapping)

Table 8 Debris Management Strategy

Source: Author

Material	Reused (%)	Recycled (%)	Down-cycled (%)	Use
Stone (Basalt Stone wall)	80%	0%	20%	Wall are kept intact, leftover stone used as site fill
Timber Rafters	90%	0%	10%	Reusing rafters, leftovers used as battens
GI Sheets	50%	50%	0%	1:1 half reused, leftovers sent to recycling yard
Cement plaster	30%	0%	70%	Debris crushed and used as fill
Floor Screed	50%	0%	50%	Screed debris for filling/landscape
Brick patches (infill)	70%	0%	30%	Salvaged and broken bricks reused as sub-base
Internal brick partition	70%	0%	30%	Broken brick chips reused
Timber Fenestration	90%	0%	10%	Repair and reuse, scraps will be used for joinery

The deconstruction of the substance resulted in both recyclable materials and debris that is impossible to take away. Instead of accepting this debris as waste, all materials were identified into streams of reusable, recycled, and down-cycled material based on their physical appearance, wearability and their applicability in a second use.

The components that can be reused are stone, timber, and brick as they are in a good condition and can be readily

rediscovered, and cement-based layers, e.g., plaster and floor screed, are usually down-cycled since they are fragmented and shattered during the destruction process.

This distribution will mean that a significant part of the remaining material will be reused on-site or recycled in other processing plants, or used as fill or sub-base material, and so a large amount of landfill disposal and the pollution it generates will be avoided.

Comparison of Baseline and Proposed Model

Table 9 Comparison of Baseline & Proposed Model

Source: Author

Roof	Material	Unit	Material manufacturing emissions		
			Quantity	Emissions Factor	Material Emissions (kg -CO ₂ e)
	Electrogalvanized steel sheet ("corrugated zinc")	kg	120	3	360
	Air-dried sawn timber	kg	2250	-1.3	-2925
	Electrogalvanized steel sheet ("corrugated zinc")	kg	100	3	300
	Electrogalvanized steel sheet ("corrugated zinc")	kg	1250	3	3750
Floor	Material	Unit	Material manufacturing emissions		
			Quantity	Emissions Factor	Material Emissions (kg -CO ₂ e)
	Tile adhesive for ceramic/concrete tiles	kg	800	0.47	376
	Cement floor screed (concrete screed)	kg	13125	0.18	2363
	Glazed ceramic floor tiles	kg	2500	0.67	1675
	PCC Bed	kg	30,000	0.145	4350
Wall	Material	Unit	Material manufacturing emissions		
			Quantity	Emissions Factor	Material Emissions (kg -CO ₂ e)
	Stone (crushed)	kg	1,46,025	0.009	1314
	Cement based plaster	kg	6195	0.44	2726
	Brick (common/facing)	kg	2390	0.39	932
	Cement mortar	kg	9765	0.14	1367
	Brick (common/facing)	kg	7245	0.39	2826

RESULT

The baseline assessment has documented an embodied carbon of 19.4 tonnes CO₂e, wall and floor systems have the biggest proportion because of the mass of the material and the cement composition. The 4R framework is used to determine that stone masonry and timber are highly recoverable materials, whereas finishes like plaster and mortar are not very reusable.

The proposed retrofit is 3.8 tonnes CO₂e, with a reduction of 15.6 tonnes CO₂e (80.4) being reached. The

structural stone and timber are reused or held up, about 80–90 percent has been reused and this would greatly lessen the need to input new materials and the resource expenditure used.

As the observations show, retention of the existing materials is more productive than reuse by dismantling, especially of heavy materials, like the stone, when further processing and transportation diminish the overall benefits. Reduction of carbon on the embodiment level is thus dominated by the need to reduce new material requirements,

and selective retention proves to be the most efficient approach.

DISCUSSION

The results align with the existing literature that pinpoints material retention as one of the primary measures to minimize embodied carbon. According to research by Ding (2016) and Lutzkerndorf and Balouktsi (2022), reuse and retention of materials greatly reduces emissions.

In the same manner, the case studies of adaptive reuse indicate that conservation of structural systems has a reduced carbon impact than demolition and reconstruction. Nevertheless, as literature widely encourages reuse, this paper discusses a critical difference: retention in place is frequently more efficient than reuse, particularly in the case of high-mass materials. This brings in a material-specific view which is not as highlighted in the existing studies.

The methodology is consistent with the existing standards like ISO 14044 and EN 15978, in which the embodied carbon is determined as the product of the material quantities and emission factors. The spreadsheet-based tool (SDI) is used to achieve the consistency with these standards and simplify the process to be used in practice. The methodology adopted in this study offers a more accessible material-level framework compared to the traditional LCA techniques, which tend to be complex and require a lot of data.

Compared to literature on large-scale buildings, this work shows that small-scale buildings can have significant carbon savings, with a reduction of 80.4 being observed, supporting the usefulness of retrofit strategies at various scales.

CONCLUSION

The research concludes that the best approach to the minimization of embodied carbon in the case of retrofit is selective material retention. Using the 4R-based methodology, the study shows that the 4R of material-level decision-making are capable of making a substantial carbon reduction. The framework provides a viable and scaled means of incorporating carbon evaluation into the design, especially to small scale buildings.

LIMITATIONS

Although the reuse scenario allows gaining a comparative idea of possible carbon savings, some limitations are to be accepted. It depends on standardized emission factors, which might not adequately reflect the

differences in local material production processes or regional supply chains (Hammond, G., & Jones, C. (2011). *Inventory of Carbon and Energy (ICE), Version 2.0*. Bath: University of Bath.)

The avoided emission estimates are based on the assumption that the used materials directly substitute new materials, which is not necessarily possible because of design limitations, quality differences, or regulations. Moreover, processing and transportation effects are estimated by generalized assumptions and real values can be different according to the logistics and methods of handling on the sites.

The assessment also uses visible material condition as a determinant of reuse potential, but structural shortcomings or long-term structural problems are not factored in. In addition, the research assumes a cradle-to-gate scope, excluding impacts related to installation, maintenance and end-to-life scenarios, which could influence the overall carbon balance. (Royal Institution of Chartered Surveyors, 2017)

REFERENCES

Books

- [1] Ashby, M.F. (2013) Materials and sustainable development. Oxford: Butterworth-Heinemann.
- [2] Akin, B.A. (2020) Sustainable building assessment. Abingdon: Routledge.
- [3] Buckley, A. & O'Malley, K. (eds.) (2021) Embodied carbon in buildings: a life-cycle approach. London: ICE Publishing.
- [4] European Commission (2018) Life cycle assessment of buildings: a practice guide. Luxembourg: Publications Office of the European Union.
- [5] Keeping, M. & Shiers, D. (2019) Sustainable building design: principles and practice. Hoboken: Wiley-Blackwell.
- [6] Macdonald, D. (2011) Adaptive reuse: extending the lives of buildings. Abingdon: Routledge.
- [7] Preservation Green Lab (2011) The greenest building: quantifying the environmental value of building reuse. Washington, DC: National Trust for Historic Preservation.

Journal Articles

- [8] Ding, G.K.C. (2016) *Embodied carbon mitigation and reduction in the built environment – What does the evidence say?* Journal of Environmental

- Management, 181, pp.687-700. Available at: <https://doi.org/10.1016/j.jenvman.2016.08.036>
- [9] Lützkendorf, T. & Balouktsi, M. (2022) *Embodied carbon emissions in buildings: explanations, interpretations and recommendations*, Buildings and Cities. DOI:10.5334/bc.257
- [10] Savoie, É. (2025) *Key factors for revitalising heritage buildings through adaptive reuse*, Buildings and Cities. DOI:10.5334/bc.495
- [11] Vafaie, F. (2023) *Adaptive reuse of heritage buildings: a systematic literature review*, Journal of Cultural Heritage.
- [12] Odoi-Yorke, F. (2025) *Embodied energy in buildings: Two decades of research*, (Journal),
- [13] Hu, M. (2024) *Assessing the environmental benefits of adaptive reuse in historic buildings through life cycle analysis*, Journal of Sustainable Built Environment.
- [14] Huang, Y. (2024) *Including embodied carbon in assessing renovation options for historic buildings*, J. Housing & Built Environment, 33.
- [15] Griffiths, L. (2023) *A Case Study for future re-use of buildings to reduce carbon*, ArchScience
- NIST (2023) *Systematic Review of Embodied Carbon Assessment and Reduction Methods*, NIST SP.1324