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Quantification of the contribution of low-weight demountable and modular construction to the sustainable level of buildings

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Abstract

This study, for the first time, provides a quantitative assessment of the contribution of low-weight, demountable and modular construction systems to the sustainability level of a building through the application of 11 of the most representative and internationally implemented Green Building Rating Systems (GBRS).

The sustainability scores achieved by a prefabricated, demountable, and modular residential building (R4House) were systematically compared with those obtained by a conventional non-demountable building, which was used as a baseline reference. In both cases, the evaluation was conducted using the same set of 11 major and widely recognized GBRS. The results demonstrate that all of the analyzed rating systems identify a higher level of sustainability associated with demountable and modular construction. However, the magnitude of the improvement varies substantially across the different GBRS, with increases ranging from 1.4% to 17.41%. Only three of the rating systems clearly recognize and reflect the evident advantages of demountable and modular construction, whereas the remaining systems assign these construction approaches a relatively low weight. Furthermore, four of the GBRS scarcely acknowledge their benefits, despite the significant environmental advantages inherent to low-weight, prefabricated, modular, and demountable construction systems.

The outcomes of this study can be considered generalizable, as they indicate that existing GBRS frameworks lack sufficient sensitivity to detect and properly evaluate small-scale variations associated with low-weight demontable and modular construction. Nevertheless, further research of a similar nature is required to corroborate the findings and to accurately quantify the contribution of demountable and modular construction to the overall sustainability performance of buildings.

Keywords: Construction Modular, Sustainable Evaluation, Demountable Construction, Green Building Rating System

Introduction

This study quantifies for the first time the contribution of low-weigth demountable and modular construction to the sustainable level of a building using 11 of the most representative and internationally used GBRS (Green Building Rating Systems).

The scores of a prefabricated, demountable and modular building (R4House) built with containers were compared with those of a non-demountable building (a baseline), in both cases using 11 of the most important GBRS. All GBRS have found that demountable and modular construction provides a higher level of sustainability. However, the resulting scores varied widely (from an increase of 1.4% to an increase of 17.41%), and only three GBRS clearly identified the obvious advantages of demountable and modular construction, while the rest value it very little, and four of them barely valued it, despite its important environmental advantages.

The results of this case study are generalizable, since the different existing GBRS do not have the capacity to detect small changes in low-weight modular and prefabricated demountable construction systems. However similar studies should be carried out to confirm the results obtained and accurately quantify the contribution of demountable and modular construction to the sustainable level of buildings.

Introduction

This paper presents, for the first time, a quantitative assessment of the contribution of low-weight modular and demountable construction systems to the overall sustainability performance of buildings. Modular and demountable construction has attracted increasing research interest in recent years due to the wide range of advantages associated with this approach. In particular, this construction typology integrates the benefits of modular construction with those inherent to prefabricated and industrialized construction processes [1-9]. In addition, it incorporates the functional, economic, and sustainability-related advantages derived from the use of container-based systems [10-15].

Prefabricated and industrialized construction is characterized by the on-site assembly of building components that are manufactured under controlled factory conditions. Modular construction can be understood as a specific form of industrialized construction in which components of predefined size and standardized dimensions are produced, allowing their flexible use and reconfiguration in different building contexts. Demountable construction refers to prefabricated building systems that can be assembled and disassembled with relative ease and without generating significant construction or demolition waste.

Previous research has identified and classified a wide range of demountable construction systems, highlighting their general technical and functional advantages , as well as their environmental and sustainability-related Benefits [16-36]. Nevertheless, comprehensive and systematic sustainability assessments of demountable construction remain scarce in the scientific literature, indicating the need for more rigorous and holistic evaluation approaches [37-41]. Moreover, to date, no study has specifically quantified the contribution of low-weight demountable construction to the overall sustainability level of buildings.

In recent years, multivariate assessment tools known as Green Building Rating Systems (GBRS) have been widely implemented to evaluate the overall sustainability performance of buildings. Sustainability is inherently a multidimensional concept that encompasses energy use, resource consumption, emissions, waste generation, and other environmental indicators. Accordingly, GBRS integrate multiple criteria and indicators to assess these dimensions in a comprehensive manner and to provide an aggregated sustainability score. However, despite their wide application, GBRS have been used very little so far to quantify the level of sustainability of modular and demountable construction.

The primary objective of this study is to address this research gap. To this end, a specific low-weight modular and demountable building was evaluated using 11 of the most representative and widely applied GBRS currently in use. In parallel, a hypothetical non-demountable version of the same building (ND-R4House) was assessed as a baseline reference. By systematically comparing the results obtained for both cases, the contribution of demountable construction to the sustainability level of the building was quantitatively determined.

The selected case-study building is considered representative of low-weight modular and demountable construction systems in general. Nevertheless, further case studies of a similar nature should be conducted to corroborate the findings presented herein. Despite this limitation, the results can be regarded as highly generalizable, since existing GBRS lack the sensitivity required to capture small differences among alternative demountable construction systems. Consequently, the findings provide robust insight into the capacity of current sustainability assessment frameworks to evaluate low-weight modular and demountable construction.

Context and Objectives

The main objective of this paper is to quantitatively assess the contribution of low-weight modular and demountable construction systems to the sustainability performance of a building.

A residential building constructed in Spain (R4House) was selected as the case study. Owing to its fully demountable nature, the building can be assembled, disassembled, and relocated indefinitely, allowing it to be theoretically situated in any geographical context. In parallel, a non-demountable version of the same building (ND-R4House) was evaluated and used as a baseline reference. A comparative analysis of the results obtained for both configurations enabled the quantification of the specific contribution of low-weight demountable construction to the overall sustainability performance of the building.

Given its relocatable character, R4House can be hypothetically located in any region where the selected GBRS are commonly applied. The aim is therefore to determine the sustainability score that this building would achieve when assessed using each of these rating systems.

It is important to acknowledge a recurring criticism associated with GBRS: each system has been developed within a specific environmental, climatic, and socio-economic context, which largely explains the substantial differences observed among them. This study seeks to highlight this issue for several reasons. First, although each GBRS has been designed for a particular context, it is frequently applied in a wide range of different geographical locations. For instance, LEED was originally developed in the United States, a country characterized by considerable climatic, environmental, and socio-economic diversity. This raises the question of whether a single rating system can be equally valid across such heterogeneous contexts, and whether it can be reliably extrapolated to comparable environments in Europe or Asia.

Second, in several countries, including the United Kingdom, France, Germany, Italy, and Poland, multiple GBRS are routinely used in parallel. This practice implicitly suggests that all of these systems are considered valid within the same context, which raises questions regarding their relative consistency, equivalence, and applicability.

Third, a detailed examination of the categories, indicators, and scoring methodologies of GBRS reveals that these tools generally lack the resolution required to detect small but potentially significant differences between construction systems. As a result, buildings with substantially different constructive solutions may achieve identical overall scores despite exhibiting distinct characteristics. For example, the final sustainability rating would remain unchanged whether a demountable house constructed with steel frames, shipping containers, or wood-based components is assessed. Consequently, the results obtained in this study can be extrapolated to similar single-family residential buildings. Indeed, the authors have evaluated demountable buildings with markedly different construction solutions and observed only minor variations in their respective scores.

Therefore, by comparing the outcomes produced by the different GBRS, this study not only quantifies the contribution of low-weight modular and demountable construction to building sustainability, but also provides a critical reflection on the structure, merit, legitimacy, and practical usefulness of the various GBRS currently in use.

Comparative Evaluation Methodology and Description of the Two Buildings to be Evaluated

In order to accurately quantify the contribution of low-weight modular and demountable construction to the overall sustainability score of a building, a modular and demountable residential unit (R4House) was systematically compared with a baseline scenario represented by a hypothetical non-demountable version of the same building (ND-R4House). The assessment was conducted using 11 of the most prominent and widely recognized Green Building Rating Systems (GBRS).

To streamline the analysis and enhance the clarity of the comparative evaluation, only those indicators whose scores differed between the two building configurations were included in the results. Indicators yielding identical scores for both the demountable and non-demountable versions were excluded, as they do not contribute to distinguishing the impact of demountability on sustainability performance. Consequently, the evaluation tables focus exclusively on indicators directly related to demountability, that is, criteria whose scoring is affected by whether a building can be assembled and disassembled.

Both building configurations were assessed using the same set of 11 leading GBRS, ensuring methodological consistency and enabling a robust comparison of the extent to which current sustainability assessment frameworks are capable of capturing the specific contributions of low-weight modular and demountable construction systems.

Choice of the 11 Leading GBRS Systems

Five criteria were established to guide the selection of the principal Green Building Rating Systems (GBRS) used for the sustainability assessment. These criteria included: (i) geographical and territorial representativeness; (ii) the number of buildings evaluated using each system; (iii) the number of citations indexed in the Scimago database; (iv) the number of citations identified through Google searches; and (v) the availability of complete, detailed, and accessible manuals and user guides.

On the basis of these selection criteria, a comprehensive inventory of existing GBRS was initially compiled. From this inventory, only those rating systems supported by a complete, clearly structured, and unambiguous operational manual were retained for the analysis [42]. As a result of this filtering process, a total of 11 GBRS were selected for inclusion in the study, a number that can be considered sufficiently representative for a comparative sustainability evaluation: ASGB , BEAM , BREEAM , CEDES , DNGB , GBI , GG , GS , IGBC , LEED and SBTools [43-54]. From each GBRS, the most recent and appropriate version for evaluating a single-family house has been chosen.

The evaluation system for each of these 11 GBRS is summarized below (Table 1), along with a comparison showing the different categories for each GBRS, as well as the maximum score that can be obtained in each category (Figure.1). This gives an idea of the strengths and weaknesses of each GBRS used.

Figure 1 shows a mutual comparison based in the 14 common categories to the eleven GBRS chosen were identified (even if they do not have the same name). In this way, all the indicators of each GBRS can belong to one of these categories, without any ambiguity and without any missing or extra indictors. The categories were organized into 4 groups: 1. Essential. Categories directly involved in measuring the ecological level of a building; 2. Complementary. Additional categories needed to measure properly its level of sustainability; 3. Added. Categories that are not necessary, and whose indicators are already indirectly contained in Essential or Complementary categories and could serve only to emphasize some sustainable aspects of the building, but it offsets the importance of some indicators; 4. Superfluous. Categories not related to sustainability.

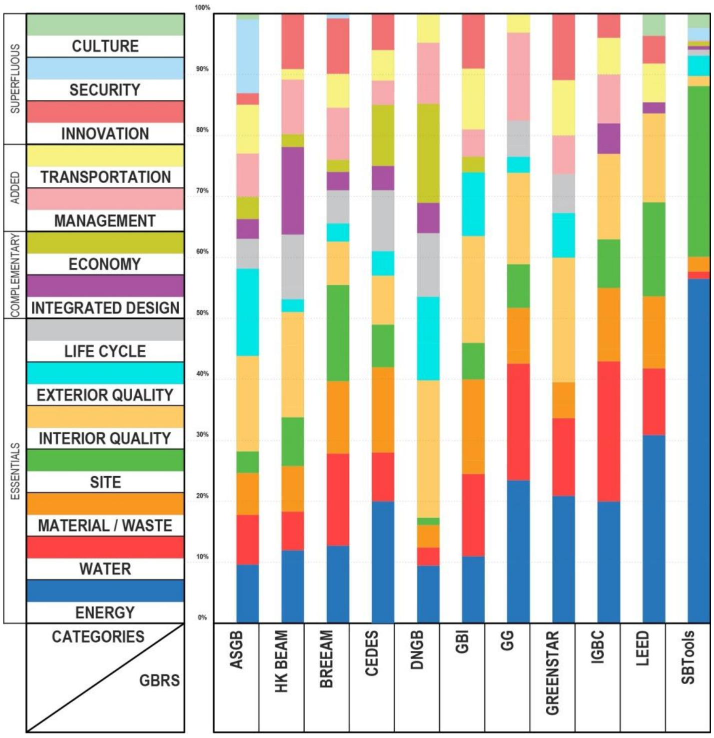

Figure 1: Mutual Comparison and Maximum Score of the Different Categories of each of the 11 GBRS

GBRS	*Evaluation strategy*
ASGB	Prerequisites of the standard must be met. The score of each index must not add up to less than 40 points. When the total score of a green building reaches 50, 60 or 80 points, the green building rating is one star, two stars or three stars respectively. This is calculated using the following formula: $\sum Q = W1\ Q1 + W2\ Q2 + W3\ Q3 + W4\ Q4 + W5\ Q5 + W6\ Q6 + W7\ Q7 + Q8$. First, the Qi score (i = 1, 2, 3, 4, 5, 6, 7) is obtained according to the grade of the item that can be scored under various indicators. Second, Q8 is the Promotion and Innovation score. Each Qi is multiplied by its Wi weight, and the Bonus Elements score is added to final evaluation score, obtaining 1, 2, or 3 stars
BEAM	It is made up of (7) categories and (22) subcategories that are scored to obtain a sum that, according to its value, obtains as a result: Certificate, Bronze, Silver, Gold, Platinum, Diamond
BREEAM	The assessment method is about ten categories that allow a maximum of 110 points. Each category has different weight regarding to total, and they are divided in subcategories, and indicators. Once the score for each category is obtained, a percentage weighting factor is applied in each case, proportionally granting the total number of 110 credits. According to the final score, the final can be: Exceptional, Excellent, Very Good, Good, Correct, or Unrated
CEDES	It incorporates eight categories and a system of indicators hierarchically structured into four levels. Each indicator has a specific, well-structured weight and can be assigned a value from 0 to 5. The final score ranges from 1 to 10
DNGB	The evaluation is based on 29 criteria, subdivided into six categories. Points are awarded to each category obtaining a partial result. Then a weighting factor is applied to them, obtaining a final result by category that, when added together, grants the certification: Bronze, Silver, Gold, Platinum.
GBI	It has 3 stages: Stage 1 Application and registration, Stage 2 Evaluation of the design, Stage 3 Completion evaluation and verification. To obtain the certification, its categories are scored and then added to determine a final result: Certified, Silver, Gold, Platinum
GG	The maximum score that can be obtained is 1000 points, divided into six categories. They are divided in subcategories, and indicators too. Some of the categories offer different assessment paths, which makes the method adaptable to some project particularities. Depending on the percentage of points obtained, 1 to 4 globes can be awarded
GS	The assessment tool awards points for the achievement of certain specific credits in each category. Once their score is calculated, an environmental weighting factor is applied, and the partial results are added. Finally, the points related to the incorporated innovations are added. The final result allows obtaining: One, two, three, four, five, six stars
IGBC	It is composed of 6 categories, which together have 37 criteria and 10 mandatory requirements. Each criterion is assigned a score. To achieve certification, the project must meet all the mandatory prerequisites and add a minimum score of 50 to 100 credits, obtaining as a result: Certificate, Silver, Gold, Platinum
LEED	It incorporates 9 categories, which together have 41 criteria. Each criterion is assigned a score and 16 mandatory requirements. To achieve certification, the project must meet all the mandatory prerequisites and add a minimum score of 50 to 110 credits, obtaining as a result: Certificate, Silver, Gold, Platinum
SBTools	It is an adaptive valuing framework for rating buildings using scores and credits that are weighted depending on the type of building. It is organized into four levels: (1) detected problems, (2) performance categories, (3) performance criteria, and (4) performance sub-criteria. According to the result, the corresponding qualification is obtained

Table 1: Summary of the method used to evaluate by the 11 GBRS

Description of the Modular and Demountable Building. R4House

General information

R4House contains two single-family houses and was built using 6 containers (Figure 1,2) [12,55]. One, with a constructed area of 173 m^2, on the ground floor has a kitchen, a living-dining room, a bathroom and a studio, and on the first floor two bedrooms and two bathrooms. The other house has a constructed area of 30 m^2 and has a living-dining room, a bathroom and a bedroom (Figure 3,4). R4House was built in 2007 and can be assembled and disassembled as many times as desired. In fact, since its construction it has been disassembled and reassembled twice [12,55].

Figure 2: R4House has been built using Six Modules, and all its Components are Removable, Including Foundations, Installations and Equipment

Figure 3: R4House was Built using Removable Components (wood-based panels, zinc sheeting, wood panels, natural stone tiles, etc.). This allows all Components to be easily Recovered, Repaired, and Reused, Maximizing the Building's Lifespan with Minimal Maintenance and thus Minimizing its Environmental Impact per unit of time

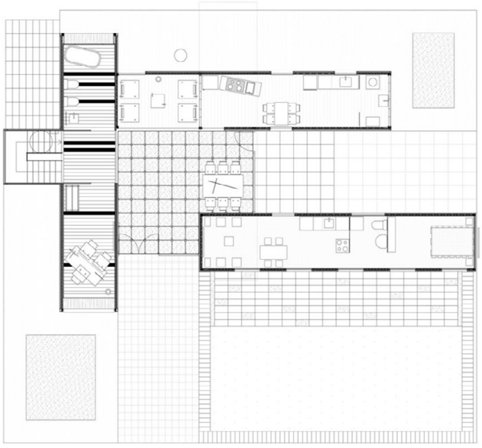

Figure 4: R4House Ground Floor Layout

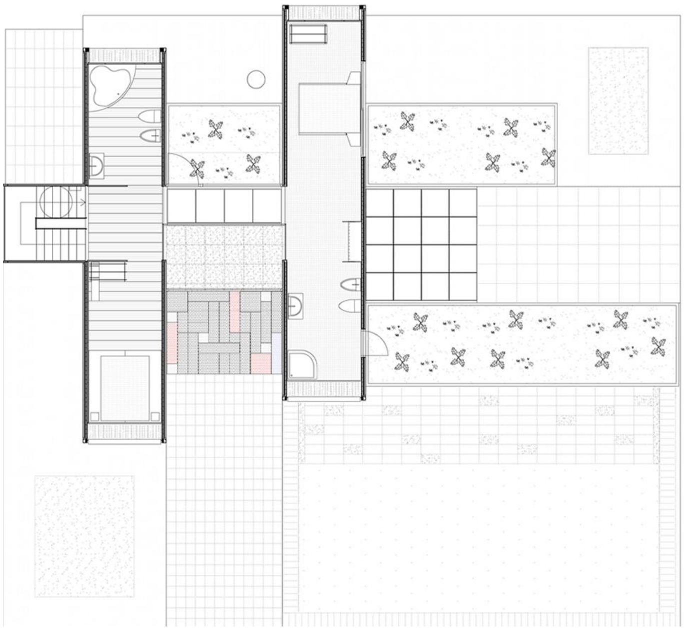

Figure 5: R4House First Floor Layout

Demountable Design

The building is modular and demountable since it was made with containers and all its components are assembled using screws and threaded nails (Figure 5-7). The building does not need a foundation, since the lower part of each container has been solidified with concrete (Type 2), so simply resting them on the ground is enough [12,55]. The interior and exterior coatings and finishes (made from wooden panels, wood derivatives, ceramics and waste panels) are assembled by means of screws, nails and pressure devices (Figure 8-10). In R4House all the components are demountable, including water pipes (threaded polypropylene pipes), drains (pressurized polyethylene pipes) and electricity (pressurized polypropylene pipes). As a result, all R4House components can be easily removed, repaired, and reused indefinitely. In this way the building can have a durability that tends to infinity and the least possible need for maintenance.

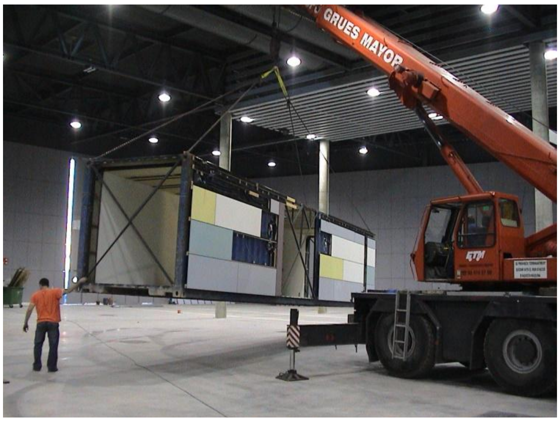

Figure 6: Each R4House Module was Partially Manufactured Separately

Figure 7: The 6 Partially Manufactured Modules were ensembled in just one day

Figure 8: After putting the 6 Partially Manufactured R4House Modules into place, Construction was Completed in Two Weeks

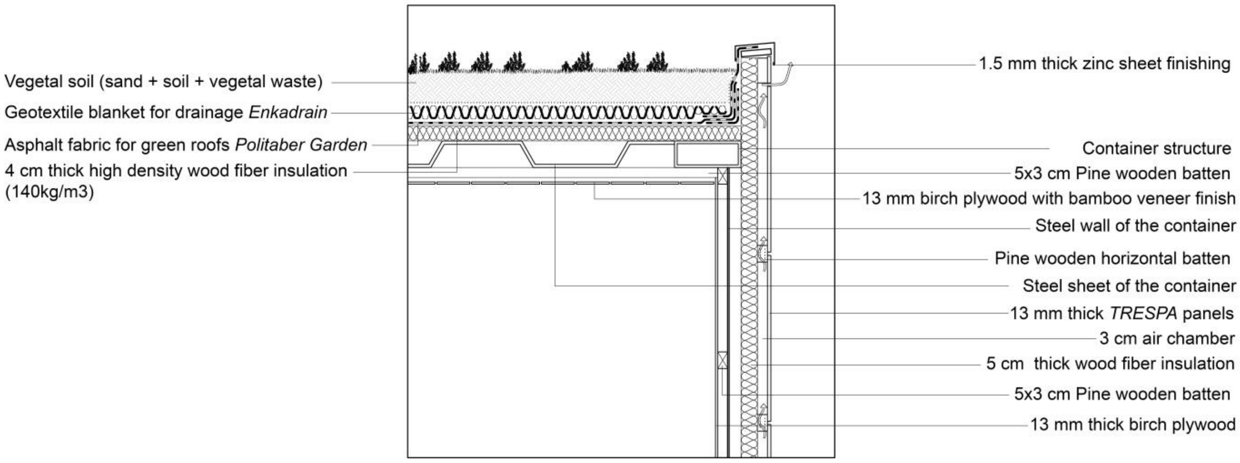

Figure 9: Detail of R4House. All Removable Covering Materials used are Indicated, Both Inside and Outside

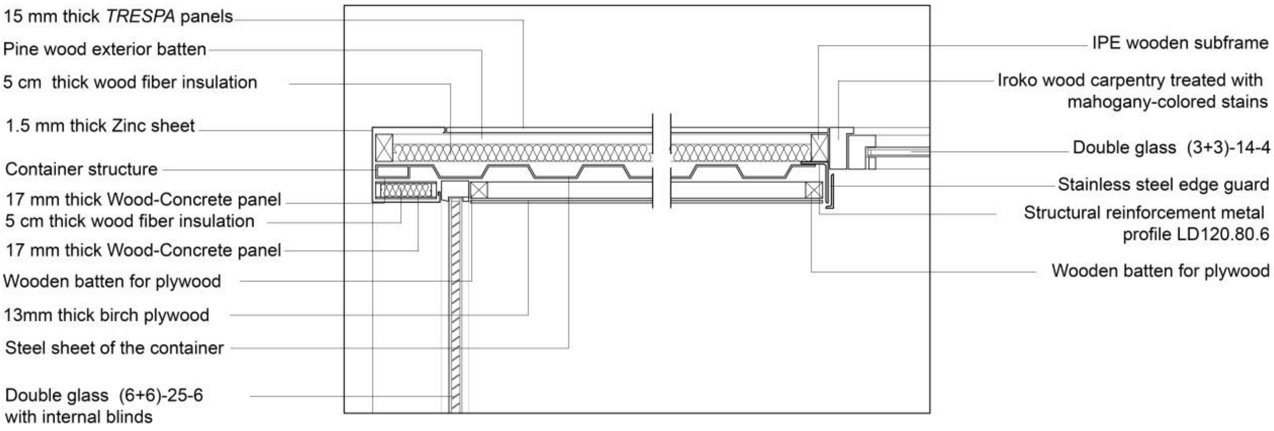

Figure 10: Detail of R4House

R4House has a high ecological sustainable level for many reasons, and also waste and healthy materials were used in its construction (Figure 11, 12) [12,55]. It was built in just three months and was designed with the aim of being able to self-regulate thermally and provide a comfortable internal temperature without the need for heating or air conditioning. However, in this work we only want to quantify the contribution of modular and demountable design in the sustainable score of the building, using the chosen 11 GBRS.

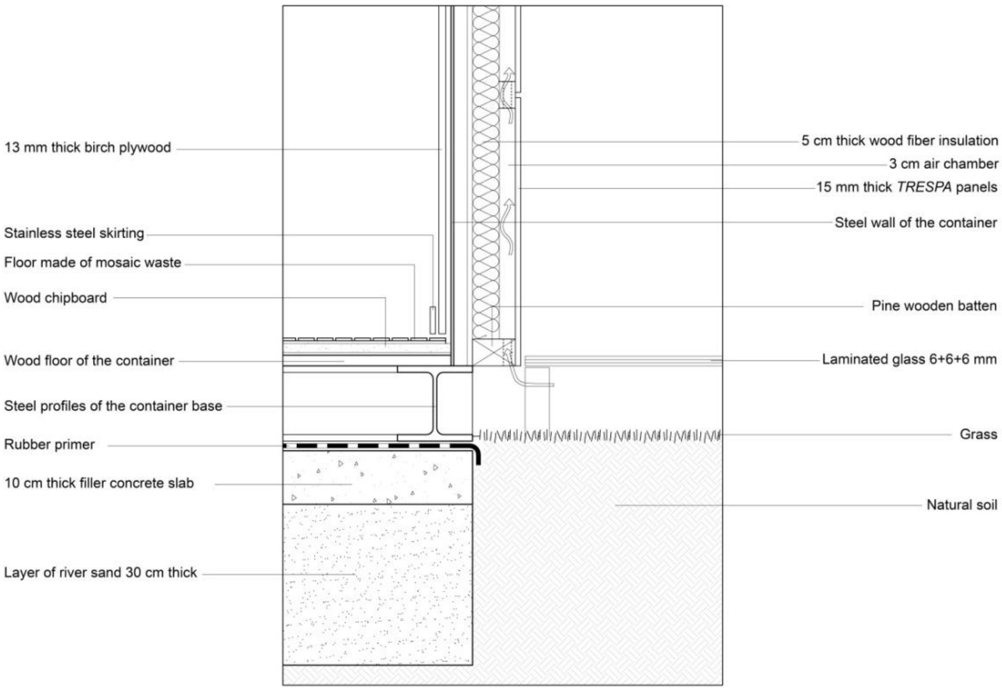

Figure 11: Detail of R4House

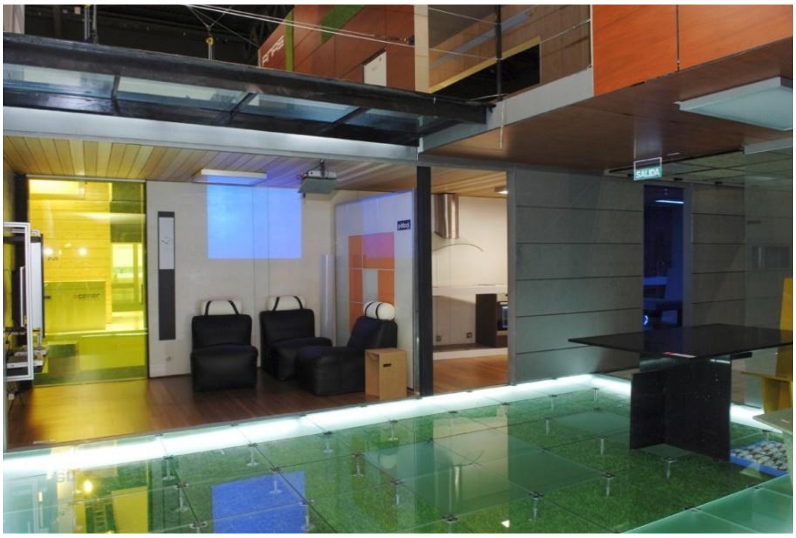

Figure 12: Only Industrial Waste was used in the Manufacture of R4House.

Although R4House meets high ecological and sustainable standards, in this work we only quantified the contribution of its demountable construction in its sustainable level, using the most leading GBRS [12,55]. As has been analyzed in previous studies, the environmental and economic advantages of demountable buildings are many, including the following [25-36]:

- Adaptability to new uses, and easy reconfiguration of the building
- Easy repair of all components
- Low energy consumption
- Maximum optimization of resources
- Minimum need for maintenance
- Quick construction
- Zero generation of emissions and waste

It is therefore assumed that the different GBRS must appropriately value these advantages and provide an important score for disassembly, as otherwise it could be deduced that these GBRS do not adequately assess it, are deficient, and should be modified.

Figure 13: R4House was Built in Three Months.

Description of the Non-Demountable Building. ND-R4House

In order to measure the differential score of the individual GBRS systems for demountable construction, R4House was compared to a reference baseline: a hypothetical non-demountable, but otherwise identical, version of R4House, known as the ND-R4House.

Therefore the specific characteristics of ND-R4House do not matter, but let us suppose for example that was built in a conventional way, like most single-family houses in Spain. The foundation is based on continuous reinforced concrete footings, the structure on load-bearing concrete block walls, reinforced concrete pillars and a slab based on prestressed semi-joists and reinforced concrete vaults. The interior is based on brickwork and gypsum-cellulose panels, the pitched roof on a conventional slab with prestressed concrete semi-joists and concrete vaults and the interior and exterior coatings are based on cement troweling and plaster with conventional plastic paints.

Comparative Evaluation Methodology

To evaluate the contribution of modular and demountable construction to the general level of sustainability, R4House was compared with ND-R4House using eleven of the most leading GBRS, considering only the indicators with different scores in each case, creating a comparative table for each GBRS. The set of indicators whose score varies when comparing a demountable with a non-demountable building is referred to as a "demountable group".

The evaluation tables show the scores obtained by both buildings:
- The score given to each indicator (strictly following the guidelines of each GBRS manual)
- The maximum possible score for each indicator.
- The weight of the indicator within the category to which it belongs.
- The weight of the category
- The conversion factor of the scoring scale of each method, to a scale of 0-100 (since some GBRS score from 0 to 75, others from 0 to 100, others from 0 to 110, others from 0 to 1000. The conversion factors used are therefore: 100/75, 100/100, 100/110, 100/1000).

A very simple process has been followed to make each table (Figure. 14). By multiplying the percentage score of an indicator (score/maximum score), by its weight within the category, by the weight of the category, and by the conversion coefficient, a value is obtained (from 0 to 100), which is the contribution of each indicator to the total score, so that adding the score of all the indicators of the "demountable-group" gives the total score that each group gives to both R4House and ND-R4House. Finally, by subtracting both scores, the contribution of demountable construction is obtained in the final score provided by each of the GBRS used.

It should be noted that each GBRS has a different internal structure and a different scoring system. Some GBRS do not have categories but only indicators, and the determination of the specific weight of each system is different and has to be calculated on a common weighting basis of 0 to 100. However, essentially all the tables show the same: the final score of each indicator on a scale from 0 to 100 and the total score of all of them for both houses (Tables Tables 2-12).

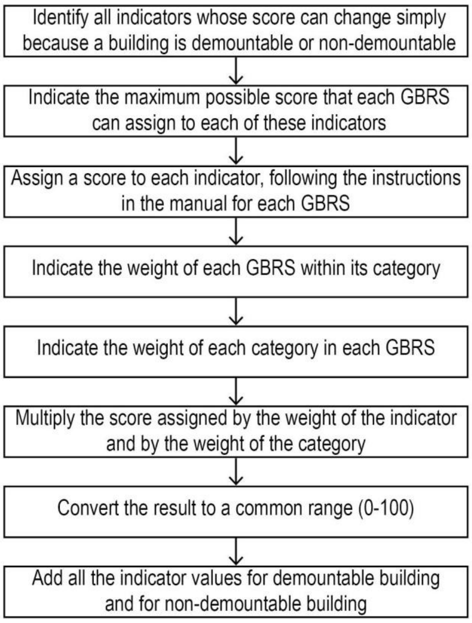

Figure 14: Process to Obtain the Quantification of the Contribution of Demountability to the Sustainable Level of Buildings Using Different GBRS

To describe the evaluation process and the contribution of each indicator in the final evaluation of the building, let us take an example from ASGB (Table 2).
The ASGB indicator "Building adaptability (BA)" has a maximum score of 18 points. This indicator has a weight of 18/100 within the category "Security and durability (SD)", and in turn this category has a weight of 10 out of 110 (ASGB has a total evaluation range of 0 to 100+10).

The R4House was given the maximum score (18), that is ((18/18) = 1). By multiplying this value (1) by the weight of the BA indicator within the category, a value of ((1) * (18/100)) is obtained, that is 0.18. Multiplying this value by the weight of the SD category in the total score gives (0.18 * (10/100)) = 0.018, based on a score of (0-110). Converting this percentage to a common base of (0-100), the final score is (0.018 * (100 / 110)) = 0.0164. That is, 1.64%.

The ND-R4House was given a score of 12 out of a maximum of 18, that is, ((12/18) = 0.66). Multiplying this value (0.66) by the weight of the BA indicator within the category gives a value of (0.66 * (18/100)), that is, 0.12. Multiplying this value by the weight of the SD category in the total score gives (0.12 * (10/100)) = 0.012, percentage based on a score of (0-110). Converting this percentage to a common base of (0-100), the final score is (0.012 * (100 / 110)) = 0.0109, i.e. 1.09%.

Repeating the process for the 5 indicators that can evaluate the demountability of a building in ASGB, R4House has a score of 4.85%, compared to 2.79% for ND-R4House. According to ASGB, a demountable building like R4House has an increase in the level of sustainability of 2.06% (4.85% – 2.79%) (Table 2).

Results

ASGB evaluation

Notes:
ASGB provides a maximum score of 100 points, and can provide an additional 10 points, therefore, the total score ranges from 0 to 110
(*1) Building adaptability, (*2) Longer useful life of components, (*3) Industrialized interior design parts, (*4) Use of recyclable, reusable and waste materials, (*5) Structural system and industrialized components, (*6) Security and durability, (*7) Resource conservation, (*8) Improvement and innovation

Demountable group		*R4House*						*ND-R4House*					
Indicators	Category	Score	Max. Score	Indicator weight	Category weight	Result (0-110)	Result (0-100)	Score	Max. Score	Indicator weight	Category weight	Result (0-110)	Result (0-100)
BA (*1)	SD (*6)	18	18	18/100	10%	1.80	1.64%	12	18	18/100	10%	1.20	1.09%
LULC (*2)	SD	10	10	10/100	10%	1.00	0.91%	6	10	10/100	10%	0.60	0.55%
IIDP (*3)	RC (*7)	8	8	8/200	20%	0.80	0.73%	4	8	8/200	20%	0.40	0.36%
URRWM (*4)	RC	12	12	12/200	20%	1.20	1.09%	6	12	12/200	20%	0.60	0.55%
SSIC (*5)	II (*8)	10	10	10/190	10%	0.53	0.48%	5	10	10/190	10%	0.27	0.24%

Partial Score		4.85%		2.79%
Difference				2.06%

Table 2: ASGB Indicators Involved in Modular and Demountable Construction. Score Differences Between R4Houseand ND-R4House

ASGB has 5 indicators involved in demountable construction and therefore, their scores vary in the evaluation of R4House, and ND-R4House. The score difference for both cases is only 2.06 % ecause ASGB does not consider many important factors such as: Economic cost, Resources needed, Level of exploitation of resources, Energy consumption in building construction and in demolishing/disassembling.

BEAM evaluation

Notes:

BEAM provides a maximum score of 100 points, and can provide an additional 10 points, therefore, the total score ranges from 0 to 110

(*1) Modular and standardized design, (*2) Prefabrication, (*3) Adaptability and deconstruction, (*4) Materials and waste

Demountable group		*R4House*						*ND-R4House*					
Indicators	Category	Score	Max. Score	Indicator weight	Category weight	Result	Result (0-100)	Score	Max. Score	Indicator weight	Category weight	Result	Result (0-100)
MSD (*1)	MW (*4)	2	2	2/35	9%	0.51	0.47%	1	2	2/35	9%	0.26	0.23%
PREF (*2)	MW	4	4	4/35	9%	1.03	0.93%	1	4	4/35	9%	0.26	0.23%
AD (*3)	MW	2	2	2/35	9%	0.51	0.47%	0	2	2/35	9%	0.00	0.00%

Partial Score		1.87%		0.47%
Difference				1.40%

Table 3: BEAM Indicators Involved in Modular and Demountable Construction. Score Differences Between R4Houseand ND-R4House

BEAM has only 3 indicators involved in demountable construction and therefore, their score varies in the evaluation of R4House, and ND-R4House. The score difference for both cases is only 1.40% and this is because BEAM does not consider many important factors such as: Economic cost, Resources needed, Level of exploitation of resources, Energy consumption in building construction and in demolishing/disassembling.

BREEAM Evaluation

Notes:

BREEAM provides a maximum score of 100 points, and can provide an additional 10 points, therefore, the total score ranges from 0 to 110

(*1) Management, (*2) Materials, (*3) Waste

Removable group		*R4House*						*ND-R4House*					
Indicators	Category	Score	Max. Score	Indicator weight	Category weight	Result (0-110)	Result (0-100)	Score	Max. Score	Indicator weight	Category weight	Result (0-110)	Result (0-100)
MAN02	MAN (*1)	4	4	19.05%	11%	2.10	1.91%	1	4	19.05%	11%	0.52	0.47%
MAT05	MAT (*2)	1	1	7.14%	15%	1.07	0.97%	0	1	7.14%	15%	0	0%
WST01	WST (*3)	3	5	45.45%	6%	1.64	1.49%	0	5	45.45%	6%	0	0%
WST06	WST	1	2	18.18%	6%	0.55	0.50%	0	2	18.18%	6%	0	0%

Partial Score		4.87%		0.47%
Difference				4.40%

Table 4: BREEAM Indicators Involved in Modular and Demountable Construction. Score Differences Between R4House and ND-R4House

BREEAM has only 4 indicators involved in demountable construction, each of which gave different scores when evaluating both homes. The score difference in both cases is only 4.40% because BREEAM does not consider many important factors such as: Economic cost, Energy consumption in building construction and in demolishing/disassembling.

CEDES Evaluation

Notes:

(*1) Resources optimization, (*2) Energy consumption in building construction, (*3) Energy consumption in demolishing/disassembling, (*4) Reduction of Waste and emissions, (*5) Economic cost

Demountable group		*R4House*						*ND-R4House*					
Indicators	Category	Score	Max. Score	Indicator weight	Category weight	Result	Result (0-100)	Score	Max. Score	Indicator weight	Category weight	Result	Result (0-100)
1.2.1	RO (*1)	5	5	0.072	18%	-	1.30%	2	5	0.072	18%	-	0.52%
1.2.4	RO	4	5	0.306	18%	-	4.41%	1	5	0.306	18%	-	1.10%
1.2.6	RO	4	5	0.225	18%	-	3.24%	3	5	0.225	18%	-	2.43%
2.4	ECIC (*2)	5	5	0.115	34%	-	3.91%	2	5	0.115	34%	-	1.56%
2.7	ECID (*3)	5	5	0.024	34%	-	0.82%	1	5	0.024	34%	-	0.16%
4	WE (*4)	5	5	1	12%	-	12%	1	5	1	12%	-	2.4%
6	EC (*5)	5	5	1	10%	-	10%	5	5	1	10%	-	10%

Partial Score		35.68%		18.17%
Difference				17.51%

Table 5: CEDES Indicators Involved in Modular and Demountable Construction. Score Differences Between R4House and ND-R4House

CEDES is the best-performing GBRS and has 7 indicators involved in demountable construction and therefore their scores vary in the evaluation of R4House, and ND-R4House. The score difference for both cases is 17.51%.

DNGB Evaluation

Notes:
(*1) Environmental quality, (*2) Economic quality, (*3) Technical quality, (*4) Process quality

Demountable group		***R4House***						***ND-R4House***					
Indicators	Category	Score	Max. Score	Indicator weight	Category weight	Result	Result (0-100)	Score	Max. Score	Indicator weight	Category weight	Result	Result (0-100)
ENV1.1	ENV (*1)	122.5	130	10/24	25%	-	9.82%	60	130	10/24	25%	-	4.81%
ENV1.2	ENV	120	135	5/24	25%	-	4.63%	115	135	5/24	25%	-	4.44%
ECO1.1	ECO (*2)	70	130	4/10	25%	-	5.38%	47,5	130	4/10	25%	-	3.65%
TEC1.6	TEC (*3)	110	125	3/9	25%	-	7.33%	60	125	3/9	25%	-	2.40%
PRO1.6	PRO (*4)	280	280	2/10	25%	-	5.00%	180	280	2/10	25%	-	3.21%
PRO2.1	PRO	110	110	2/10	25%	-	5.00%	85	110	2/10	25%	-	3.86%

Partial Score		37.16%		22.38%
Difference				14.79%

Table 6: DNGB Indicators Involved IN MODULAR AND DEMOUNTABLE CONSTRUCTION. Score Differences Between R4House and ND-R4House.

DNGB has 6 indicators involved in demountable construction, each of which gave different scores when evaluating R4House, and ND-R4House. The score difference in both cases was 14.79% and this was because DNGB does not consider some factors such as: Economic cost, Resources needed, Level of exploitation of resources.

GBI Evaluation

Notes:
(*1) Sustainable site plan management, (*2) Material resources

Demountable group		***R4House***						***ND-R4House***					
Indicators	Category	Score	Max. Score	Indicator weight	Category weight	Result	Result (0-100)	Score	Max. Score	Indicator weight	Category weight	Result	Result (0-100)
SM7	SSPM (*1)	2	2	-	-	-	2%	0	2	-	-	-	0%
MR1	MRSC (*2)	2	2	-	-	-	2%	1	2	-	-	-	1%
MR2	MRSC	2	2	-	-	-	2%	0	2	-	-	-	0%
MR6	MRSC	2	2	-	-	-	2%	0	2	-	-	-	0%

Partial Score		8%		1%
Difference				7%

Table 7: GBI Indicators Involved in Modular and Demountable Construction. Score Differences Between R4House and ND-R4House

GBI has 4 indicators involved in demountable construction, each of which gave different scores in evaluating R4House, and ND-R4House. The score difference in both cases was 7% because GBI does not consider many important factors such as: Economic cost, Resources needed, Level of exploitation of resources, Energy consumption in building construction and demolishing/disassembling.

GG Evaluation

Notes:
(*1) Project Management, (*2) Materials

Demountable group		***R4House***						***ND-R4House***					
Indicators	Category	Score	Max. Score	Indicator weight	Category weight	Result (0-1000)	Result (0-100)	Score	Max. Score	Indicator weight	Category weight	Result (0-1000)	Result (0-100)
1.3 LCCA	PM (*1)	12	12	-	-	12	1.20%	0	12	-	-	0	0%
5.2 PLC	MAT (*2)	39	39	-	-	39	3.90%	10	39	-	-	10	1%
5.5.1 S&E	MAT	11	22	-	-	11	1.10%	0	22	-	-	0	0%
5.5.2 MROS	MAT	8	8	-	-	8	0.80%	0	8	-	-	0	0%
5.7.1 OSFC	MAT	4	4	-	-	4	0.40%	2	4	-	-	2	0.2%
5.7.2 DFD	MAT	6	6	-	-	6	0.60%	0	6	-	-	0	0%

Partial Score		8.00%		1.20%
Difference				6.80%

Table 8: GG Indicators Involved in Modular and Demountable Construction. Score Differences Between R4House and ND-R4House

GG has 6 indicators involved in demountable construction, each of which gave different scores when evaluating R4House, and ND-R4House. The score difference in both cases was 6.80% because GG does not consider some factors such as: Economic cost, and Energy consumption in building construction.

GS Evaluation

Notes:

GS provides a maximum score of 100 points, and can provide an additional 10 points (innovation), therefore, the total score ranges from 0 to 110

(*1) Management, (*2) Materials

Demountable group		R4House						ND-R4House					
Indicators	Category	Score	Max. Score	Indicator weight	Category weight	Result (0-110)	Result (0-100)	Score	Max. Score	Indicator weight	Category weight	Result (0-110)	Result (0-100)
5	MGMT (*1)	2	2	-	-	2	1.818%	1	2	-	-	1	0.909%
19	MAT (*2)	7	7	-	-	4	6.364%	3	7	-	-	3	2.727%
22	MAT	1	1	-	-	3	0.909%	0	1	-	-	0	0.000%

Partial Score		9.09%		3.64%
Difference				5.46%

Table 9: GS Indicators Involved in Modular and DEMOUNTABLE CONSTRUCTION. Score Differences Between R4House and ND-R4House.

GS has only 3 indicators involved in demountable construction, each of which gave different scores when evaluating R4House, and ND-R4House. The score difference in both cases was only 5.46% because GS does not consider many important factors such as: Economic cost, Resources needed, Level of exploitation of resources.

IGBC Evaluation

Notes:

IGBC provides a maximum score of 75, therefore, the total score ranges from 0 to 75

(*1) Material Resources

Demountable group		R4House						ND-R4House					
Indicators	Category	Score	Max. Score	Indicator weight	Category weight	Result (0-75)	Result (0-100)	Score	Max. Score	Indicator weight	Category weight	Result (0-75)	Result (0-100)
C2	MR (*1)	1	1	-	-	1	1.33%	0	1	-	-	0	0%
C3	MR	2	2	-	-	2	2.66%	2	2	-	-	2	2.66%

Partial Score		3.99%		2.66%
Difference				1.33%

Table 10: IGBC Indicators Involved in Modular and Demountable Construction. Score Differences Between R4House and ND-R4House.

IGBC has only 2 indicators involved in demountable construction, each of which gave different scores when evaluating R4House, and ND-R4House. The score difference in both cases was only 1.33% because IGBC does not consider many important factors such as: Economic cost, Resources needed, Level of exploitation of resources, Energy consumption in building construction, and demolishing/disassembling.

LEED Evaluation

Notes:

LEED provides a maximum score of 100 points, and can provide an additional 10 points, therefore, the total score ranges from 0 to 110

Indicators of the manual for single-family housing

(*1) Environmentally Preferable Products, (*2) Construction and Demolition Waste Management, (*3) Materials and Resources

Demountable group		R4House						ND-R4House					
Indicators	Category	Score	Max. Score	Indicator weight	Category weight	Result (0-110)	Result (0-100)	Score	Max. Score	Indicator weight	Category weight	Result (0-110)	Result (0-100)
EPP (*1)	MR (*3)	4	5	-	-	4	3.64%	3	5	-	-	3	2.73%
CDWM (*2)	MR	1	2	-	-	1	0.91%	0	2	-	-	0	0

Partial Score		4.55%		2.73%
Difference				1.82%

Table 11: LEED Indicators Involved in Modular and Demountable Construction. Score Differences Between R4House and ND-R4House.

LEED has only 2 indicators involved in demountable construction, each of which gave different scores in evaluating R4House, and ND-R4House. The score difference in both cases was only 1.82% because LEED does not consider many important factors such as: Economic cost, Resources needed and Level of exploitation of resources, Energy consumption in building construction, and in demolishing/disassembling.

SBTools Evaluation

Notes:

(*1) Energy and Resources Consumption, (*2) Environmental Loadings , (*3) Service Quality, (*4) Cost and Economic Aspects

Demountable group		*R4House*						*ND-R4House*					
Indicators	Category	Score	Max. Score	Indicator weight	Category weight	Result	Result (0-100)	Score	Max. Score	Indicator weight	Category weight	Result	Result (0-100)
B 1.1	ERC (*1)	5	5	6.48%	-	-	6.48%	3	5	6.48%	-	-	3.89%
B 1.2	ERC	5	5	3.24%	-	-	3.24%	3	5	3.24%	-	-	1.94%
B 3.3	ERC	5	5	0.20%	-	-	0.20%	0	5	0.20%	-	-	0.00%
B 3.5	ERC	5	5	0.20%	-	-	0.20%	3	5	0.20%	-	-	0.12%
B 3.6	ERC	5	5	0.20%	-	-	0.20%	0	5	0.20%	-	-	0.00%
C 1.1	EL (*2)	5	5	4.86%	-	-	4.86%	3	5	4.86%	-	-	2.92%
C 1.2	EL	3	5	4.86%	-	-	2.92%	0	5	4.86%	-	-	0.00%
E 4.1	SQ (*3)	5	5	0.05%	-	-	0.05%	3	5	0.05%	-	-	0.03%
E 4.2	SQ	5	5	0.41%	-	-	0.41%	3	5	0.41%	-	-	0.25%
E 4.3	SQ	3	5	0.05%	-	-	0.03	0	5	0.05%	-	-	0.25%
G 1.1	CEA (*4)	5	5	0.10%	-	-	0.10%	0	5	0.10%	-	-	0.00%
G 1.2	CEA	5	5	0.10%	-	-	0.10%	0	5	0.10%	-	-	0.00%
G 1.3	CEA	5	5	0.10%	-	-	0.10%	3	5	0.10%	-	-	0.06%

Partial Score	18.89%	9.46%
Difference		9.43%

Table 12: Indicators of SBTool Involved in Modular and Demountable Construction. Score Differences Between R4House and ND-R4House.

SBTools has 13 indicators involved in demountable construction, each of which gave different scores in evaluating R4House and ND-R4House. The score difference in both cases was only 9.43% because SBTools does not consider some factors such as: Economic cost, Resources needed, Level of exploitation of resources.

The results of the comparative evaluation by each GBRS were the following: ASGB: 2.06 %, BEAM: 1.40 %, BREEAM: 4.40 %, CEDES: 17.51 %, DNGB: 14.79 %, GBI: 7 %, GG: 6.80 %, GS: 5.46 %, IGBC: 1.33 %, LEED: 1.82 % and SBTool: 9.43 % (Tables 13, 14).

GBRS	ASGB	BEAM	BREEAM	CEDES	DNGB	GBI	GG	GS	IGBC	LEED	SBTool
Score R4House	4.85	1.87	4.87	35.68	37.16	8.00	8.00	9.09	3.99	4.55	18.89
Score ND-R4House	2.79	0.47	0.47	18.17	22.38	1.00	1.20	3.63	2.66	2.73	9.46
Score difference	**2.06**	**1.40**	**4.40**	**17.51**	**14.79**	**7.00**	**6.80**	**5.46**	**1.33**	**1.82**	**9.43**

Table 13: Score Differences Between R4House and ND-R4House for the 11 GBRS

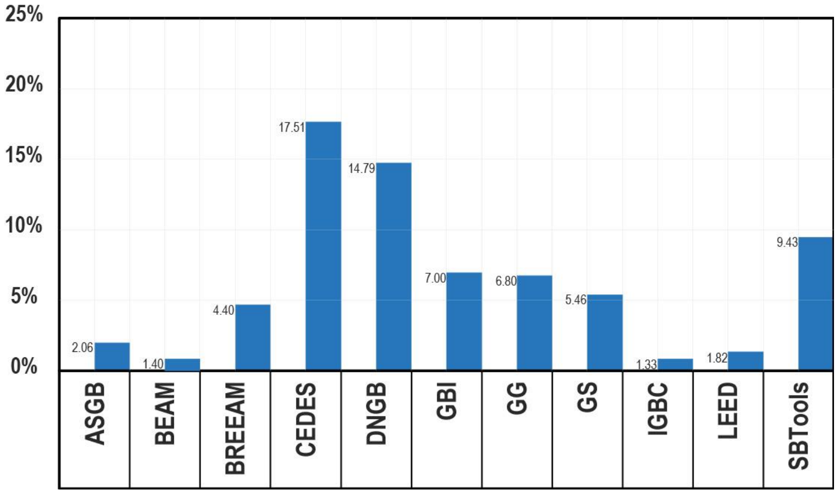

Table 14: Contribution of Demountable Construction to a Building's Sustainability Level, Using 11 GBRS

R4House can be dismantled and reassembled as many times as desired. In addition, all its components are easily dismantled, repairable and reusable, so the durability of the building can be maximized and with minimal maintenance required the environmental impact per unit of time can be minimized. Likewise, its construction reduced energy consumption to a minimum, resources were optimized to the maximum and the generation of emissions and waste was greatly reduced. It could thus be expected that all the GBRS would adequately value these environmental advantages by giving to R4House a high score, although this was not the case.

Only three GBRS adequately assessed the sustainable level of modular and demountable construction (CEDES: 17.51 %, DNGB: 14.79 %, SBTools: 9.43) while the rest gave it a low score, and four gave it an extremely low score (IGBC: 1.33 %, BEAM: 1.40 %, LEED 1.82 %, ASGB: 2.06 %). However, the most surprising aspect of the results is the disparity in the scores obtained.

Taking into account the average scores of the 11 GBRS, the contribution of low-weight demountability to the level of sustainability of buildings is 6.54% ((2.06 + 1.40 + 4.40 + 17.51 + 14.79 + 7.00 + 6.80 + 5.46 + 1.33 + 1.82 + 9.43) / 11 = 6.54).

However, if only CEDES, DNGB and SBTools are taken into account, the contribution of demountability to the level of sustainability of buildings is 13.91% ((17.51 + 14.79 + 9.43) / 3 = 13.91).

Discussion

This study quantified the contribution of low-weight modular and demountable construction to the sustainability level of buildings. For this purpose, a representative case study building, R4House, was analyzed as an example of low-weight modular and demountable construction systems using 11 Green Building Rating Systems (GBRS).

The results demonstrate that low-weight modular and demountable construction leads to an increase in the overall sustainability level of buildings. Although the analysis was based on a single case study, the findings can be considered generalizable, as the GBRS employed in the evaluation lack the resolution necessary to detect minor variations among low-weight modular and demountable construction systems. Moreover, this study has significant implications for practitioners, policymakers, and standard-setting bodies, as it provides, for the first time, a robust reference value. According to the GBRS considered most appropriate in this study, the use of low-weight demountable construction results in an increase in building sustainability of up to 13.91%.

Despite this overall positive outcome, substantial discrepancies were observed among the results produced by the different GBRS. Only three of the rating systems adequately captured and reflected the sustainability benefits of a demountable modular dwelling, whereas the remaining systems assigned it limited relevance, and three of them attributed an extremely low score. Such variability is problematic, as it implies that a building's assessed level of sustainability depends heavily on the specific GBRS selected. This finding suggests that the GBRS analyzed are not fully suitable for consistently and accurately evaluating building sustainability. Nevertheless, further comparative research is required to determine whether alternative GBRS may be more appropriate for this purpose.

It should be noted that a growing body of literature has questioned the validity of existing GBRS. Some studies raise concerns about their credibility due to the substantial differences among rating systems, which often lead to divergent results when assessing the same building. This situation is largely attributed to the absence of an internationally agreed definition of sustainability and the lack of a common framework for achieving and evaluating it [56]. Other research argues that current GBRS fail to properly assess sustainability because architectural design is insufficiently considered within their scoring methodologies [15,28,57-60]. Even more critical studies conclude that, when analyzing multiple buildings certified under certain GBRS, no significant improvements in energy efficiency or resource optimization are observed compared to conventional buildings [57,58,61,62]. Furthermore, an increasing number of publications strongly criticize the practical usefulness of some of the most widely recognized GBRS, such as LEED [63,64]. In light of these limitations, current GBRS should be substantially revised or replaced by more suitable assessment frameworks.

It is often argued that the substantial differences among GBRS are justified by the wide environmental and socio-economic variability between countries. However, significant disparities also exist within individual countries, such as China, the United States, Italy, Brazil, Germany, and France, where a single GBRS is frequently imposed nationwide. Conversely, many GBRS have been explicitly designed for international application and are, in practice, used across diverse regions. In addition, there are countries in which several markedly different GBRS are commonly applied simultaneously, including the United Kingdom, France, Spain, Portugal, and Brazil.

The underlying cause of the pronounced differences among current GBRS lies in the fact that they are based on divergent interpretations of sustainability, often shaped by specific economic and institutional interests. Consequently, an international consensus on the concept of sustainability is urgently required. Based on such a consensus, a global conceptual and taxonomic framework should be established to support the development of new and more appropriate GBRS. While these future rating systems would inevitably incorporate minor adaptations to reflect local socio-economic and environmental conditions, they should be grounded in a shared and coherent understanding of sustainability.

Without a broadly accepted definition of sustainability and an internationally recognized GBRS framework, genuine sustainable development and truly sustainable construction cannot be achieved. The concept of sustainability must therefore be defined through international agreement, and a robust conceptual framework should be proposed to guide the development of new GBRS capable of overcoming the shortcomings of current systems. Notably, several proposals for more valid and legitimate GBRS already exist and may serve as reference frameworks for the development of GBRS [47].

Until such an international consensus is reached, existing GBRS should be improved. In this regard, two key recommendations are proposed. First, greater emphasis should be placed on architectural design, rather than predominantly on technical devices and add-on technologies. Second, the weighting of individual indicators should be revised to achieve a more balanced and coherent assessment structure. To support this process, a table identifying opportunities for improvement and areas for development has been prepared for each of the 11 GBRS analyzed in this study (Table 15).

GBRS	*Categories and scoring system*	*Opportunities*	*Areas of Growth*
ASGB	Safety and Durability, Health and Comfort, Living Comfort, Resource Conservation, Livable Environment, Improvement and Innovation. (1 star, 2 stars, 3 stars)	Very balanced categories and indicators. Values the innovation to carry out sustainable strategies. Categories well grouped	Too much importance to prerequisites. Official guides and tools are written only in Chinese. Does not give importance to waste / emissions
BEAM	Integrated design and construction management, Sustainable site, Materials and waste, Energy Use, Water Use, Health and Wellbeing, Innovations and Additions (Diamond, Platinum, Gold, Silver, Bronze, Certified)	Values decrease in resource consumption through industrialization. The category's weights are very balanced	Too much relative importance of interior quality. The assessment must be renewed every 5 years. The assessment environment is too close
BREEAM	Management, Health and Well-being, Energy, Transport, Water, Materials, Waste, Soil and Ecology, Pollution and Innovation. (Unrated, Correct, Good, Very Good, Excellent, or Exceptional)	Importance of resource optimization. Values passive design	Does not give importance to natural energy. Passive design doesn't have much weight
CEDES	Optimization of resources, Reduction in energy consumption, Use of natural energy sources, Reduction of waste and emissions, Increased health and quality of life of building occupants, Economic cost, Social adequacy, Complementary sustainable aspects (final score: 1 to 10)	Hierarchical system of categories and indicators, avoiding oversized and undersized indicators. Design properly assessed	The weights of the categories and indicators must be adapted to each socio-economic and environmental environment.
DNGB	Ecological quality, Economic quality, Sociocultural and Functional quality, Technical quality, Process quality, Site quality. (Bronze, Silver, Gold, Platinum)	It values life cycle, resource optimization and bioclimatic design and component recovery	Little value to energy, water consumption and waste. Too many bonus points and difficulty in scoring
GBI	Energy efficiency, Indoor environment quality, Planning and Sustainable management of the Site, Materials and Resources, Water efficiency, Innovation. (Platinum, Gold, Silver, Certified)	The buildings continue to be evaluated in their use. Easy to use	Does not value design and disassembly. Little value to economy. High value to site
GG	Project Management, Site, Energy, Water efficiency, Materials, and indoor environment. (One to four green globes)	It includes design for deconstruction, modular and prefab construction	Does not give importance to natural energy sources.
GS	Management, Indoor environmental quality, Energy, Transportation, Water, Materials, Land use and ecology, Emissions and innovation. (1 star, 2 stars, 3 stars, 4 stars, 5 stars, 6 stars)	It values bioclimatic design, construction and monitoring	It does not value the use of natural energy sources
HQE	General aspects, Quality of Life, Respect for the environment, Economic performance. (Approved, Good, Very good, Excellent, Exceptional)	Takes into account the local context. It refers to the disassembly of the building	Too much importance to equipment performance. Does not give much importance to bioclimatic design
LEED	Integrative process, Location and Transportation, Sustainable sites, Water efficiency, Energy and Atmosphere, Materials and Resources, Indoor environmental quality, Innovation, Regional priority. (Platinum, Gold, Silver, Certified).	It has a relatively simple operation	It does not give importance to bioclimatic design. In many categories points can be added using technology
SBTool s	Site development and Infrastructure, Energy and Resource consumption, Indoor environmental loads, Environmental quality, Service quality, Social, cultural and perceptual aspects, Costs and Economic aspects. (−1 , 0, 1, 3, 5)	Adaptable to all regions with their cost variation. International	Little importance to indoor air quality. Gives much importance to energy consumption and site

Table 15: Categories, Scores, Opportunities and Areas of Growth of the 11 GBRS

Conclusions

This study quantifies, for the first time, the contribution of light-weight modular and demountable construction to the sustainability performance of buildings. To this end, a fully demountable house and a comparable non-demountable house were evaluated using eleven Green Building Rating Systems (GBRS), and the resulting scores were comparatively analyzed. The selected GBRS were ASGB, BEAM, BREEAM, CEDES, DNGB, GBI, GG, GS, IGBC, LEED, and SBTools.

The case study building, R4House, is entirely demountable, with components that can be easily assembled and disassembled. This characteristic allows the elements to be removed from the building, repaired, and reused multiple times, thereby maximizing durability and minimizing environmental impact per unit of time.

Given the substantial environmental advantages associated with demountable construction—such as extended service life, reduced environmental impact over time, lower emissions and waste generation, optimized resource use, low energy consumption, and the elimination of programmed obsolescence—it would be reasonable to expect all GBRS to appropriately recognize these benefits through high sustainability scores. However, this expectation was not met.

Although all eleven GBRS assigned a higher sustainability level to the demountable building compared to the non-demountable one, eight of them yielded relatively low scores despite the evident environmental benefits of demountability. Only three GBRS provided scores that can be considered adequate. Moreover, the results exhibited significant variability among the eleven GBRS, which is problematic, as the same building received markedly different sustainability ratings depending on the assessment system applied.

The first conclusion of the study is that, based on the results obtained, CEDES, DNGB, and SBTools are the GBRS that most effectively assess modular and demountable construction. When only these three systems are considered, the contribution of demountability to the overall sustainability level of buildings is quantified as 13.91%. The findings of this case study are largely generalizable, as most GBRS demonstrate limited capability to distinguish between different demountable construction systems.

The second conclusion is that the majority of current GBRS are unable to accurately assess sustainability in relation to demountable construction and therefore require substantial modification.

Further research is undoubtedly necessary, including the application of additional GBRS and the analysis of other case studies. Nevertheless, this study provides practitioners interested in fully demountable buildings with a valuable reference regarding the potential contribution of demountability to building sustainability.

Data Availability Statement (DAS)

The data that support the findings of this study are available from the corresponding autor (De Garrido, Luis), upon reasonable request.

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