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ARE WOOD BUILDINGS MORE CIRCULAR? A COMPARATIVE STUDY ON BUILDING CIRCULARITY BETWEEN REINFORCED CONCRETE AND TIMBER STRUCTURES

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ABSTRACT: Given the global emphasis on sustainable development, the construction industry is increasingly prioritising advancements in building circularity (BC). This study conducted a comparative analysis on BC of multi-storey reinforced concrete (RC) and timber frame structural systems: developing two digital models, a RC structure utilising conventional materials and a timber structure employing wood-based materials; performing structural analysis in *Midas Gen* to establish comparable foundations; and quantitatively assessing the circularity performances of the two structure types across four levels: materials, elements, systems and the building as a whole. The results highlighted the significant advantages of wood-based materials in enhancing BC at specific levels. This study offers architects and practitioners new perspectives and theoretical foundations for design decisions and material selection.

KEYWORDS: timber frame structures, wood-based materials, building circularity assessment, comparative study

1 – INTRODUCTION

Concrete and steel are the primary materials used for constructing multi-storey buildings. Due to the material properties and the construction methods, reinforced concrete (RC) buildings are typically demolished at the end of their life. The resulting waste is typically downcycled, which only extends the linear flow from virgin material to waste, rather than facilitating a circular loop. Compared to concrete and steel, wood-based materials are often used in prefabricated construction, offering more reversible connection options, which significantly enhances their potential for dismantling and subsequent direct reuse. This reusability contributes to reducing the environmental impact of timber buildings over their entire life cycle.

Previous studies on timber buildings have commonly used LCA (Life Cycle Assessment) and LCC (Life Cycle Cost) to analyse their environmental impact and economic benefits. However, few studies have quantified the improvements in circularity that have been achieved through the extensive use of wood-based materials [1]. Therefore, this study aims to establish a comparative basis for two building models utilising fundamentally different materials, and subsequently quantify their circularity by advanced assessment frameworks, and analyse their circular potential. Accordingly, it clearly identifies the specified roles and influences of wood-based materials in enhancing the building circularity (BC).

2 – METHODOLOGY

Initially, two material combinations respectively for RC and timber structures were predefined. The RC model incorporated concrete and steel for beams, columns, shear walls and floors, and concrete blocks for partition walls and external walls. The timber model included beams and columns in glued laminated timber (GLT), shear walls and floors in cross laminated timber (CLT), and partition walls and external walls made from OSB panels and lumbers. Second, structural models of both RC and timber buildings were developed in *Midas Gen* to achieve closely matched fundamental natural periods (FNP). So that, their structural layout, component dimensions and distribution were determined. Third, two building information models (BIMs) were correspondently created component by component in *Revit* based on the extracted material weights from the structural modelling results. This provided the Bill of Materials (BOM) with all the needed information of used building materials in the models. Finally, the Whole Building Circularity Indicator (WBCI) values of two building types were calculated and analysed (Fig. 1).

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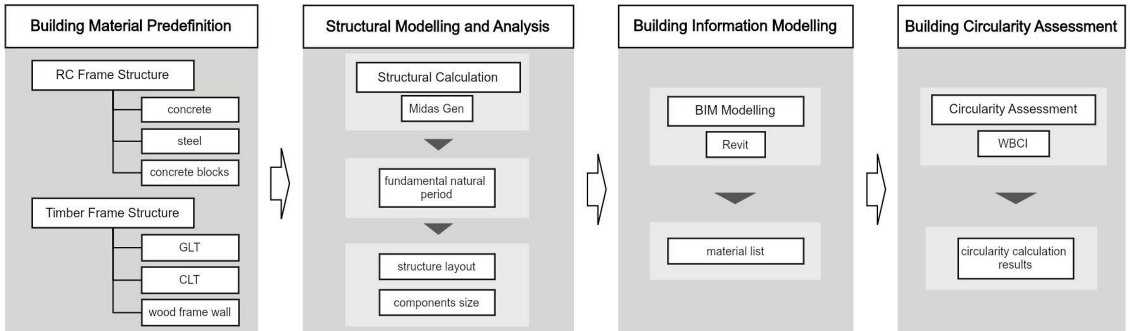

Figure 1. Research roadmap.

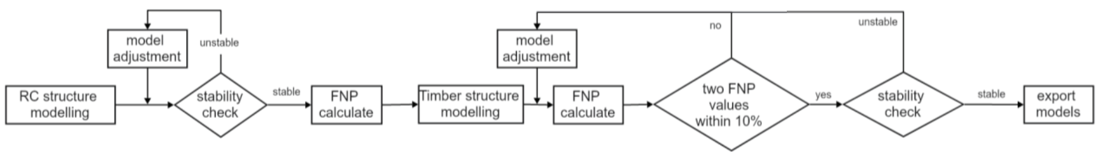

Figure 2. Structural calculation process.

2.1 STRUCTURAL MODELLING

The second step for structural modelling followed the workflow illustrated in Fig. 2. A 7-storey frame structure with the predefined RC material combination has been proposed. The built-in design and stability verification tools in *Midas Gen* comprehensively assessed the RC model's structural stability. If the stability check failed, modifications to the model's mass or layout must be implemented. Successful verification confirmed compliance of the load-bearing elements with specified axial, flexural, and shear strength requirements under anticipated loads [2]. Additionally, using the FNP analysis tool, the structural stress state and deformation patterns could be visualised, providing insights into the system's behaviour under load [3]. The FNP value is influenced by the structural layout and the mass distribution of components, offering a quantitative measure of the model's performance [4].

Then, a 7-storey timber structure was modelled with the same storey heights and column grids as the determined RC model. The FNP of the timber model was then calculated and compared with that of the RC model. If the difference between the two FNP values exceeded 10%, adjustments had to be made to the dimensions and distribution of the load-bearing components in the timber model [5]. Once the FNP convergence criterion was met, the timber model's stability check would be carried out under the same loading conditions as the RC model. These evaluations also encompassed axial, flexural and shear strength of the load-bearing components, as well as inter-storey displacement checks. If the model failed to meet these stability criteria, the load-bearing components went for adjustments. The FNP and stability checks repeated until all the standard requirements were satisfied [6]. It was only here that all the parameters of the two models were finalised.

2.2 BUILDING INFORMATION MODELLING

Following the determination of material, component dimensions and spatial distribution for both models, the third step implemented the data flow from the structural information in Midas Gen to the building information in Revit. The conversion process adhered to a three-stage technical protocol: geometric data mapping, material property assignment, and BOM output generation. The implementation procedure comprised the following systematic operations: Based on the structural axis coordinates and cross-sectional parameters of components exported from Midas Gen, 3D building models were constructed in Revit; Subsequently, the material library in Revit was created, where material properties were defined and corresponding material attributes were assigned to each component; Finally, the BOM was exported to provide data for subsequent circularity assessments.

2.3 CIRCULARITY ASSESSMENT

To accurately evaluate the contribution of wood-based materials to BC, this study employed the WBCI, which is the most representative assessment framework so far available [7]. Equations involved in the calculations, starting from the material level, step by step to the element level, system level, and finally the building levels, are detailed in Tab. 1.

Table 1: Equations for BCI calculation [7]

Equation	NO.
$MCI = Max(0, 1 - U \times LFI)$	(1)
$U = \frac{0.9}{min(FL, TL)/L_{brand}}$	(2)
$LFI = \frac{V + W}{2M'}$	(3)
$M' = M + M_{cl} + M_{rm}$	(4)
$M_{cl} = \emptyset_l \times m_i$	(5)
$M_{rm} = \frac{TL}{RM} \times Mass\ required\ in\ one\ maintenance$	(6)
$V = M'(1 - F_u - F_r - F_b)$	(7)
$W = W_o + W_C + W_{cl} + W_{rm}$	(8)
$W_O = M(1 - C_u - C_r - C_b)$	(9)
$W_C = M(1 - E_C)C_r$	(10)
$ECI = \sum MCI_i \times MNI_i$	(11)
$MNI_i = \frac{m_i}{\sum m_i}$	(12)
$SCI = \sum ECI_i \times EDI_i$	(13)
$EDI_i = \frac{\sum DDF_i \times m_i}{7 \times \sum m_i}$	(14)
$WBCI = \frac{BFS}{LK} \sum SCI_i \times LK_i$	(15)
$LK = \sum LK_i$	(16)

The material masses could be directly extracted from the BIMs. Other data required for these calculations were either derived from Ref. [7, 8] or defined by the authors themselves (Tab. 2).

The building design lifetime was set at 50 years, and the service life was 20 years. It was assumed that the timber building was completely prefabricated, so the material wastage rate was 0. In addition, the material wastage rate was set at 0.01 for concrete, 0.03 for steel, and 0.05 for concrete blocks [9]. It is noted that this study does not account for the waste generation during the building operation and maintenance.

All materials in the RC model were set to be virgin, while the materials in the timber model were defined to incorporate various bio-based fractions. Among them, lumbers were 100% bio-based, and OSB boards were 90%, typically containing 10% of glue [10]. The bio-based material percentages of GLT and CLT have been set to 98% according to the authors' manufacturer investigation, which indicates that around 7.5 kg glue is used for 1 m³ pine GLT or CLT with a weight of 375kg.

Furthermore, research on the recycling of GLTs and CLTs have indicated that, even though the components can be completely removed, they may not be fully reused due to factors such as inadequate structural performance [11]. This study assumed a 20% reuse rate for GLT and CLT, with the remaining being recycled. Concrete, steel, concrete blocks, OSB panels and lumber were all fully recyclable [12-14].

3 – RESULTS AND ANALYSIS

3.1 MODELLING AND BILL OF MATERIALS

Both structure models were configured to be 3.36 m long, 2.28 m wide and 31.5 m high, which adopted the frame shear wall structure system (Fig.3). The layout consisted of walls (Q1-Q18), load-bearing columns (KZ01-KZ03) and beams (ZL01, ZL02, QL). The FNP of the two

Table2: Input factor values

Factor values at the material level						
	RC building			Timber building		
Materials / Factors	Concrete	Steel	Concrete blocks	GLT& CLT	OSB	Lumber
TL	50	50	50	50	50	50
FL	20	20	20	20	20	20
L_{brand}	100	100	10	100	10	10
$\emptyset_l$	0.01	0.03	0.05	0	0	0
F_u	0	0	0	0	0	0
F_r	0	0	0	0	0	0
F_b	0	0	0	0.98	0.9	1
C_u	0	0	0	0.2	0	0
C_r	1	1	1	0.8	1	1
C_b	0	0	0	0	0	0
E_C	1	1	1	1	1	1

Factor values at the system level												
	RC building						Timber building					
Elements / Factors	Beam	Column	Floor	Shear wall	External wall	Partition wall	Beam	Column	Floor	Shear wall	External wall	Partition wall
DDF	2.8	2.8	2.8	2.8	3.4	3.7	4.9	4.9	4.9	4.9	4.5	4.5

Factor values at the building level				
	RC building		Timber building	
Systems / Factors	Structure	Space plan	Structure	Space plan
LK	0.2	0.9	0.2	0.9
BFS	0.2		0.2	

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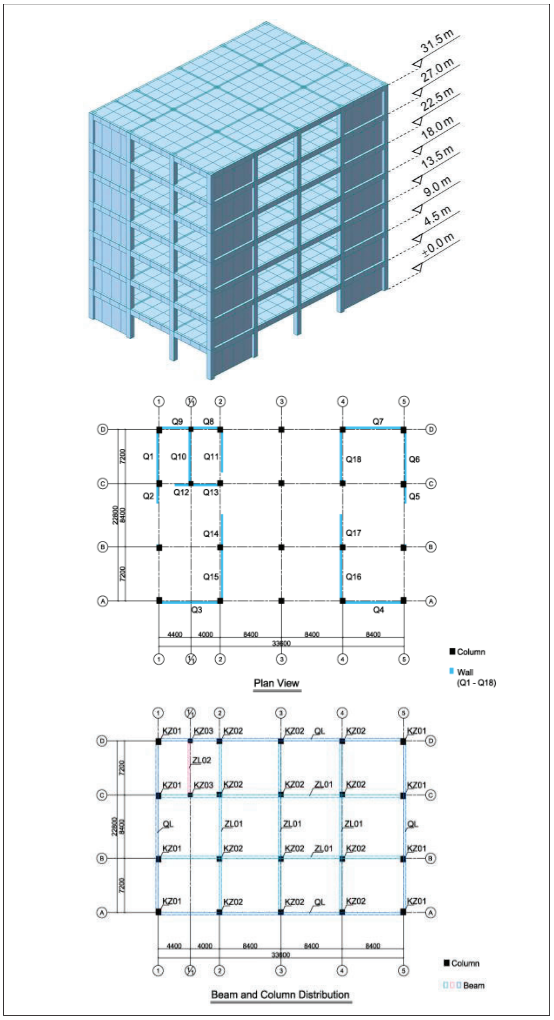

Figure 3. Basic layout of structural modelling.

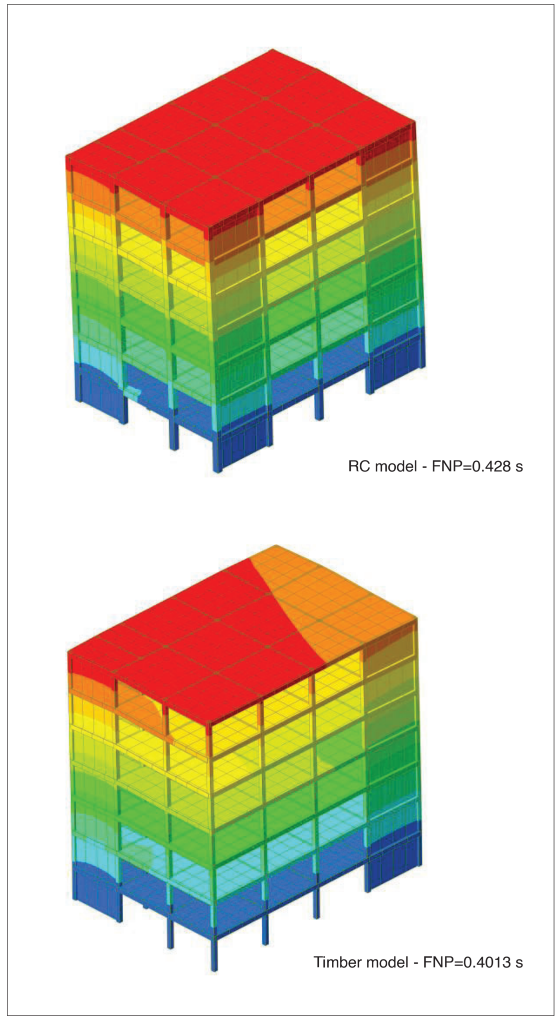

Figure 4. Deformation trend and FNP.

models got close to each other, at 0.4287 s for the RC model and 0.4013 s for the timber model, indicating a difference of 2%. Fig. 4 represents the displacements of two models that have similar colour distribution patterns, with a gradual transition from blue at the bottom to red at the top. This indicates that the deformation trend of the two models is the same.

The BOM summarisd the material specifications, dimensions and masses of the structural components of the RC and timber models (Tab. 3, Tab. 4). The results indicate that the timber building has 3 fewer shear walls, and smaller beams and columns than the RC building. On one hand, timber components are characterised by their lightweight and high strength, which enables smaller structural section dimensions to meet basic structural requirements. On the other hand, the formula for the FNP, $T = 2\pi\sqrt{\frac{m}{k}}$, indicates that for similar periods, the mass m and stiffness k need to be proportionally adjusted. Therefore, for wood-based building with lower stiffness, the overall mass should be reduced by using smaller cross-sectional sizes of components to achieve similar periods. The reduced number of shear walls in the timber building model reflects that timber building, which use GLTs and CLTs as structural components, exhibit superior lateral stiffness and ductility, compared to the RC building. So, it has better seismic performance and is able to maintain greater integrity and stability during earthquakes.

3.2 CIRCULARITY ASSESSMENT RESULTS

Based on the WBCI calculation equation and the BOM obtained from the BIMs, the circularity of the two building types has been assessed (Tab. 5).

At the material level, the circularity of all materials in the RC building was lower than that in the timber one. Concrete blocks achieved the highest material circularity

Table.3: RC building materials

Components	Element No.	Section Size (mm)	Materials	Weight (kg)	Total Weight (kg)
Column	KZ01	700*800	Concrete	833673.60	25932.72
	KZ02	700*700			
	KZ03	600*600	Steel	25932.72	
Beam	ZL01	300*800	Concrete	1309704.00	1350133.18
	ZL02	250*500			
	QL	300*800	Steel	40429.18	
Floor	150 (thickness)		Concrete	2016672.00	2080990.40
			Steel	64318.40	
Shear Wall	Q1, Q3, Q4, Q6 - Q9	300 (thickness)	Concrete	510528.00	521841.94
			Steel	11313.94	
External Wall	Q2, Q5	200 (thickness)	Concrete blocks	42680.00	
Partition Wall	Q10 – Q18	200 (thickness)	Concrete blocks	673600.00	

Table 4: Timber building materials

Components	Element No.	Section Size (mm)	Materials	Weight (kg)	
Column	KZ01	500*500	GLT	72420.60	
	KZ02	500*500			
	KZ03	500*500			
Beam	ZL01	300*600	GLT	132027.00	
	ZL02	300*600			
	QL	300*500			
Floor	105 (thickness)		CLT	264694.50	
Shear Wall	Q1, Q4, Q6, Q7	105 (thickness)	CLT	36855.00	
External Wall	Q2, Q3, Q5, Q8, Q9	120 (thickness)	OSB	10202.24	13777.73
			Lumber	3575.49	
Partition Wall	Q10 – Q18	120 (thickness)	OSB	23619.05	31896.62
			Lumber	8277.57	

indicator (MCI) of 0.76 in the RC building, while the highest MCI in the timber building was 1 for lumber. The MCI is influenced by the fractions of input material types (F_b, F_r and F_u), the fractions of material collected for different purposes (C_b, C_r and C_u) and the material utility (U). The lifespans of concrete blocks and lumber (FL=20 years) are longer than the established system lifetimes (L_{brand}=10 years), which indicates superior material efficiency and longevity of these two materials. Concrete blocks were less circular than lumber because they are not bio-materials (F_b=0), and their construction process generates significant waste ($\emptyset_l$=0.05). The MCIs for concrete and steel in the RC building were 0, primarily because both are made entirely from virgin materials (F_b=F_r=F_u=0). In contrast, lumber in the timber building is more circular due to its 100% bio-material (F_b=1) and its fabrication process, which generates little waste on the construction site (C_r=1).

At the element level, the element circularity indicator

Table 5: Circularity in RC and timber building

RC Building					
MCI					
Concrete		Steel		Concrete blocks	
0		0		0.76	
ECI					
Column	Beam	Floor	Shear wall	External wall	Partition wall
0	0	0	0	0.76	0.76
SCI					
Structure			Space plan		
0			0.78		
WBCI					
0.13					
Timber Building					
MCI					
GLT		CLT		OSB	Lumber
0.96		0.96		0.96	1
ECI					
Column	Beam	Floor	Shear wall	External wall	Partition wall
0.96	0.96	0.96	0.96	0.98	0.98
SCI					
Structure			Space plan		
2.71			1.26		
WBCI					
0.31					

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(ECI) is positively correlated with MCI and the material normalization index (MNI). In this study, the components of the RC building had the ECI values of 0 or 0.76, in comparison to the components of the timber building, which were valued at 0.96 or 0.98. The main factor influencing the ECI is the proportion of material weight to the total weight of the component, i.e. MNI. Given the simplicity of the component compositions in this study, the components made from a single material, such as external and partition walls in RC building, and columns, beams, and shear walls in timber building, have the ECI value as the same as the MCI value of the composing material. The ECIs for the external and partition walls in the timber building can be attributed to the lumber and OSB panels, which constitute these elements and had the MCI values of 1 and 0.96 respectively.

At the system level, the system circularity indicator (SCI) is positively correlated with ECI and the design disassembly factors (DDF). The RC building's space plan system showed the SCI of 0.78, while its structure system 0. The structure system of the timber building scored the highest SCI of 2.71, followed by its space plan system at 1.26. The primary reason for these results is the varying DDFs, which were given as input factors by the authors (Tab. 2). In the RC building, partition walls and external walls in the space plan system were chemically bonded to adjacent members with filled chemical connections, e. g. cast-in-place concrete. These connections, which are inherently difficult to separate, reduced the potential for component reuse, resulting in a low SCI value. In contrast, the timber building's structure system utilises soft connections between columns, beams, and shear walls, which facilitate easy disassembly and component reuse. However, partition walls and external walls have a lower prefabrication degree and less accessible connections than structural elements, making the space plan less circular.

At the whole building level, the RC building with the WBCI value of 0.13 exhibited a lower circularity than the timber building with 0.31. Due to the calculation rules of WBCI, its value is only affected by the SCI, the building flexibility score (BFS) and the level of importance (LK). Since the values of BFS (0.2) and LK (0.2 for structure and 0.9 for space plan) were predefined the same for both building types (Tab. 2), the higher system circularity of timber building (2.71 for structure and 1.26 for space plan) then contributed to its higher building circularity.

4 – DISCUSSION

4.1 COMPARABILITY OF MODELS

This study established two models that were comparable in terms of structural stability, and then evaluated the BC in both models. The approach that solely relies on the building's structural indicator, the FNP, for the development of the structure modelling, ignores other aspects of true building projects.

This foundational methodology can be further enhanced by introducing additional indicators to assist in modelling, including indoor thermal comfort, fire resistance, acoustic insulation performance. The core purpose of introducing other indicators is to make the models more comparable and evaluate the circularity of the two models more scientifically based on more identical or similar preconditions.

4.2 INDICATORS OF BC ASSESSMENTS

Although the WBCI used in this study is regarded as comprehensive, it ignores the affection of the ratio of reuse, recycling, and biodegradation to the MCI value. Because direct reuse of waste materials is more beneficial for BC than downcycling, the management of waste materials significantly influences the material's circularity. Thus, it is crucial to distinguish between different recycling strategies, such as by incorporating weighting factors.

Likewise, the total amount of used material doesn't directly influence the BCI results, since the real core of the WBCI assessment mechanism is the source of the building material, either virgin, recycling material or bio-based materials. This study revealed that the lightweight and high-strength properties of wood effectively reduced the number of structural components in the timber building, but the decrease in the total material consumption has less correlation to the BC. This also indicates that the WBCI assessment is still not perfect and cannot reflect the concept of material reduction in building design.

4.3 STRATEGIES FOR ENHANCING BC

Summarising the results and analyses above, the factors that significantly impact BC are material efficiency and longevity, the origin of building materials, the waste generated during construction and the connections between components. Understanding and optimising these factors can effectively improve BC and promote sustainable building development. These strategies include the selection of building materials to enhance the benefits of the materials, based on the life cycle of the building systems. For example, a building's structure system typically has a longer service life than its space plan system, such as partition walls. Therefore, the lifespan of materials used in space plan systems can be shorter than those used in structure systems. This approach reduces waste from materials replacement when only the building's spatial layout changes, and allows for the optimal allocation and efficient use of materials.

Using bio-materials such as wood, as well as recycled materials, also plays a significant role. Bio-materials ensure that no environmentally threatening waste is generated. Recycled materials help to reduce existing waste and lessen the environmental burden. Prefabricated components reduce waste generated on-site, and soft connections facilitate the dismantling and reuse of building elements, thereby further reducing waste over the building life cycle. For instance, the dimensions of OSB panels and their connection to lumber directly affect the accessibility of wall modification and the amount of waste generated during the process.

5 – CONCLUSION

This study has simulated and evaluated multi-storey building models with two different material types, concrete and steel and wood-based materials. The aim was to quantify and comparatively analyse the benefits of wood based materials in BC. To ensure comparability, this study developed two building models with identical structural layouts and similar FNP. Based on this, the BOM for each model were exported using BIM software. Utilising the WBCI assessment framework, the circularity of both models was then quantitatively analysed at the levels of materials, elements, systems and whole building. The results showed that the use of wood-based materials significantly enhances the BC at specific levels. This study has established a methodology for comparing BC based on structural similarity, and demonstrated the significant circularity benefits of wood-based materials.

6 – ABBREVIATIONS

For the convenience of readers, the acronyms and abbreviations of the proper nouns in the equations for building circularity are listed and explained at the end of the paper.

BCI - building circularity indicator
BFS - building flexibility score
C_b - fractions of material collected for bio decomposition
C_r - fractions of material collected for recycling
C_u - fractions of material collected for reuse
DDF - design disassembly factor
E_C - efficiency of recycling process
ECI - element circularity indicator
EDI - element disassembly index
F_b - fraction of input materials that are bio-based
FL - functional lifetime
F_r - fraction of input materials that are recycled
F_u - fraction of input materials that are reused
L_{brand} - lifetime of various systems
LFI - linear flow index
LK - level of importance
M - material that ends up as product
M′ - total mass
MCI - material circularity indicator
M_{cl} - additional material required during construction
m_i - mass of material
MNI - material normalization index
M_{rm} - additional material required during maintenance and repairs
RC - reinforced concrete
RM - periodic maintenance cycle
SCI - system circularity indicator
TL - technical life
U - utility of product
V - virgin material input
W - material wastage
W_C - recycling material output
W_{cl} - construction loss
W_O – unrecoverable material output
W_{rm} - maintenance and repair of material outputs
WBCI - whole building circularity indicator
$\emptyset_l$ - measure of material lost during construction

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