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A METHOD FOR ASSESSING THE FLEXIBILITY OF BUILDINGS TO DISMANTLE AND REUSE THEIR STRUCTURAL ELEMENTS

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A b s t r a c t

The aim of the article is to develop and verify a method for assessing building structural solutions in terms of their susceptibility to dismantling and reuse, referred to as circular flexibility. The novelty of the approach lies in its focus on load-bearing elements and the application of a simple Weighted Sum Model (WSM) that enables the comparison of structural solutions already at the design stage. The research question posed is: Does the Weighted Sum Model (WSM) allow for a reliable comparison of the reuse potential of structural elements? The model is based on three criteria: assembly technology, execution technology, and material type. Based on expert evaluations, indicators (WSM_{bud}) were calculated for ten completed European buildings. The results confirmed that the method allows for measurable comparison of structures and can support design decisions. The limitations include the subjectivity of assessments and the need for calibration of threshold values. Further research will involve verifying the method on new buildings and comparing it with other MCDA techniques.

Keywords: circular architecture, reuse, building structure, dismantling, circular economy (CE)

1. INTRODUCTION

The construction sector consumes the largest quantities of natural resources. In Europe, it accounts for approximately 50% of total material consumption and generates over 35% of construction and demolition waste [1][2]. Globally, it also has a major impact on the climate, being responsible for nearly 40% of CO_2 emissions [3]. The main reason for this situation is the dominance of a linear resource use model-extraction, processing, use, and disposal [4]. As a result, only 20-30% of construction waste is reused, usually in the form of low-quality aggregates [4][5][6].

In response to these challenges, the concept of circular architecture has emerged, aiming to extend the life cycle of resources while maintaining their functional value [7]. This issue has been widely discussed in the scientific literature. Pomponi and Moncaster developed a research framework for the circular economy in the construction sector, emphasizing that its implementation requires new design

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approaches and systemic organizational changes throughout the building life cycle [8]. Ghisellini et al. pointed out that the transition to a circular economy demands concurrent environmental, economic, and social transformations integrated into both the design and operational stages [9]. Kirchherr et al., after analyzing 114 definitions of the circular economy, demonstrated that the concept remains inconsistent, and most interpretations focus mainly on the reduce–reuse–recycle principles, while neglecting the systemic transformation of production and design processes [10].

In architecture, this approach translates into designing buildings that can be adapted or dismantled [11][12]. At the design level, these principles are implemented through the Design for Disassembly (DfD) and Design for Adaptability (DfA) strategies [13]. Research confirms that both strategies constitute key pillars of circular architecture. DfD enables the recovery of components and reduction of waste [14], whereas DfA allows for spatial adaptation to changing user needs without interfering with the load-bearing structure [15]. Their application contributes to extending the life cycle of buildings and reducing embodied carbon emissions. In practice, this approach is promoted by the Open Building movement, which advocates for the hierarchical separation of structural and user layers [16][17].

The growing interest in implementing circular architecture principles in construction practice has led to the development of tools that enable the assessment of material circularity. One of the best-known indicators is the Material Circularity Indicator (MCI), developed by the Ellen MacArthur Foundation, which assesses material flows and their potential for recycling and reuse throughout a product’s life cycle [18]. At the European level, the Level(s) framework, developed by the European Commission, integrates environmental, health, and cost indicators throughout the building life cycle [19]. In Poland, the Circular Economy in Construction Compendium was developed under the CIRCON project by the Polish Green Building Council (PLGBC). It includes a set of indicators addressing secondary material use (SMU), material reuse potential (MRP), spatial reversibility (SR), and a composite circularity index (CI) summarizing assessment results [4].

However, existing assessment systems mainly focus on material or environmental aspects, neglecting the structural analysis of buildings [6]. Yet, it is precisely the load-bearing elements that account for the largest share of embodied carbon. According to the Technical University of Denmark, they are responsible for up to 80% of total emissions [20]. The literature also highlights the lack of clear design guidelines and a consistent definition of a “circular building,” which results in inconsistent design practices and difficulties in comparing research outcomes [10][15].

To address this gap, the present paper proposes a method for assessing the susceptibility of building structures to dismantling and reuse, defined as circular flexibility. Unlike existing indicators (MCI, Level(s)), it focuses on the load-bearing structure of a building and its technical reversibility. The research question is: Does the Weighted Sum Model (WSM) allow for a reliable and transparent comparison of the reuse potential of structural elements?

The study analyzed ten completed European buildings from 2013-2023 located in the Netherlands, Denmark, and the United Kingdom. These objects represent different functions (office, residential, hotel, and temporary) and diverse structural systems. The selection was purposive, based on the availability of structural data and the application of DfD/DfA principles, making the sample representative for verifying the method.

The research was based on assessments by ten experts in architecture and construction. Although the number of respondents was limited, the pilot phase allowed for testing the method’s applicability. Future research will expand the sample and compare results with other Multi-Criteria Decision Analysis (MCDA) techniques.

2. OBJECT OF THE STUDY

The subject of the study is the applicability of the multi-criteria Weighted Sum Model (WSM) for the analysis and evaluation of buildings' circular flexibility. The analysis focuses on structural elements - columns, beams, floors, foundations, and roof structures - selected due to their crucial role within the load-bearing system and their significant contribution to the embodied environmental impact [6][20].

Ten completed buildings were selected for the analysis, recognized as representative examples of circular architecture and described in case studies published by the Circon initiative and the Open Building movement [22][23]. These buildings, constructed between 2013 and 2023 in Western and Northern Europe, are frequently referenced in the literature as examples of circular architecture and represent diverse structural systems - from steel and timber frames to reinforced concrete structures - allowing for a comparative assessment of reuse potential.

The sample was selected purposively and included only buildings containing all analyzed types of structural elements, where technologies enabling disassembly or adaptation had been applied.

3. METHODOLOGY

This paper presents the results of a pilot study aimed at assessing the circular flexibility of buildings in terms of the potential for reuse of their structural elements, using the Weighted Sum Model (WSM), which belongs to the group of Multi-Criteria Decision Analysis (MCDA) methods [24]. The choice of WSM is justified by its computational simplicity, clarity of interpretation, and previous applications in construction-related research. However, it should be emphasized that this model assumes linear weighting and does not account for interdependencies between criteria, which represents a limitation. Future research will involve verifying the method by comparing the results with other MCDA techniques, such as the Analytic Hierarchy Process (AHP) and the Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) [21].

Three criteria were selected for the study: assembly technology, execution technology, and material type. These criteria and their respective variants were defined based on the analysis of ten selected buildings and a literature review concerning assembly techniques, prefabrication, and structural materials.

The study was conducted through a two-stage expert survey. Ten specialists participated - architects (n = 6) and civil engineers (n = 4) - all with experience in structural design. The sampling was purposive, corresponding to the exploratory nature of the study. The aim was not to achieve statistical representativeness but to identify general tendencies. The inclusion of end users would not be appropriate at this stage, as they lack the necessary technical knowledge of assembly and execution technologies. In subsequent stages, it will be advisable to expand the group of respondents to include designers and contractors with varying professional experience.

Experts evaluated 14 variants using a five-point Likert scale [25] and distributed 10 points among the three criteria to determine their relative importance.

Table 1. Interpretation scale of expert evaluation results

WSM value	**Level of circular flexibility of technologies and materials**
1.00 – 1.79	Very low
1.80 – 2.59	Low
2.60 – 3.39	Moderate
3.40 – 4.19	High
4.20 – 5.00	Very high

The Weighted Sum Model (WSM) was applied for the calculations. This method was selected due to its computational simplicity and the transparency of interpretation, particularly in studies involving a limited number of respondents.

Normalized weights (w_i) were calculated (Eq. 3.1) as the ratio of the points assigned to a given criterion to the total number of points distributed by all experts:

$$w_i = \frac{\Sigma p_i}{\Sigma p} \tag{3.1}$$

Σp_i - total number of points assigned to the given criterion,
Σp - total number of points assigned by all experts.

The mean values of the evaluated variants ($\underline{x_i}$) were calculated (Eq. 3.2) as the arithmetic mean of expert ratings:

$$\underline{x} = \frac{\Sigma x_{i,e}}{n} \tag{3.2}$$

$\Sigma x_{i,e}$ - total score of a given variant,
n – number of expert evaluations.

The final circular flexibility index for a structural element (WSM) was determined (Eq. 3.3) as the weighted sum of the criterion scores:

$$WSM = w_1 * x_1 + w_2 * x_2 + w_3 * x_3 \tag{3.3}$$

x_1 - rating of assembly technology,
x_2 - rating of execution technology,
x_3 - rating of material type,
w_1, w_2, w_3 - normalized weights assigned to each variable.

For each building, a composite index (WSM_{bud}) was calculated (Eq. 3.4) as the mean of all WSM values:

$$WSM_{bud} = \frac{WSM_1 + WSM_2 + WSM_3 + WSM_4}{4} \tag{3.4}$$

WSM_1 - circular flexibility index for columns and beams,
WSM_2 - circular flexibility index for floors,
WSM_3 - circular flexibility index for foundations,
WSM_4 - circular flexibility index for roof structures.

Final WSM_{bud} values were rounded to two decimal places. For interpretation purposes, a six-level classification scale was applied, with constant equal intervals of 0.25 within the range of 3.00 to 4.00. These intervals were established empirically to ensure clarity of data interpretation and comparability between buildings.

Table 2. Classification of building circular flexibility level based on WSM_{bud}

WSM_{bud} value	**Level of building circular flexibility**
< 3.00	Very low
3.00 – 3.24	Low
3.25 – 3.49	Moderate
3.50 – 3.74	High
3.75 – 4.00	Very high
> 4.00	Extremely high

4. RESULTS

4.1. Normalized weights of variables

The assigned weights reflect the relative importance of each variable in assessing circular flexibility. The highest weight was attributed to assembly technology (0.415), indicating that the method of joining components has a decisive influence on the possibility of disassembly and material recovery. Material type (0.300) and execution technology (0.285) received slightly lower yet comparable values. This suggests that while material properties and execution methods affect reuse potential, they remain secondary to the assembly approach.

Table 3. Normalized weights of variables

Assessment variable (x)	**Total score ($\Sigma\ x_{i,e}$)**	**Normalized weight (w_i)**
Assembly technology (x_1)	41.5	0.415
Execution technology (x_2)	28.5	0.285
Material type (x_3)	30.0	0.30
Suma	**100.00**	**1.00**

4.2. Average scores for variables according to experts

In terms of assembly technology, the highest ratings were assigned to solutions with easily reversible joining of components, such as passive assembly (4.80), mechanical assembly (4.40) and snap-in assembly (4.10). The lowest ratings were given to permanent methods, including wet pouring (1.00), thermal assembly (1.60) and chemical assembly (1.90), due to the limited ability to separate components without damaging them.

Table 4. Average scores for assembly technology

Assembly technology (x_1)	**Average rating (1-5)**
Mechanical installation (e.g. screws, anchors, fasteners)	4.40
Passive installation (e.g. dry layering)	4.80
Clip-in / push-in assembly (e.g. clips, tongue-and-groove)	4.10
Hybrid assembly (e.g. mechanical bond with adhesive/resin)	2.80
Chemical assembly (e.g. adhesives, resins)	1.90
Thermal assembly (e.g. welding, sealing)	1.60
Wet casting (e.g. casting directly on site)	1.00
Joint filling (e.g. joint filling)	1.50

In the assessment of fabrication technology, prefabrication received the highest score (4.50), assessed as a method conducive to separation. Monolithic fabrication (1.20) was considered less conducive to recovery due to the durability of the connections.

Table 5. Average scores for performance technology

Construction technology (x_2)	**Average rating (1-5)**
Prefabrication (elements prepared off-site)	4.50
Monolithic (elements made on site)	1.20

For materials, wood (4.80) and steel (4.20) were rated highest, confirming their relatively easy dismantling and reuse. Lower values were given to concrete (1.70) and reinforced concrete (1.30) due to their weight, durability and vulnerability to demolition damage.

Table 6. Average scores for construction materials

Type of material (x_3)	**Average rating (1-5)**
Wood	4.80
Steel	4.20
Concrete	1.70
Reinforced concrete	1.30

4.3. Case descriptions and partial results

This subsection presents ten case studies of buildings completed between 2013 and 2023, recognized as examples of circular architecture. For each building, the main structural solutions are described, with particular emphasis on the types of materials used and the applied assembly and execution technologies.

The accompanying tables show partial WSM calculation results for the four primary structural components: columns and beams, floors, foundations, and roofs. Each table includes the mean expert ratings (x_1-x_3) and the normalized weights (w_1-w_3) assigned to the three variables - assembly technology, execution technology, and material type. The last column contains the partial WSM value for a given structural element, while the WSM $_{bud}$ value at the bottom of the table represents the average score for the entire building.

The purpose of this subsection is to present the source data and structural framework of the analyzed buildings. The interpretation and comparison of results are discussed in Section 4.4.

4.3.1. The Green House, Utrecht, the Netherlands, 2018, design: cepezed

Fig. 1. The Green House: front elevation, oblique view, and technical detail. Source: cepezed, ArchDaily

The building features a modular structural layout composed of prefabricated steel columns and beams assembled mechanically, achieving a WSM score of 4.37. The floors, made of prefabricated wooden panels (mechanical assembly), reached a value of 4.55, indicating a very high level of circular flexibility.

The ground level, constructed from prefabricated reinforced concrete slabs (mechanical assembly), achieved a score of 3.66, slightly lower due to material-related constraints. The foundations, made of prefabricated concrete blocks laid in layers (passive assembly), also obtained 3.66. The roof, consisting of glass panels supported by a prefabricated steel truss (mechanical assembly), reached 4.37. The overall average for the building was WSM $_{bud}$ = 4.24, classifying the object as exhibiting *very high circular flexibility* [26][27].

Table 7. Values of variables and final WSM index for structural elements of Green House building

Structural component	Assembly		Execution		Material		Result WSM
	x_1	w_1	x_2	w_2	x_3	w_3	
Columns and beams	4.40	0.415	4.50	0.285	4.20	0.30	4.37
Ceilings	4.40	0.415	4.50	0.285	4.80	0.30	4.55
Foundations	4.80	0.415	4.50	0.285	1.30	0.30	3.66
Roof	4.40	0.415	4.50	0.285	4.20	0.30	4.37
						WSM_{bud}	4.24

4.3.2. Alliander Headquarters, Duiven, the Netherlands, 2015, design: RAU Architects

Fig. 2. Alliander Headquarters: front views and design detail. Source: RAU Architects, ArchDaily

The building features a modular frame structure composed of prefabricated steel columns and beams assembled mechanically, achieving a WSM score of 4.37. The floors, made of prefabricated reinforced concrete slabs with joint grouting, reached a value of 2.30, indicating limited potential for reuse. The foundations, constructed from reinforced concrete slabs in monolithic (cast-in-place) technology, scored 1.15, confirming low dismantlability. The roof, made of prefabricated steel panels supported by steel trusses (mechanical assembly), achieved 4.37. The overall average for the building was WSM $_{bud}$ = 3,05 [28][29].

Table 8. Variable values and WSM index for structural elements of the Alliander Headquarters building

Structural component	Assembly		Execution		Material		Result WSM
	x_1	w_1	x_2	w_2	x_3	w_3	
Columns and beams	4.40	0.415	4.50	0.285	4.20	0.30	4.37
Ceilings	1.50	0.415	4.50	0.285	1.30	0.30	2.30
Foundations	1.00	0.415	1.20	0.285	1.30	0.30	1.15
Roof	4.40	0.415	4.50	0.285	4.20	0.30	4.37
						WSM_{bud}	3.05

4.3.3. Temporary Court, Amsterdam, the Netherlands, 2016, design: cepezed

Fig. 3. Temporary Court: front view, construction phase, and technical detail. Source: cepezed

The temporary court building features a steel frame structure composed of prefabricated columns and beams assembled mechanically, achieving a WSM score of 4.37. The floors, made of prefabricated hollow-core slabs (hybrid assembly), reached 2.83, indicating moderate structural flexibility. The foundations, consisting of reinforced concrete footings and monolithic slabs (cast-in-place technology), showed a low score of 1.15. The roof, composed of prefabricated steel panels supported by steel trusses (mechanical assembly), achieved 4.37. The overall average for the building was WSM_{bud} = 3.18 [30][31].

Table 9. Variable values and WSM index for structural elements of the Temporary Court building

Structural component	Assembly		Execution		Material		Result WSM
	x_1	w_1	x_2	w_2	x_3	w_3	
Columns and beams	4.40	0.415	4.50	0.285	4.20	0.30	4.37
Ceilings	2.80	0.415	4.50	0.285	1.30	0.30	2.83
Foundations	1.00	0.415	1.20	0.285	1.30	0.30	1.15
Roof	4.40	0.415	4.50	0.285	4.20	0.30	4.37
						WSM_{bud}	3.18

4.3.4. People's Pavilion, Eindhoven, the Netherlands, 2017, design: Overtreders W, bureau SLA

Fig. 4. People's Pavilion: elevation views and structural detail. Source: bureau SLA, ArchDaily

The pavilion features a timber frame structure composed of prefabricated wooden columns and beams assembled passively, achieving a WSM score of 4.71. The floors, made of prefabricated wooden beams (passive assembly), also reached 4.71, indicating high repeatability and ease of assembly. The foundations, composed of reinforced concrete piles (monolithic), achieved 1.15. The roof, constructed from reclaimed glass panels supported by wooden beams (mechanical assembly), reached 4.55.The overall average for the building was WSM $_{bud}$ = 3.78 [32][33].

Table 10. Variable values and WSM index for structural elements of the People's Pavilion building

Structural component	Assembly		Execution		Material		Result WSM
	x_1	w_1	x_2	w_2	x_3	w_3	
Columns and beams	4.80	0.415	4.50	0.285	4.80	0.30	4.71
Ceilings	4.80	0.415	4.50	0.285	4.80	0.30	4.71
Foundations	1.00	0.415	1.20	0.285	1.30	0.30	1.15
Roof	4.40	0.415	4.50	0.285	4.80	0.30	4.55
						WSM_{bud}	3.78

4.3.5. Superlofts Houthavens, Amsterdam, the Netherlands, 2018, design: Marc Koehler Architects

Fig. 5. Superlofts Houthavens: elevation view, module fragment, and prefabrication scheme. Source: OpenBuilding

The building has a hybrid structural layout, consisting of a modular steel frame structure in the above-ground part (80%) made of prefabricated steel columns and beams (mechanical assembly), and a monolithic reinforced concrete structure in the underground part (20%), achieving a WSM score of 3.72. The floors, made of prefabricated reinforced concrete slabs with joint grouting, reached a value of 2.30, indicating limited disassembly potential. The foundations, composed of monolithic reinforced concrete piles, scored 1.15, confirming their permanent and non-dismountable nature. The roof, made of prefabricated steel panels supported by steel trusses (mechanical assembly), achieved 4.37. The overall average for the building was WSM $_{bud}$ = 2.89 [34][35].

Table 11. Criterion values and WSM index for structural elements of the Superlofts Houthavens building

Structural component	Assembly		Execution		Material		Result WSM
	x_1	w_1	x_2	w_2	x_3	w_3	
Columns and beams	3.72	0.415	3,84	0.285	3.62	0.30	3.72
Ceilings	1.50	0.415	4,50	0.285	1.30	0.30	2.30
Foundations	1.00	0.415	1,20	0.285	1.30	0.30	1.15
Roof	4.40	0.415	4,50	0.285	4.20	0.30	4.37
						WSM_{bud}	2.89

4.3.6. Stow-Away Hotel, London, United Kingdom, 2019, design: Doone Silver Kerr

Fig. 6. Stow-Away Hotel: front elevation views and floor plan. Source: Doone Silver Kerr

The hotel features a modular structure composed of prefabricated steel shipping containers connected using a snap-fit system, achieving a WSM score of 4.24. The floors, formed by the upper steel panels of the container modules (mechanical assembly), reached 4.37. The foundations, made of reinforced concrete slabs (monolithic), obtained 1.15. The roof, composed of prefabricated steel panels (mechanical assembly), achieved 4.37. The overall average for the building was WSM $_{bud}$ = 3.53 [36][37].

Table 12. Variable values and WSM index for structural elements of the Stow-Away Hotel building

Structural component	**Assembly**		**Execution**		**Material**		**Result** WSM
	x_1	w_1	x_2	w_2	x_3	w_3	
Columns and beams	4.10	0.415	4.50	0.285	4.20	0.30	4.24
Ceilings	4.40	0.415	4.50	0.285	4.20	0.30	4.37
Foundations	1.00	0.415	1.20	0.285	1.30	0.30	1.15
Roof	4.40	0.415	4.50	0.285	4.20	0.30	4.37
						WSM_{bud}	3.53

4.3.7. Circl, Amsterdam, the Netherlands, 2017, design: de Architekten Cie

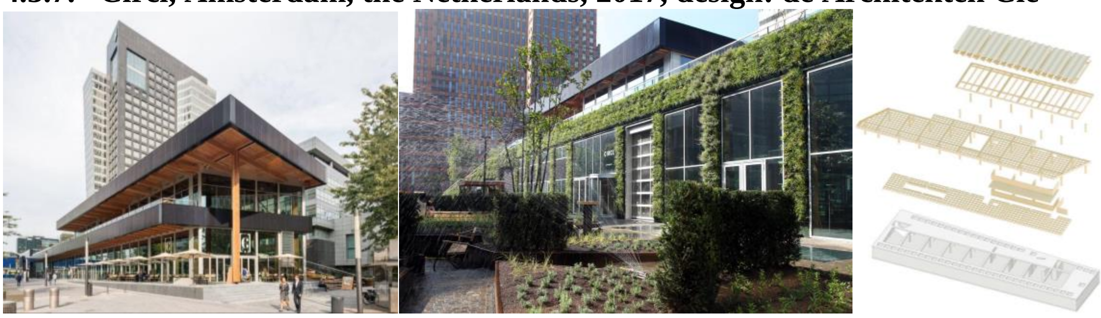

Fig. 7. Circl: elevation views and structural scheme. Source: Circl.nl, cie.nl.

The building features a frame structure made of prefabricated columns and beams assembled mechanically, achieving a WSM score of 4.55. The floors, composed of prefabricated recycled concrete panels (mechanical assembly), reached 3.62. The foundations, made of monolithic reinforced concrete slabs, obtained 1.15. The roof, consisting of prefabricated wooden panels connected with a snap-fit system, achieved 4.42. The overall average for the building was WSM $_{bud}$ = 3.44 [38][39].

Table 13. Variable values and WSM index for structural elements of the Circle building

Structural component	Assembly		Execution		Material		Result WSM
	x_1	w_1	x_2	w_2	x_3	w_3	
Columns and beams	4.40	0.415	4.50	0.285	4.80	0.30	4.55
Ceilings	4.40	0.415	4.50	0.285	1.70	0.30	3.62
Foundations	1.00	0.415	1.20	0.285	1.30	0.30	1.15
Roof	4.10	0.415	4.50	0.285	4.80	0.30	4.42
						WSM_{bud}	3.44

4.3.8. Juf Nienke Apartments, Amsterdam, the Netherlands, 2023, design: RAU, SeARCH

Fig. 8. Juf Nienke Apartments: elevation views and building sections. Source: Open Building.

The building has a hybrid structural layout, consisting of a modular steel frame structure in the above-ground part (80%) made of prefabricated steel columns and beams (mechanical assembly), and a monolithic reinforced concrete structure in the underground part (20%), achieving a WSM score of 3.82. The floors, made of prefabricated wooden panels (mechanical assembly), reached 4.55. The foundations, composed of a monolithic reinforced concrete slab (cast-in-place), achieved 1.15. The roof, made of prefabricated wooden panels (mechanical assembly), also reached 4.55. The overall average for the building was WSM $_{bud}$ = 3.52 [40][41].

Table 14. Variable values and WSM index for structural elements of the Juf Nienke Apartments building

Structural component	Assembly		Execution		Material		Result WSM
	x_1	w_1	x_2	w_2	x_3	w_3	
Columns and beams	3.72	0.415	3.84	0.285	4.10	0.30	3.82
Ceilings	4.40	0.415	4.50	0.285	4.80	0.30	4.55
Foundations	1.00	0.415	1.20	0.285	1.30	0.30	1.15
Roof	4.40	0.415	4.50	0.285	4.80	0.30	4.55
						WSM_{bud}	3.52

4.3.9. Triodos Bank, Driebergen-Rijsenburg, the Netherlands, 2019, design: RAU Architecten

Fig. 9. Triodos Bank: aerial view, front elevation, and structural section. Source: ArchDaily.

The building features a timber frame structure composed of prefabricated wooden columns and beams assembled mechanically, achieving a WSM score of 4.55. The floors, made of prefabricated wooden panels (mechanical assembly), also reached 4.55. The foundations, consisting of a monolithic reinforced concrete slab, obtained 1.15. The roof, made of prefabricated wooden panels (mechanical assembly), achieved 4.55. The overall average for the building was WSM $_{bud}$ = 3.70 [42][43].

Table 15. Variable values and WSM index for structural elements of the Triodos Bank building

Structural component	Assembly		Execution		Material		Result WSM
	x_1	w_1	x_2	w_2	x_3	w_3	
Columns and beams	4.40	0.415	4.50	0.285	4.80	0.30	4.55
Ceilings	4.40	0.415	4.50	0.285	4.80	0.30	4.55
Foundations	1.00	0.415	1.20	0.285	1.30	0.30	1.15
Roof	4.40	0.415	4.50	0.285	4.80	0.30	4.55
						WSM_{bud}	3.70

4.3.10. Upcycle House, Nyborg, Denmark, 2013, design: Lendager Arkitekter

Fig. 10. Upcycle House: elevation views and structural scheme. Source: Lendager Group

The building consists of prefabricated steel shipping containers (hybrid assembly) and achieved a WSM score of 3.75. The floor, made of prefabricated wooden panels (mechanical assembly), reached 4.55. The foundations, composed of prefabricated spiral steel piles (passive assembly), also achieved 4.55. The roof, made of aluminum sheets supported by a steel–timber frame (mechanical assembly), reached 4.35. The overall average for the building was WSM $_{bud}$ = 4.30 [44][45].

Table 16. Variable values and WSM index for structural elements of the Upcycle House building

Structural component	Assembly		Execution		Material		Result WSM
	x_1	w_1	x_2	w_2	x_3	w_3	
Columns and beams	2.80	0.415	4.50	0.285	4.20	0.30	3.75
Ceilings	4.40	0.415	4.50	0.285	4.80	0.30	4.55
Foundations	4.80	0.415	4.50	0.285	4.20	0.30	4.55
Roof	4.40	0.415	4.50	0.285	4.20	0.30	4.35
						WSM_{bud}	4.30

4.4. WSM_{bud} final results and classification of circular flexibility of buildings

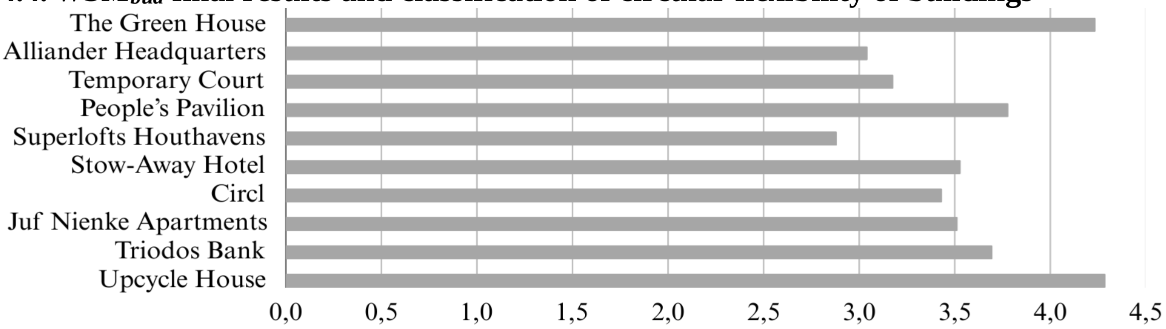

Fig. 11.Comparison of final WSM $_{bud}$ values for the analysed buildings

Based on the calculated WSM_{bud} index, a classification of the reuse potential of structural materials in the analyzed buildings was performed. The values ranged from 2.89 to 4.30 and were assigned to a six-level circular flexibility scale.

The highest values, exceeding 4.00, were obtained by Upcycle House (4.30) and The Green House (4.24), which places them in the very high circular flexibility category. These buildings demonstrate the greatest potential for the reuse of structural elements. People's Pavilion (3,78) was classified in the high flexibility category, while Triodos Bank (3.70), Stow-Away Hotel (3.53), and Juf Nienke Apartments (3.52) achieved elevated flexibility. Circl (3.44) fell within the moderate flexibility range, and Temporary Court (3.18) and Alliander Headquarters (3.05) were classified as low flexibility. The lowest result was recorded for Superlofts Houthavens (2.89), corresponding to very low flexibility.

Table 17. Final WSM $_{bud}$ values and classification of circular flexibility of buildings House building

No.	Building	WSM_{bud}	Circular flexibility classification
1	The Green House	4.24	Extremely high
2	Alliander Headquarters	3.05	Low
3	Temporary Court	3.18	Low
4	People's Pavilion	3.78	Very high
5	Superlofts Houthavens	2.89	Very low
6	Stow-Away Hotel	3.53	High
7	Circl	3.44	Moderate
8	Juf Nienke Apartments	3.52	High
9	Triodos Bank	3.70	High
10	Upcycle House	4.30	Extremely high

5. DISCUSSION

The proposed WSM-based method enables the comparison of buildings of different scales and functions, provided that complete data are available and that the adopted classification criteria are consistently applied. The criteria - assembly technology, execution technology, and material type - are clearly defined and can be implemented in design practice. As a result, the method can be applied both at the conceptual design stage and in the analysis of existing buildings, particularly in the context of adaptation, demolition, and life cycle planning.

Unlike existing tools such as the Material Circularity Indicator (MCI) [18] and Level(s) [19], which primarily focus on material flows, environmental impact, and life-cycle costs, the proposed approach explicitly considers the load-bearing structure of a building. The Level(s) framework operates within six categories (including emissions, water, health, and life-cycle costs), but it does not assess structural reversibility or the recoverability of components. Conversely, MCI concentrates on material balance without accounting for the assembly methods or physical separability of components. The proposed WSM_{bud} indicator complements both tools by introducing an evaluation of the technical flexibility of building structures.

The results confirm the high reuse potential of prefabricated systems and the application of timber and steel, while monolithic concrete and reinforced-concrete structures are identified in the literature as barriers to circular architecture [14][15]. The innovation of the WSM_{bud} model lies in its introduction of a comparable and measurable assessment of the reuse potential of structural elements. It enables the identification of the most "circular" design solutions already at the conceptual stage. An additional advantage of the model is its adaptability - it can be expanded with new criteria (e.g., dismantling costs or embodied emissions), making it a flexible tool that supports design in line with circular economy principles.

The study's limitations stem from the subjective nature of expert evaluations and the limited number of respondents. The sampling was purposive and corresponded to the exploratory nature of the study, which aimed to test the applicability of the method. The WSM model is based on an additive combination of weights and scores, which simplifies the real relationships between variables. In further research, cross-validation using the Analytic Hierarchy Process (AHP) and Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) is planned, as these methods allow for hierarchical structuring of criteria and the consideration of nonlinear relationships among variables.

The applied circular flexibility classification is based on an empirical data distribution and requires calibration when analyzing a different set of buildings. Despite these limitations, the proposed method systematizes the process of assessing the reusability of structural systems and can support designers in making decisions aligned with the principles of the circular economy. The results also highlight the need to develop clear design guidelines that would promote structural solutions facilitating the disassembly and recovery of building components.

6. CONCLUSIONS

The study confirmed that the Weighted Sum Model (WSM) allows for a reliable and measurable comparison of the reuse potential of building structural elements, thereby addressing the stated research question.

The most significant factor determining circular flexibility is the assembly technology and the extent of reversible connections within the load-bearing structure, which directly influence the potential for reuse. The highest values were achieved by prefabricated timber and steel structures (WSM_{bud} >

4,0), while the lowest scores were recorded for monolithic concrete and reinforced concrete systems (WSM_{bud} < 3,2).
The main limitations of the study include the simplifications inherent to the WSM model and the subjective nature of expert assessments. Future research will involve increasing the number of respondents - including representatives from engineering practice - and comparing the results with those obtained using AHP and TOPSIS methods to verify ranking consistency and weight sensitivity. Subsequent stages will also extend the method to include economic (LCC) and environmental (LCA) criteria, enabling a more comprehensive evaluation.
The proposed method complements existing circularity assessment tools (MCI, Level(s)) by incorporating the structural dimension - a key factor in terms of embodied emissions and building longevity. Consequently, it represents a practical decision-support tool and a starting point for the development of detailed design guidelines for circular architecture.

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