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Critical Review of the Material Criteria of Building Sustainability Assessment Tools

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Abstract: Comparative analysis of the material criteria embedded in building sustainability assessment tools was performed. The material-related issues were identified, classified, and summarized. A framework, the triple bottom line of sustainability (environment, economy, and society), was used to examine the material assessment criteria, evaluation parameters, and descriptions. The material criteria were evaluated to identify the current features and weaknesses as balanced material assessments for sustainable development. The criteria showed significant differences in their scopes in covering the social and economic aspects beyond the environmental aspect. For comprehensive sustainability assessment purposes, it is essential that adequate attention be paid to all three dimensions. Finally, this paper proposes the indicators of the sustainable material assessment from an analysis of all the material-related items.

Keywords: sustainability; material; building sustainability assessment; green building rating systems; architecture; building; BREEAM; LEED; CASBEE; LBC; G-SEED

1. Introduction

1.1. Motivation

Sustainability has grown to become one of the most important and progressive trends in architecture over the last two decades [1]. This has resulted in new policies, technological advances, transformative industrial practices, and social consciousness for a sustainable built environment [2,3]. In addition, considerable efforts have been made to develop codified standards, including assessment tools. A number of building sustainability assessment tools have been proposed, based on extensive research experience [4,5]. They have contributed significantly to understanding the relationship between buildings and the environment, and empowering professionals to deal with current and future sustainability issues [5,6]. In addition, building clients measure and reduce the environmental impacts of their buildings and, in doing so, produce higher value, lower risk assets [7]. They play a leading role in encouraging higher environmental standards voluntarily than what the market is expected to bear. Furthermore, they are encouraged to adopt innovations in design, products, processes, technology, and systems for more sustainable buildings [8–10].

In this stream of placing emphasis on sustainability in architecture, environmental issues surrounding the materials used are also highlighted in addition to conventional attributes, such as aesthetics, durability, function, cost, and constructability [11]. The environmental issues of materials are numerous, and include pollution, natural resource depletion, habitat and species loss, energy and performance, health and productivity of occupants, etc. The majority of assessment tools include the material category as a major issue, whose weights range from 10% to 20% [9]. In addition, the material requirements become increasingly stringent as their scope expands.

As the next step, the sustainability assessment spans from a mono-dimensional aspect (environment) to multi-dimensional aspects of the built environment [6,12]. The three primary aspects of sustainability, i.e., environment, economy, and society, are adopted broadly as the basic themes in elaborating the assessment tools including material issues.

The main scope of this paper is to review the material-related assessments in different tools, along with unique features, similarities, and disparities. The paper discusses the current state of their commitment towards the true sustainability of building materials.

1.2. Literature Review

Since building sustainability assessment tools were introduced in the 1990s, they have become an active research field [13,14]. Other authors, who provided general descriptions of each tool, have made a comparison of the contextual and methodological aspects of tools. Ding [5] examined the development, role, and limitations of current assessment methods when ascertaining the building sustainability used in different countries. This led to a discussion of the concept of developing a sustainability model based on a multi-dimensional approach. T. Saunders [7] looked at the four most commonly used tools in the Building Research Establishment (BRE) research report to launch the international version of the BRE Environmental Assessment Method (BREEAM). Berardi [9] compared six tools and analyzed a sample of buildings to determine the most important criterion that is achieved in the rating system. Forsberg and Malmborg [15] compared five tools of Northern Europe, and Braganca et al. [14] and Ali et al. [16] proposed the tools for Portugal and Jordan, respectively, which were based on case studies of assessment tools. Existing comparative studies mostly include BREEAM, Leadership in Energy and Environmental Design (LEED), and Comprehensive Assessment System for Built Environment Efficiency (CASBEE). In the case of the Living Building Challenge (LBC), several studies, such as Kudryashova et al. [1] and Kamali and Hewage [17], defined it as the most stringent tool compared to the others. In addition, there have been multiple studies on the Green Standard for Energy and Environmental Design (G-SEED) in Korea to develop it further by benchmarking the world-leading tools. Kim et al. [18] compared the operation strategies with other major tools. Han and Kim [19] examined architectural professionals' needs and preferences with regard to sustainable building guidelines in Korea, with a specific focus on the various guideline attributes.

Recently, several studies dealt with specific issues, such as energy and water. Lee and Burnett [20] reported the results of an energy use assessment of three tools. Over Arup and Partners [21] compared the energy and water-related credit requirements for eight tools. Waidyasekara et al. [22] compared eleven tools in terms of the water efficiency and conservation. Gong et al. [23] compared the life-cycle assessment (LCA) of four tools including G-SEED. Wei et al. [24] analyzed the indoor air quality (IAQ) in 31 tools.

In contrast, only a few papers have focused on the material criteria of the assessment tools but their research scope was limited. Rahardjati et al. [25] compared the Green Building Index (GBI) from Malaysia and Greenship from Indonesia regarding how they evaluated the building material component. They only identified the limited items under the "*Materials*" categories. Castro-Lacouture et al. [26] focused on the optimal selection of materials, and proposed a mixed integer optimization model that incorporated the design and budget constraints while meeting the requirements of LEED in Colombia. Yoon and Park [27] analyzed the material-related issues on an urban scale. They compared the neighborhood sustainability assessment tools as well as urban design guidelines, including cases in the UK, the US, Japan, and Korea. The present study used a similar methodology, but on a building-scale.

1.3. Objectives and Paper Outline

This paper is composed of five sections. Section 2 discusses the selection of the five assessment systems, and introduces a framework for comparative analysis, i.e., the triple bottom line of sustainability. Section 3 examines only material-related items in detail from the results of an analysis of each tool. Those items are analyzed based on the three primary aspects of sustainability, and are grouped according to keywords. Section 4 discusses the findings through a comparative study. In addition, the indicators under the three aspects are derived and defined. Finally, Section 5 connects the findings with the research intent, and suggests subsequent steps for future research.

2. Methodology

2.1. Delimitation of the Research Subject: Selection of the Five Building Sustainability Assessment Tools

Many rating systems for sustainability assessments are available worldwide. Among these, this study selected five tools. The most adopted tools were considered along with their information accessibility and global recognition. These were BREEAM, LEED, and CASBEE. BREEAM was the first assessment tool launched for new office buildings in 1990. This has made an impact worldwide with other counties developing their own systems [28]. Among those, LEED and CASBEE are recognized internationally as the world's leading methods [26].

In particular, this study included LBC. Braganca et al. [14] classified two extreme trends: the complexity and diversity of indicators, and the evolution towards better usability through a common understanding and simplicity. BREEAM, LEED, and CASBEE belong to the first group while LBC belongs to the second. LBC provides considerably more advanced sustainability criteria and requires the highest and strictest standards [1,11,17]. To understand the diverse approaches, it should be compared with the others. Lastly, G-SEED of Korea was included in the comparison and discussion of the directions for improvement.

Briefly, the scope of this study is limited to five tools applicable to the new construction of office buildings. They are NC-INT of BREEAM (2016), BD+C: NC of LEED (2014, v4.0), BD/NC of CASBEE (2014), LBC (2016, v3.1), and NC/Non-residential of G-SEED (2016). To be completely objective, all information was obtained directly from the official websites or documents of each rating system.

2.2. Base of the Framework: The Triple Bottom Line of Sustainability

The definition of sustainability from the World Commission on Environment and Development (WCED) in 1987 [29] states that a development must consider simultaneously the environmental, economic, and social dimensions, which is a holistic and inter-disciplinary approach [3,12,30]. In this manner, a sustainable idea also expresses the interconnected nature of these three areas and leads to an economically feasible, socially viable, and environmentally responsible project outcome [31].

The concept of sustainability can include the following: (1) the need for environmental protection of air, water, soil, and biodiversity; (2) the need for economic development to overcome poverty, local economy, efficiency, adaptability, costs, the economic value of the building, and productivity of the occupants; and (3) the need for social justice, cultural diversity, local communities, and quality of spaces. In addition, the satisfaction, equity, health, and wellbeing of people are included [6,13,30].

The perspective of the triple bottom line has some important advantages, including sustainability assessment applications. Several studies have reviewed the assessment tools to interrelate the three primary dimensions of sustainability and have highlighted the need for a comprehensive and integrated framework [6,32,33]. On the other hand, many studies comparing assessment tools revealed the material to be an environmental indicator [30,33]. This study proposes the application of the triple bottom line of sustainability to sustainable material assessments.

3. Analysis: Material-Related Items in Building Sustainability Assessment Tools

3.1. "*Material*" Category

A critical aspect of assessment tools is the selection of appropriate criteria and weights given to each category [9]. This subsection examines how each tool assigns the "*Material*" category in terms of its weight and number of items. All five tools are composed of multiple categories ranging from six to nine, and has the "*Material*" category in common, as highlighted in Table 1. As shown in Figure 1, their weights are 12.5%, 13%, 15%, and 15% in BREEAM, LEED, CASBEE, and G-SEED, respectively (LBC does not have credits/weights). All tools commonly show that the weight of "*Material*" is after those of energy, site, and indoor environment quality (IEQ).

Table 1. Comparison of the five assessment categories.

BREEAM			LEED			CASBEE			LBC			G-SEED		
Category	**W (%)**	**I**	**Category**	**W (%)**	**I**	**Category**	**W (%)**	**I**	**Category**	**W (%)**	**I**	**Category**	**W (%)**	**I**
Management	12	5	Integrative process	1	1	Indoor Environment	20	22	Place	-	4	Land Use and Transport	10	7
Health and Wellbeing	14	9	Location and Transportation	16	8	Quality of Service	15	30	Water	-	1	Energy and Pollution	30	8
Energy	19	9	Sustainable Sites	10	7	Outdoor Environment (On-site)	15	4	Energy	-	1	**Materials and Resources**	**15**	**6**
Transportation	8	6	Water Efficiency	11	7	Energy	20	5	Health and Happiness	-	3	Water	10	4
Water	6	4	Energy and Atmosphere	33	11	**Resources and Materials**	**15**	**13**	**Materials**	**-**	**5**	Management	7	4
Material	**12.5**	**4**	**Materials and Resources**	**13**	**7**	Off-site Environment	15	15	Equity	-	4	Ecology	10	5
Waste	7.5	6	Indoor Environment Quality	16	11	-			Beauty	-	2	Indoor Environment Quality	18	10
Land Use and Ecology	10	4	(Innovation)	(+6)	(+2)				-			(Innovative Design)	(+10)	(+10)
Pollution	6.5	5	(Regional Priority)	(+4)	(+4)							-		
(Innovation)	(+10)	(+1)	-											
9	100	52	7	100	52	6	100	98	7	-	20	7	100	44
(+1)	(+10)	(+1)	(+2)	(+10)	(+6)							(+1)	(+10)	(+10)

W: Weight (%); C: Credits; S: Scores; I: No. of Items; ( ): Additional.

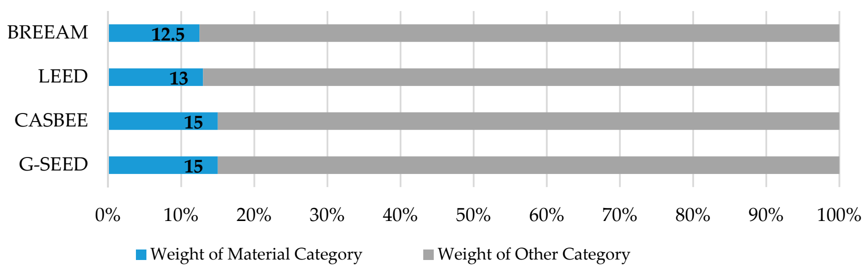

Figure 1. Quantitative comparison of the weight in the "*Material*" category.

In addition, the percentages of items under the "*Material*" category are 8% (4/52 items), 13% (7/52 items), 13% (13/98 items), 25% (5/20 items), and 14% (6/44 items) in BREEAM, LEED, CASBEE, LBC, and G-SEED, respectively, as shown in Figure 2. On the other hand, the material-related items are not limited within the "*Material*" category, but are spread over a range of categories, which will be investigated in Section 3.2.

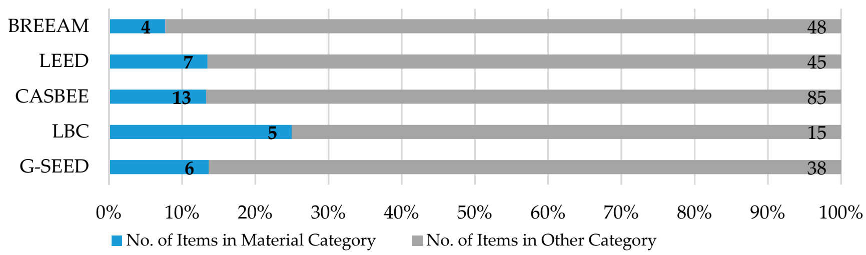

Figure 2. Quantitative comparison of the number of items in the "*Material*" category.

The "*Material*" category of the five tools announces their intent [11,34–37]. Commonly, they aspire to minimize the environmental impacts throughout the building life cycle, such as low-embodied impact, improved performance, and resource efficiency. Generally, the economic and social aspects of sustainable development are not an explicit concern in their aim except for LBC. BREEAM only mentioned the "responsible way" for the procurement of materials [34]. In contrast, LBC emphasizes all three aspects in its intent, which mentioned "a materials economy that is non-toxic, ecologically restorative, transparent, and socially equitable" and "a truly responsible material economy" [11].

3.2. *Material-Related Items in Multiple Categories*

This subsection analyzes all the material-related items and categorizes them into three dimensions of sustainability. Each item can belong to one or multiple dimensions because they can be interrelated. Before this can be done, the scope of the material-related items needs to be defined.

This study considered only construction materials. For example, most items belong to the categories of materials and waste. In addition, toxic materials and acoustic-related materials are included in the categories of health, pollution and IEQ. Building envelope materials, which are insulation, glazing, etc., are included in the energy category. Interestingly, the innovation (BRREAM, LEED, and G-SEED) or regional priority (LEED) categories can be related or not depending on the projects; however, they are important items to consider because they expand the possibilities.

On the other hand, this study excluded the several items, which are not considered as construction materials. For example, "products", such as lighting and water fixtures are not included. In addition, "refrigerant" and "fire retardants" which are chlorofluorocarbon (CFC)-based substances and "cleaning products" are not considered. Items about how to store and collect recyclables during the operation phase are also excluded.

3.2.1. BREEAM, NC-INT (2016)

BREEAM consists of nine categories, including the "*Material*" category [2,34]. All material-related items are shown selectively in Table 2 and Figure 3 (19/52 items, 6/9 categories). BREEAM uses an explicit weighting system, which has a different combination according to the project types. Therefore, it is a relative value, which makes the value of each issue impossible to calculate.

Under the "*Management*" category, three items deal with the material issue. "*Project Brief and Design*" focuses on the integrated design process (IDP). In terms of the material, various aspects (technical, legal, environmental, etc.) are consulted and planned from the early stages of a project, which relates to all three values of sustainability. "*Life-cycle Costing and Service Life Planning*" includes the development of the component level life-cycle cost (LCC) options, such as the envelope and finishes (economic). "*Responsible Construction Practices*" includes legally harvested and traded timber as a prerequisite. In addition, it has credits to monitor the transport of materials and waste. This relates to the responsible material industry (social), which aims to protect nature (environmental).

Table 2. List of the material-related criteria in BREEAM.

Category	I	C	W (%)	Related to Material: I	Related to Material: C	Related to Material: Minor Items	Envir.	Econo.	Soci.
Management	5	21	12	3	4	Project Brief and Design	●	●	●
					4	Life-cycle Costing and Service Life Planning		●	
					6	Responsible Construction Practices	●		●
Health and Wellbeing	9	25	14	4	6	Visual Comfort		●	●
					5	Indoor Air Quality		●	●
					3	Thermal Comfort		●	●
					4	Acoustic Performance		●	●
Energy	9	21	19	2	15	Reduction of Energy Use and Carbon Emissions	●	●	
					3	Low Carbon Design	●	●	
Transportation	6	8	8	0	0	-	-	-	-
Water	4	10	6	0	0	-	-	-	-
Material	4	12	12.5	4	6	Life-cycle Impacts	●		
					4	Responsible Sourcing of Construction Products	●		●
					1	Designing for Durability and Resilience	●	●	
					1	Material Efficiency	●	●	
Waste	6	9	7.5	5	4	Construction Waste Management	●	●	
					1	Recycled Aggregates	●	●	
					1	Speculative Finishes	●	●	
					1	Adaptation to Climate Change	●	●	
					1	Functional Adaptability	●	●	
Land Use and Ecology	4	10	10	0	0	-	-	-	-
Pollution	5	11	6.5	1	5	Surface Water Run-off	●		
Total	52	-	100	19	-	-			
(+Innovation)	1	10	(+10)	(1)	(10)	(Innovation)	-	-	-

C: Credit; I: No. of Items; W: Weight (%); +: additional; ( ): can be related or not; ●: Matching.

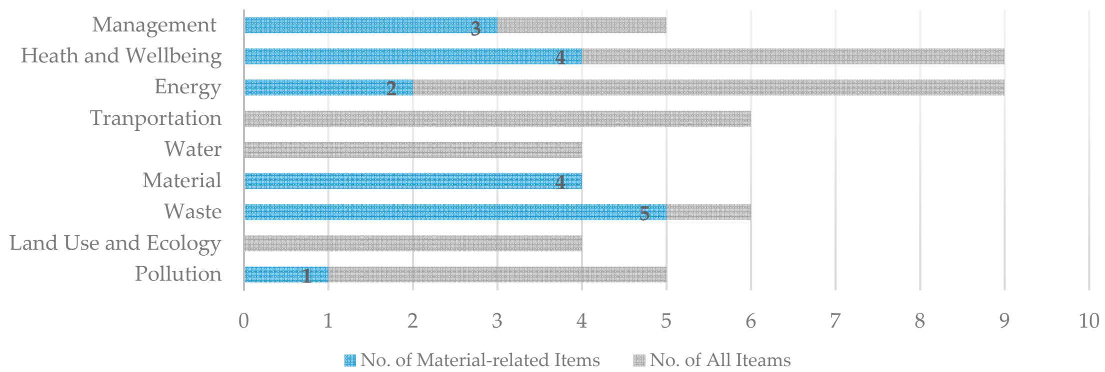

Figure 3. Ratio of materials-related items in BREEAM.

The "*Health and Wellbeing*" category is about Indoor Environmental Quality (IEQ) and four items related to materials. "*Visual comfort*" relates to the surface reflectance when calculating the daylight factors and illuminances. "*Indoor Air Quality*" prohibits asbestos as a prerequisite, and minimizes the formaldehyde and total volatile organic compounds (TVOC) emitted from the interior materials (paints and coatings, insulation, adhesives and sealants, etc.). "*Thermal Comfort*" refers to the insulation material and the reflection of the interior finish. "*Acoustic Performance*" is related to sound insulation materials. Therefore, all four items are related to the occupants' health and comfort (social) and productivity (economic).

In the "*Energy*" category, two items consider the materials. "*Reduction of Energy Use and Carbon Emissions*" aims to improve the energy performance. "*Low Carbon Design*" encourages the adoption of a passive design. Both are related to building envelope materials, including insulation, thermal mass, and renewable energy-related materials. They aim to reduce carbon use (environmental) and eventually reduce the energy cost (economic).

All four items of the "*Material*" category are included. First, "*Life-cycle Impacts*" encourages the use of robust and appropriate LCA tools and consequently the specifications of materials with low environmental impact over the full building life-cycle (environmental) using the environmental product declarations (EPD) [38]. Second, "*Responsible Sourcing of Construction Products*" evaluates the specifications and procurement of responsibly sourced materials (social) for protecting nature (environmental). Its prerequisite is for timber, which should be harvested and traded legally. Third, "*Designing for Durability and Resilience*" aims to protect the building elements (walls, glazing, etc.) by environmental factors (biological agents, pollutants, etc.) and material degradation effects (corrosion, fading, etc.). This item pursues a longer material life (economic), which helps reduce material use (environmental). Fourth, "*Material Efficiency*" focuses on the use of fewer materials, reuse of existing materials, and procurement of materials. In addition, it adopts alternative means of design or construction to lower the material use and waste (environmental), which can eventually effect the construction cost (economic).

In the "*Waste*" category, five items are included. "*Construction Waste Management*" aims to promote resource efficiency in two parts: construction waste reduction and diversion of resources from landfill. "*Recycled Aggregates*" aims to use recycled and secondary aggregates. "*Speculative Finishes*" aims to finish only the selected area according to the occupant. These three items aim to minimize the material use and waste (environmental), which can eventually affect the construction cost (economic). "*Adaptation to Climate Change*" and "*Functional Adaptability*" aim to expand the building lifespan (economic), which help reduce material use (environmental). "*Adaptation to Climate Change*" focuses on the structural and fabric resilience to withstand hazards or the increased pressures of weather. This is related to the durability and weather proofing of materials. "*Functional Adaptability*" includes the easily replicable fabric and structure, and interior finishes.

In the "*Pollution*" category, "*Surface Water Run-off*" includes permeable paving materials to protect nature from pollution (environmental). The last category, "*Innovation*", can be included or not depending on the project.

3.2.2. LEED, BD+C: NC (v4.0, 2014)

LEED is composed of six basic categories, including "*Materials and Resources*" [35,39]. Table 3 and Figure 4 present the material-related items (17/52 items, 4/6 categories). LEED is based on credits and points, which is different from BREEAM.

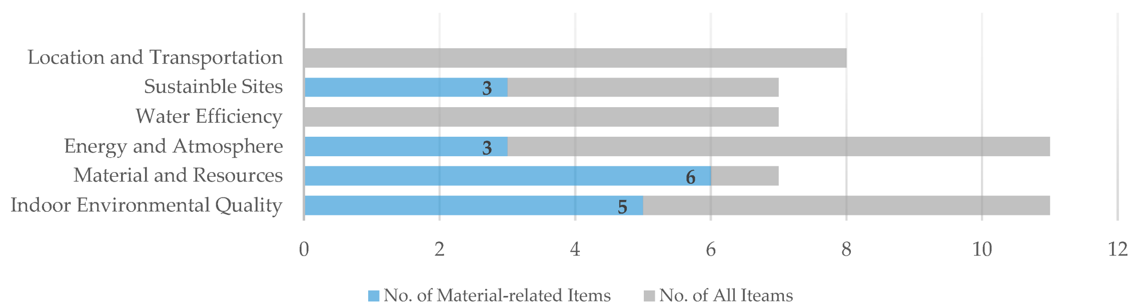

Figure 4. Ratio of materials-related items in LEED.

Table 3. List of the material-related criteria in LEED.

Category	I	C	Related to Material				Envir.	Econo.	Soci.
			I	C	Minor Items				
-	1	1	1	1	Integrative Process		●	●	●
Location and Transportation	8	16	0	0	-		-	-	-
Sustainable Sites	7	10	3	1	Site Assessment		●	●	
				3	Rainwater Management		●		
				2	Heat Island Reduction		●		
Water Efficiency	7	11	0	0	-		-	-	-
Energy and Atmosphere	11	33	3	R	Minimum Energy Performance		●	●	
				18	Optimize Energy Performance		●	●	
				3	Renewable Energy Production		●	●	
Materials and Resources	7	13	6	R	Construction and Demolition Waste Management Planning		●	●	
				5	Building Life-Cycle Impact Reduction		●		
				2	Building Product Disclosure and Optimization	Environmental Product Declarations	●	●	●
				2		Sourcing of Raw Materials	●	●	●
				2		Material Ingredient	●	●	●
				2	Construction and Demolition Waste Management		●	●	
Indoor Environmental Quality	11	16	5	2	Enhanced Indoor Air Quality Strategies			●	●
				3	Low-Emitting Materials			●	●
				1	Thermal Comfort			●	●
				2	Interior Lighting			●	●
				1	Acoustic Performance			●	●
Total	52	100	17	29	-				
(+Innovation)	2	6	(1)	(5)	(Innovation)		-	-	-
(+Regional Priority)	4	4	(1)	(4)	(Regional Priority: Specific Credit)		-	-	-

C: Credit; I: No. of Items; P: Prerequisite; R: Required; +: additional; ( ): can be related or not; ●: Matching.

The "*Integrated Process*" promotes the IDP; it covers the basic envelope attributes (insulation values, and glazing characteristics) and lighting levels (interior surface reflectance values). In addition, it includes the significant downsizing of building systems, such as the exterior materials and interior finishes. Currently, it focuses mainly on environmental issues but it can be expanded to multi-dimensions (environmental, economic, and social).

In the category of "*Sustainable Site*", three items are related. "*Site Assessment*" assesses the site conditions before the design. This includes construction materials with existing recycle or reuse potential (environmental), which is related to the construction cost (economic). "*Rainwater Management*" can affect permeable paving materials to avoid runoff pollution (environmental), even though its requirements do not specify it. "*Heat Island Reduction*" relates to climate change (environmental), which contains land/building surface materials, such as the solar reflectance (SR) value and open-grid systems.

In the category of "*Energy and Atmosphere*", three items are related. "*Minimum-*" or "*Optimize Energy Performance*" and "*Renewable Energy Production*" can affect the building envelope materials. All three items focus on low carbon (environmental) and the effects on energy cost (economic).

In the category of "*Materials and Resources*", six items except for "*Storage and Collection of Recyclables*" are included. "*Construction and Demolition Waste Management (Planning)*" aims to reduce the waste disposed in landfill and incineration facilities by recovering, reusing, and recycling (environmental). This can also affect the material cost (economic). "*Building Life-cycle Impact Reduction*" includes a range of optional strategies to encourage adaptive reuse and optimize the environmental performance of materials by LCA (environmental). "*Building Product Disclosure and Optimization*" is composed of three items regarding transparent information (social) to encourage the use of materials for which life-cycle information is available (environmental, economic, and social). In particular, products sourced within 160 km of the site are considered for this credit achievement calculation. The first item, "*Environmental Product Declarations*", encourages the use of certified materials by EPD or third parties. The second item, "*Sourcing of Raw Materials*", requests information on the raw material source that meets at least one of the responsible extraction criteria. For example, manufacturers participate in the extended producer responsibility program. Bio-based materials must meet the Sustainable Agriculture Network's Sustainable Agriculture Standard. Wood products must be certified by the Forest Stewardship Council (FSC) or USGBC. In addition, it encourages the use of materials that meet reuse/recycled content criteria. The last item, "*Material Ingredient*", has three optional requirements. Option 1 is the material ingredient reporting to demonstrate the chemical inventory (Health Product Declaration, etc.). Option 2 is the Material Ingredient Optimization using the paths (Cradle-to-Cradle Certified, etc.). Option 3 is the Product Manufacturer Supply Chain Optimization, which aims to minimize the use and generation of harmful substances.

In the category, "*Indoor Environmental Quality*", five items are related to materials, which consider the occupants" health and comfort (social), and productivity (economic). "*Enhanced Indoor Air Quality Strategies*" includes the materials of entryway systems for exterior contamination prevention. "*Low-Emitting Materials*" aims to reduce the VOC in the interior materials. "*Thermal Comfort*" deals with the building envelope and thermal mass, and "*Interior Lighting*" impacts the interior surface reflectance. "*Acoustic Performance*" needs to comply with the sound transmission ratings and reverberation time requirements, which are relevant to materials with acoustic finishes.

In addition, the last two categories of "*Innovation*" and "*Regional Priority*" may or may not be included depending on the project.

3.2.3. CASBEE, BD/NC (2014)

CASBEE assesses the environmental quality (Q) and the environmental load reduction (LR) of a building separately to ultimately evaluate the Built Environment Efficiency (BEE) [36,40]. CASBEE has the scoring criteria ranging from level 1 to level 5. In addition, each item has its weighting coefficients for scoring according to the building types to obtain the whole-building result. Thus, the value of each issue category cannot be calculated because it is dependent on the final score. Table 4 and Figure 5 present the items related to materials (28/89 items, 6/6 categories), which are the most diverse and detailed.

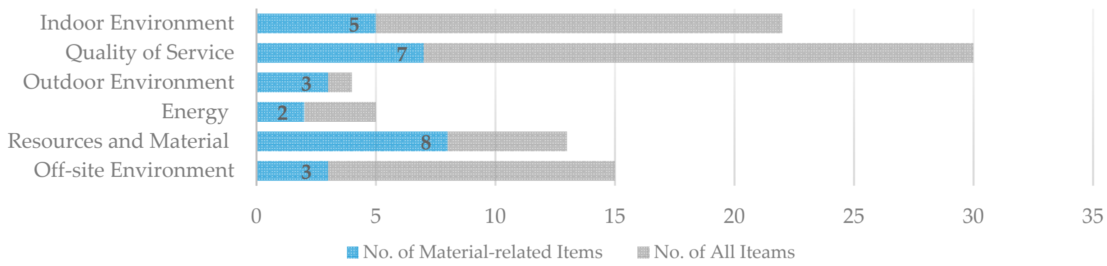

Figure 5. Ratio of materials-related items in CASBEE.

Table 4. List of the material-related criteria in CASBEE.

	Category		I	W (%)	Related to Material				Envir.	Econo.	Soci.
					I	Minor Items					
Environmental Quality of Building	Q1	Indoor Environment	22	0.4	5	Sound Environment	Sound Insulation	Sound Insulation of Openings		●	●
								Sound Insulation of Partition Walls		●	●
							Sound Absorption			●	●
						Thermal Comfort	Room Temperature Control	Perimeter Performance		●	●
						Air Quality	Source Control	Chemical Pollutants		●	●
	Q2	Quality of Service	30	0.3	7	Service Ability	Amenity	Décor Planning			●
							Maintenance	Design that Considers Maintenance	●	●	●
						Durability and Reliability	Service life of component	Service Life of Structural Materials	●	●	
								Necessary Refurbishment Interval for Exterior Finishes	●	●	
								Necessary Renewal Interval for Main Interior Finishes	●	●	
								Necessary Replacement Interval for Air Conditioning and Ventilation Ducts	●	●	
								Necessary Renewal Interval for HVAC and Water Supply and Drainage Pipes	●	●	
	Q3	Outdoor Environment (On-site)	4	0.3	3	Townscape and Landscape					●
						Local Characteristics and Outdoor Amenity	Attention to Local Character and Improvement of Comfort				●
							Improvement of the Thermal Environment on Site				●
Environmental Load Reduction of Building	LR1	Energy	5	0.4	2	Control of Heat Load on the Outer Surface of Buildings			●	●	
						Efficiency in Building Service System			●	●	
	LR2	Resources and Materials	13	0.3	8	Reducing Use of Non-renewable Resources	Reducing Use of Materials		●	●	
							Continuing Use of Existing Structural Frames, etc.		●	●	
							Use of Recycled Materials as Structural Materials		●	●	
							Use of Recycled Materials as Non-structural Materials		●	●	
							Timber from Sustainable Forestry		●		●
							Efforts to Enhance the Reusability of Components and Materials		●	●	
						Avoiding the Use of Materials with Pollutant Content	Use of Materials without Harmful Substances		●		
							Elimination of CFCs and Halons	Foaming Agents	●		
	LR3	Off-site Environment	15	0.3	3	Consideration of Global Warming			●		
						Consideration of Local Environment	Heat Island Effect		●		
						Consideration of Surrounding Environment	Light Pollution	Measures for Reflected Solar Glare from Building Walls	●		
Total			89	-	28	-					

I: No. of Items; W: Weight; ●: Matching.

All six items under Q1, the "*Indoor Environment*" category relate to the occupants" health/comfort/safety (social), and productivity (economic). First, in "*Sound Environment*", "*Sound Insulation of Openings*" and "*Sound Insulation of Partition Walls*" evaluate sash windows and other fixtures as well as the partition walls between rooms. "*Sound Absorption*" relates to the sound absorbing materials of the ceiling, floor, and walls. In "*Thermal Comfort*", "*Perimeter Performance*" evaluates the ability to block the thermal infiltration from the surroundings through window systems, exterior walls, and roof and floor. The level of insolation blocking and insulation performance, such as the overall heat transfer coefficient (U) and shading coefficient (SC) are required. For "*Air Quality*", "*Chemical Pollutants*" evaluates the construction materials with low emission levels of VOCs other than formaldehyde.

Q2, the "*Quality of Service*" category, includes seven items. For "*Service Ability*", "*Décor Planning*" evaluates how pleasant and comfortable the building is. For example, natural and ecological materials can be used with an ecological theme. This is associated with the occupants' aesthetic satisfaction (social). Next, "*Design that Considers Maintenance*" refers to the occupants' wellbeing by easy maintenance (social), and evaluates the efforts in interior finishes, façades, etc. Examples include highly dirt- or water-resistant materials, and water-washable materials. In addition, it can relate the longevity of the material (environmental, economic). For "*Durability and Reliability*", five parts of the service life are evaluated: structural, exterior wall finishing, main interior finishing materials, ducts, and pipes. For example, the lifespan of exterior wall finishes is divided into five levels ranging from level 1 (less than 10 years) to level 5 (30 years or more). This is related to the durability (economic), which results in reduced material use (environmental).

Q3, the "*Outdoor Environment (On-Site)*" category, has three items. "*Townscape and Landscape*" evaluates the building features in harmony with the surrounding landscape in the color and form, and locally significant materials used in the building exterior. Similarly, the local materials used in the building structure, interior finishes or exterior space are assessed in "*Attention to Local Character and Improvement of Comfort*". Both are about locality and harmony (social). In "*Improvement of the Thermal Environment on Site*", the exterior finishes that help alleviate the thermal impact on pedestrian areas are assessed, which is for the pedestrian's wellbeing (social).

LR1, the "*Energy*" category focuses on low carbon (environmental) and the impacts on the energy cost (economic). "*Control of Heat Load on the Outer Surface of Buildings*" can relate to insulating materials. "*Efficiency in Building Service System*" evaluates the primary energy consumption of the entire service system. Thus, renewable energy related materials may be included.

LR2, the "*Resources and Materials*" category contains eight items, while "*Water Resources*", "*Fire Retardant*", and "*Refrigerants*" are excluded. "*Reducing Use of Non-renewable Resources*" has six sub-items. "*Reducing Use of Materials*" encourages the use of high-strength materials. "*Continuing Use of Existing Structural Frames, etc.*" assesses the reuse of existing building frames. "*Use of Recycled Materials as Structural Materials*" and "*Use of Recycled Materials as Non-structure materials*" evaluate whether recycled materials are used. Examples of structural materials include blast furnace slag aggregate, Eco cement, etc. Examples of non-structural materials are diverse, including tiles, cladding, etc. "*Timber from Sustainable Forestry*" aims to reduce the use of timbers from tropical rainforests or illegally logged forests. "*Efforts to Enhance the Reusability of Components and Materials*" measures the easier recycling for the demolition and disposal stage. Structural frames with painted finishes are an example of easy separation. In this sense, plastered walls, mortar, and tile are difficult to separate and are uncountable. Therefore, the four items except for "*Timber from Sustainable Forestry*" focus on the resource efficiency (environmental), which are also related to cost (economic). "*Timber from Sustainable Forestry*" emphasizes the responsibility of the material industry (social) as well as a reduced impact on nature (environmental).

Two items under the "*Avoiding the Use of Materials with Pollutant Content*" category are related to a low impact on air (environmental). "*Use of Materials without Harmful Substances*" evaluates the reduction of chemicals, such as VOCs, metallic compounds, etc. They are related to adhesives, sealants, paints, etc. "*Foaming Agents*" evaluate the ozone-depleting potential (ODP) and global warming potential (GWP) impacts. This is related to the expanded plastic materials among insulation materials, such as polyurethane, polystyrene, etc.

LR3, the "*Off-site Environment*" category includes three items. First, "*Consideration of Global Warming*" uses life-cycle CO_2 ($LCCO_2$) emissions as the index for low carbon (environmental). Second, "*Heat Island Effect*" evaluates the ground covering and building cladding materials to reduce the thermal impact (environmental). Third, "*Measures for Reflected Solar Glare from Building Walls*" evaluates the light pollution caused by the reflected glare for habitat (environmental); it includes the application of anti-reflection films, surface treatments, etc.

3.2.4. LBC (v3.1, 2016)

LBC defines the most rigorous standard and all imperatives are mandatory [11,41]; it is based on the actual rather than modeled or anticipated performance for at least one year. This suggests a larger and more holistic vision than the other tools. It is comprised of seven performance categories called "*petals*", which are subdivided into twenty imperatives. Table 5 and Figure 6 present the material-related items (8/20 imperatives, 3/7 petals).

Table 5. List of the material-related criteria in LBC.

Category	I	Related to Material		Envir.	Econo.	Soci.
		I	Minor Items			
Place	4	0	-	-	-	-
Water	1	0	-	-	-	-
Energy	1	1	Net Positive Energy	●	●	
Health and Happiness	3	2	Healthy Interior Environment Biophilic Environment		●	● ●
Materials	5	5	Red List Embodied Carbon Footprint Responsible Industry Living Economy Sourcing Net Positive Waste	● ● ● ● ●	 ● ●	 ● ●
Equity	4	0	-	-	-	-
Beauty	2	0	-	-	-	-
Total	20	8	-			

I: No. of Items; ●: Matching.

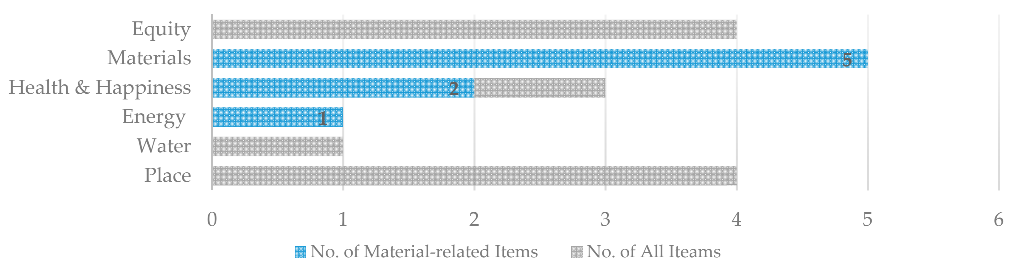

Figure 6. Ratio of materials-related items in LBC.

In the "*Energy* "petal", the "*Net Positive Energy*" requires 105% of the project's energy be supplied by on-site renewable energy (environmental), which effects the energy cost (economic). This may influence the material selection, such as the highly insulated envelope, shading device, etc.

In "*Health and Happiness*", two items are related to the materials. First, "*Healthy Interior Environment*" is about the occupants' health or comfort (social), and productivity (economic). This includes the issues of all interior materials that have the potential to emit VOC. This specifies the materials of an entry approach to reduce the number of particulates from outdoors. "*Biophilic Environment*" focuses on the occupants' psychological value (social). It nurtures the innate human/nature connection to engage through historical, cultural, ecological, and climatic studies, which examine the site and context of the project. The material selections can be considered to achieve this. For example, local materials can be chosen to connect the place, climate, and culture through place-based relationships. Natural materials can be preferred to evolve human–nature relationships.

In "*Material*", all five imperatives cover the material issues extensively. "*Red List*" lists 22 kinds of toxic materials, including asbestos, PVC, VOC, etc. (environmental). "*Embodied Carbon Footprint*" considers reducing carbon (environmental) by accounting for the total embodied carbon (tCO_2e). "*Responsible Industry*" encourages a responsible industry and transparent information in materials (social) to protect nature (environmental). The imperative advocates for the development and the adoption of third-party certified standards for sustainable resource extraction and fair labor practices, such as the FSC for timber and the Natural Stone Council (NSC) for stone. All projects must use a certain amount of Declare product, which is the product ingredients like a nutrition-label to transform the building materials market through transparency and open communication [42]. "*Living Economy Sourcing*" is about using the regional product, which contributes to the expansion of a regional economy (economic) and to locality and harmony (social), as well as to reducing the environmental impacts by transportation (environment). Interestingly, it restricts the distance from the construction site, not only for products like LEED, but also for practices and services, such as consultants and subcontractors. Finally, "*Net Positive Waste*" aims to reduce or eliminate waste during the entire building life cycle to reduce the impact on nature (environment) and the construction costs (economic). This considers the appropriate durability in the design phase of product optimization and collection, of wasted materials in the construction phase, and of a plan for the adaptable reuse and deconstruction in the end of life phase.

3.2.5. G-SEED, NC (Non-Residential) (2016)

G-SEED is comprised of 44 items under seven categories. Unlike BREEAM and LEED, the new "*ID*" category has 10 specific items to obtain additional credits [43]. Table 6 and Figure 7 show the material-related items ($15_{(+4)}$ /$44_{(+10)}$ items, 5/7 categories). Like BREEAM, its scoring is a weighting system according to the project types.

In the "*Energy and Pollution*" category, "*Energy Performance*" and "*Renewable Energy*" are about low carbon (environmental) and its effects on the energy cost (economic). They are related to the building envelope materials.

"*Materials and Resources*", contains five items except for "*Storage and Collection of Recyclables*". The first four items are related to the G-SEED Material Certification [44]. They share transparent information (social) about the life-cycle environmental impact of a product (environmental). They are evaluated in four ways: EPD, low carbon, recycling, and less harmful materials. First, the "*Use of EPD Certified Products*" recommends the use of EPD-certified products. Second, the "*Use of Low Carbon Materials*" encourages the use of carbon footprint product (CFP)-labeled merchandize [45]. Third, the "*Use of Recycling Materials*" promotes the consumption of recycling materials referenced by the Good Recycled (GR) mark or Eco-label [46,47]. This item combines low carbon by using less material, which consequently affects the costs (economic). Fourth, the "*Use of Less Harmful Materials*" is referenced by Eco-label [46].These four items count the number of materials. On the other hand, the fifth item, "*Use of Green Materials*", is related to all four items, introduced previously, but differently; it calculates the construction fee.

In the "*Water*" category, "*Rainwater Management*" includes the permeable surface material for low impact development (LID) (environmental).

In the "*Ecology*" category, "*Ratio of Ecological Areas*" promotes the ecological area by counting the different earth covering conditions, such as green roof, permeable paving, etc. (environmental). This is calculated from the different coefficients depending on the paving materials.

The "*Indoor Environment Quality*" category deals with the occupants' health or comfort (social), and productivity (economic). "*Using Low VOC Emitting Products*" assesses the use of less formaldehyde and VOC emitting interior materials. "*Acoustic Performance between Rooms*" and "*Acoustic Performance from Traffic Noise*" refers to the wall/ceiling and sound insulation materials.

"*ID*", Innovative Design, was newly added to the latest version, and includes four material-related items out of ten. First, "*Innovative Green Building Plan and Design*" encourages the design of innovative and specialized designs in four categories, including materials. In addition, it requests the IDP from the early stages of the project. "*Zero Energy Building*" is related to building envelope materials. "*LCA*" requires calculating the LCA of building materials. "*Reuse of Main Structure in Existing Building*" encourages the reuse of existing structures of 30%–60%.

Table 6. List of the material-related criteria in G-SEED.

Category	I	C	W (%)	Related to Material			Envir.	Econo.	Soci.
				I	C	Minor Items			
Land Use and Transport	7	14	10	0	0	-	-	-	-
Energy and Pollution	8	29	30	2	12 3	Energy Performance Renewable Energy	● ●	● ●	
Materials and Resources	6	15	15	5	4 2 2 2 4	Use of EPD Certified Products Use of Low Carbon Materials Use of Recycling Materials Use of Less Harmful Materials Use of Green Materials	● ● ● ● ●	 ● 	● ● ● ● ●
Water	4	14	10	1	5	Rainwater Management	●		
Management	4	8	7	0	0	-	-	-	-
Ecology	5	17	10	1	6	Ratio of Ecological Areas	●		
Indoor Environment Quality	10	20	18	3	3 2 2	Using Low VOC Emitting Products Acoustic Performance between Rooms Acoustic Performance from Traffic Noise		● ● ●	● ● ●
Total	44	-	100	15	-	-			
+ Innovative Design	10	19	Max + 10	4	3 3 2 5	Innovative Green Building Plan and Design Energy and Pollution—Zero Energy Building Material—LCA Material—Reuse of Main Structure in Existing Building	● ● ● ●	● ● ●	●

C: Credit; I: No. of Items; W: Weight (%); +: Additional; ●: Matching.

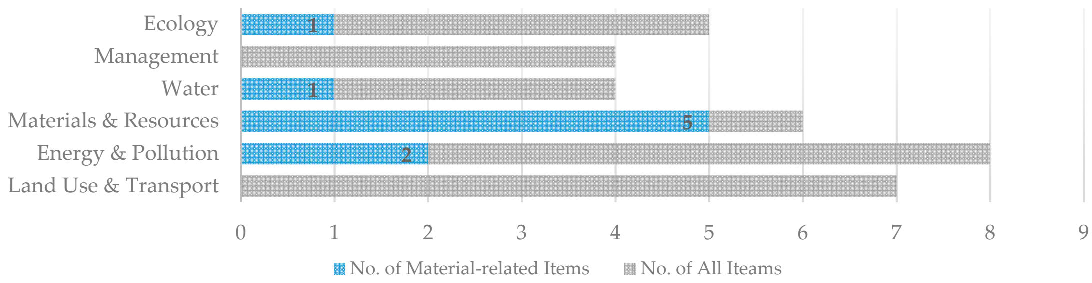

Figure 7. Ratio of materials-related items in G-SEED.

3.3. Summary of Material-Related Items

Commonly, material-related items are not only covered in the "*Material*" category, but are also spread over multiple categories, such as "*Energy*", "*Indoor Air Quality*", etc. In the case of CASBEE, the material-related items exist in all categories. On the other hand, some items under "*Material*" category are excluded, because they are not construction materials. For example, items related to water resources (CASBEE) and the storage of recyclables (LEED and G-SEED) are not counted.

As listed in Tables 2–6 and Figures 3–7, CASBEE includes more classifications of minor items than the other tools. Twenty-eight items then cover most diverse issues including pedestrians' comfort, easy maintenance, etc. In contrast, as shown in Figure 8, LBC has the highest quantity ratio of the material assessment items, which is approximately 40%, followed by BREEAM (37%), G-SEED (34%), LEED (33%), and CASBEE (31%). In contrast to Figure 2, its range (31%–40%) is much higher than the number of items under the "*Material*" categories (8%–25%). This shows that the material is related to multiple major sustainability issues.

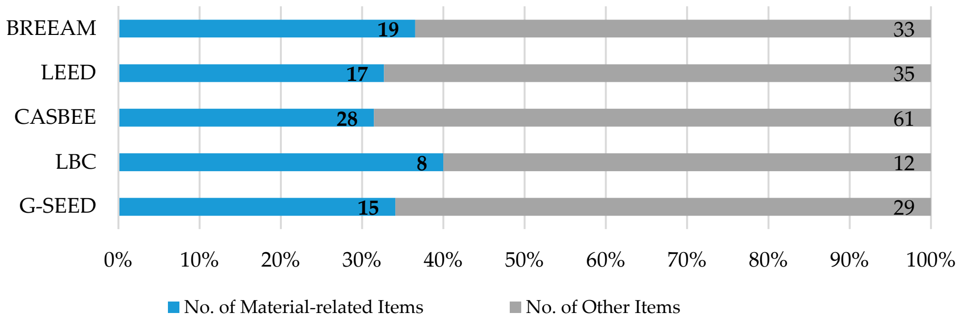

Figure 8. Quantitative comparison of the number of material-related items.

3.4. Reorganizing by Keywords

To examine the similarities and differences in the material criteria of sustainability assessment, all items are sorted and grouped according to the three aspects of sustainability and keywords, as listed in Table 7.

Table 7. List of the material-related items by three sustainability dimensions and keywords.

Envir.	Econo.	Soci.	BREEAM	LEED	CASBEE	LBC	G-SEED	Keywords
●	●	●	Project Brief and Design	Integrative Process	-	-	+ (Innovative Green Building Plan and Design)	**IDP**
●			-	◇ Material Ingredient	Use of Materials without Harmful Substances	Red List	Use of Less Harmful Materials	**Toxic**
					Foaming Agents		◙ Use of Green Materials	
			Surface Water Run-off	Rainwater Management	-	-	Rainwater Management	**Run-off**
			-	-	Measures for Reflected Solar Glare from Building Walls	-	-	**Light Pollution**
			-	Heat Island Reduction	Heat Island Effect	-	-	**Heat Island**
			-	-	-	-	Ratio of Ecological Areas	**Ecological Areas**
●	●		Reduction of Energy Use and Carbon Emissions	Minimum Energy Performance	Control of Heat Load on the Outer Surface of Buildings	Net Positive Energy	Energy Performance	**Energy Performance**
				Optimize Energy Performance			Renewable Energy	
			Low Carbon Design	Renewable Energy Production	Efficiency in Building Service System		+ (Zero Energy Building)	
●	●			△ Building Life-cycle Impact Reduction	Continuing Use of Existing Structural Frames, etc.	◎ Net Positive Waste	+ (Reuse of Main Structure in Existing Building)	**Reuse**
				◆ Sourcing of Raw Materials	Efforts to Enhance the Reusability of Components and Materials			
			Recycled Aggregates	◆	Use of Recycled Materials as Structural Materials	-	Use of Recycling Materials	**Recycle**
					~as Non-structural Materials		◙	
			Construction Waste Management	Construction and Demolition Waste Management	-	◎	-	**Reduce Construction Waste**
				~Planning				
			Material Efficiency	-	Reducing Use of Materials	-	-	**Reduce Using Material**
			Speculative Finishes					
			-	Site Assessment	-	-	-	**Assessment**
●			-	-	Consideration of Global Warming	Embodied Carbon Footprint	Use of Low Carbon Materials	**Embodied CO_2/$LCCO_2$**
							◙	
●			Life-cycle Impacts	△			+ (LCA)	**LCA**
	●		Life-cycle Costing and Service Life Planning	-	-	-	-	**LCC**

Table 7. *Cont.*

Envir.	Econo.	Soci.	BREEAM	LEED	CASBEE	LBC	G-SEED	Keywords
●	●		Designing for Durability and Resilience	-	Service Life of Structural Materials	-	-	**Durability and Adaptation**
			Adaptation to Climate Change		Necessary Refurbishment Interval for Exterior Finishes			
					Necessary Renewal Interval for Main Interior Finishes			
					Necessary Replacement Interval for Air Conditioning and Ventilation Ducts			
			Functional Adaptability		Necessary Renewal Interval for HVAC and Water Supply and Drainage Pipes			
●	●	●	-	▲ Environmental Product Declarations	-	◈ Living Economy Sourcing	-	**Local Economy (Regional Materials)**
				◆				
				◇				
●		●	Responsible Construction Practices	◆	Timber from Sustainable Forestry	★ Responsible Industry	-	**Responsibility**
			Responsible Sourcing of Construction Products					
●		●	-	▲	-	★	Use of EPD Certified Products	**Transparent Information**
				◆				
				◇			◙	
	●	●	Indoor Air Quality	Low-Emitting Materials	Chemical Pollutants	Healthy Interior Environment	Using Low VOC Emitting Products	**Indoor Air Quality**
				Enhanced Indoor Air Quality Strategies				
			Acoustic Performance	Acoustic Performance	Sound Insulation of Openings	-	Acoustic Performance between Rooms	**Indoor Sound Comfort**
					~of Partition Walls			
					Sound Absorption		~from Traffic Noise	
			Thermal Comfort	Thermal Comfort	Perimeter Performance	-	-	**Indoor Thermal Comfort**
			Visual comfort	Interior Lighting	-	-	-	**Indoor Visual Comfort**
		●			Improvement of the Thermal Environment on Site			**Outdoor Comfort**
		●	-	-	Décor Planning	Biophilic Environment	-	**Aesthetic/Psychological**
●	●	●	-	-	Design that Considers Maintenance	-	-	**Easy Maintenance**
		●	-	▲	Townscape and Landscape	◈	-	**Locality and Harmony**
				◆	Attention to Local Character and Improvement of Comfort			
				◇				

◆, ◇, ◙, ▲, △, ◎, ★, etc.: match repeatedly, +( ): additional items.

4. Discussion and Findings

4.1. Selection of Indicators and Keywords

The keywords listed in Table 7 are grouped (aggregated, and categorized) in three dimensions. In a further step, various keywords form subgroups in a hierarchical system [14]. The indicator is then expressed by a value derived from a combination of keywords, which is effective for comparing the five systems.

Originally, most assessment tools were designed to measure the building environmental performance. Through revision over a few decades, economic and social values have been added and strengthened [48]. As shown in Table 8, the latest tools include economic and social criteria as well as environmental. Figure 9 shows that the environmental aspects (51%) are still the most similar, followed by economic (13%) and social (39%).

First, IDP is an essential integrative concept, which can relate to any of the three aspects: environmental, economic, and social. In the case of material, through IDP, its various aspects can be consulted and designed when balancing and making trade-offs from the early stages of the design process [30]. They are comparatively newly added items in BREEAM, LEED, and G-SEED. Although LBC and CASBEE do not have IDP as the item, it is a backbone to achieving a high-level in each tool.

Table 8. List of the material-related criteria by the three sustainable dimensions.

Dimensions	Indicators	Keywords		BREEAM	LEED	CASBEE	LBC	G-SEED		Total	
-	IDP			X	X			X	3	3	3
Environmental	Ecology	Pollution	Toxic		X	XX	X	XX	6	13	51
			Run-off	X	X			X	3		
			Light			X			1		
		Heat Island			X	X			2		
		Ecological Area						X	1		
	Energy	Energy Performance		XX	XXX	XX	X	XXX	11	11	
	Resource	Reuse			XX	XX	X	X	6	27	
		Recycle		X	X	XX		XX	6		
		Reduce Construction Waste		X	XX		X		4		
		Reduce Using Material		XX		X			3		
		Assessment			X				1		
		Embodied CO_2, $LCCO_2$				X	X	XX	4		
		LCA		X	X			X	3		
Economic	LCC			X					1	1	13
	Durability and Adaptation			XXX		XXXXX			8	8	
	Local Economy	Regional Materials			XXX		X		4	4	
Social	Justice	Responsibility		XX	X	X	X		5	11	39
		Transparent Information			XXX		X	XX	6		
	Wellbeing	Indoor Comfort	Air	X	XX	X	X	X	6	22	
			Sound	X	X	XXX		XX	7		
			Thermal	X	X	X			3		
			Visual	X	X				2		
		Outdoor Comfort				X			1		
		Aesthetic/Psychological				X	X		2		
		Easy Maintenance				X			1		
	Diversity	Locality and Harmony			XXX	XX	X		6	6	
SUM										106	

X: Number of related items; Sum: Total number of items.

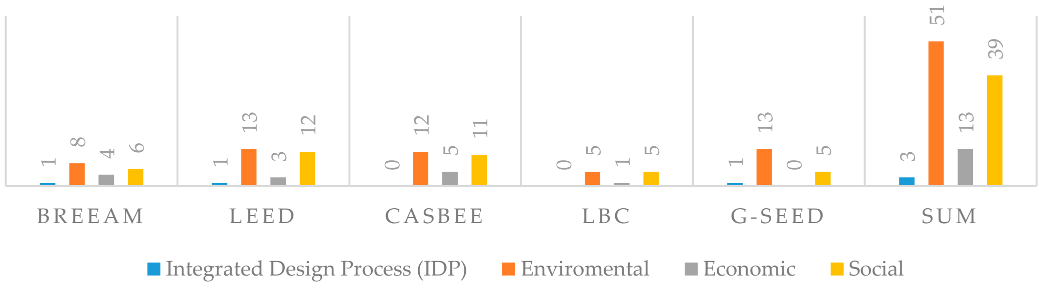

Figure 9. Quantitative comparison of total numbers of the material-related items by sustainability aspects.

4.1.1. Environmental Dimension

The environmental dimension aims to protect and enhance the environment, and can be summarized into three major topics: "*Ecology*", "*Energy*", and "*Resource*".

"*Ecology*" aims to reduce the impacts on nature and ecology; it reduces pollution from toxic materials, run-off on the surface, and light. In addition, it reduces the heat island effect and protects the ecological area. In particular, low emitting materials are the most common issues. Comparatively, the tools adopt "*Run-off*", "*Heat Island*" and "*Ecological Area*" selectively. On the other hand, in common, they are about paving or surface materials, which are considered in four tools except for LBC.

"*Energy*" demands materials that enhance the energy performance; all tools cover it intensively.

"*Resource*" aims to reduce the overall material demands. All tools promote the use of recycled and reused materials and reducing waste. "*Reduce Using Material*" of the BREEAM and CASBEE approach with a more direct manner to reduce material use. "*Assessment*" of LEED emphasizes its importance at the early design stages. Although only environmental assessment is mentioned, it can be expanded to economic and social areas.

Furthermore, sustainable design begins to shift towards the life-cycle evaluation of the main materials [49]. This is one of the most highlighted issues in the latest version of all tools. Each system adopts the conventional calculation method, such as LCA including low embodied CO_2 or $LCCO_2$. CASBEE and LBC adopted the $LCCO_2$ and the Embodied CO_2 in 2004 and 2006, respectively [50]. LEED mentioned the LCA in 2009 under the "*ID*" category as additional credits and adopted as the independent credit in v4.0 (2014) [35]. BREEAM included the LCA from 2011, while G-SEED included it as additional credits in 2016 under the "*ID*" category, which is comparatively late [23].

4.1.2. Economic Dimension

The economic dimension is for cost-efficiency with the achievement of environmental improvements; it has the lowest number of items among the three pillars. Thirteen items can be summarized into three major topics, "*Life-cycle Cost*", "*Durability and Adaptability*", and "*Local Economy*".

"*Life-cycle Cost*" encourages the use of materials by minimizing the cost throughout the life-cycle, while fulfilling the performance requirements [36]; only BREEAM has this item.

"*Durability and Adaptability*" uses materials with a long life and flexible character to easily accommodate change. BREEAM and CASBEE cover this issue intensively but the others do not.

"*Local Economy*" uses locally produced or manufactured materials that enhance the local economy and save transport distance (time and money). LEED encourages the use of regional materials but does not specify their economic value. On the other hand, LBC emphasizes its economic importance and extent from the materials themselves into practices and services under "*Living Economy Sourcing*".

Compared to other criteria, this is adopted limitedly by all five tools. Only one or two tools consider each indicator. In particular, G-SEED takes none.

4.1.3. Social Dimension

The social dimension is for social justice and cultural diversity with a focus on the human life quality. This can be summarized into three major topics, "*Justice*", "*Wellbeing*" and "*Diversity*".

"*Justice*" includes two issues, "*Responsibility*" and "*Transparent Information*". "*Responsibility*" aims to reduce the damaging social and environment impacts related to the material industries that rely on natural resource extraction and plant cultivation. All tools except for G-SEED adopt this. Second, "*Transparent Information*" emphasizes transparent communication and comparable information about the life-cycle environmental impact of materials through the use of third parties, such as EPD and Declare. Currently, it is impossible to gauge the true environmental impact and toxicity of a built environment due to a lack of product-level information, even though the assessment tools continue to highlight the need for transformative industrial practices. Although there are a huge number of "green" products for sale, there is a shortage of good publicly available data that corroborate the manufacturer's claims and provide consumers with the ability to make conscious, informed choices. Hence, transparency is vital. As a global community, open communication and honest information sharing is the only way we can transform into a truly sustainable society. On the other hand, many manufacturers are wary of sharing trade secrets that afford them a competitive advantage, and make proprietary claims about specific product contents [11]. LBC, LEED, and G-SEED cover this indicator.

"*Wellbeing*" enhances human health, safety and wellbeing using appropriate materials. All tools cover IEQ extensively. Interesting, CASBEE has a strong focus on this issue with sophisticated details, such as pedestrians' thermal comfort, easy maintenance, and aesthetic/psychological satisfaction. In particular, "*Improvement of the Thermal Environment on Site*" is unique in considering the external relationship beyond internal building.

"*Diversity*" encourages cultural diversity through the use of materials suitable for a regional context. This item helps reintegrate and minimize the negative impacts on their settings, and it identifies secure livelihoods, vibrant, and attractive communities [30]. CASBEE emphasizes this value. On the other hand, LEED encourages the use of regional materials, but does not comment on its cultural value.

4.2. Definition of Indicators

Through an analysis of five tools based on the triple bottom line of sustainability, multiple indicators are proposed to encompass the common values of sustainable materials (Table 9).

- The environmental indicators are Ecology, Energy, and Resource
- The economic indicators are Life-cycle Cost, Durability and Adaptability, and Local Economy
- The social indicators are Justice, Wellbeing, and Diversity

Table 9. Indicator definitions.

Dimension	Indicator	Definition
Environmental	Ecology	Use of materials with low impact on nature and ecology
	Energy	Use of materials to enhance energy performance
	Resource	Reduce overall material demands and use of materials with LCA
Economic	Life-cycle Cost	Use of materials with minimizing the cost throughout life-cycle
	Durability and Adaptability	Use of materials with a long life and flexible character to easily accommodate change
	Local Economy	Use of locally produced or manufactured materials to enhance local economy
Social	Justice	Use of materials from responsible industries and with transparent information about the life-cycle environmental impact
	Wellbeing	Use of materials to enhance human health, safety and wellbeing
	Diversity	Use of materials suitable to the regional context

5. Conclusions

This paper provides an overview of the material criteria in five tools for assessing building sustainability and summarized their features and weakness. In common, all tools have "*Material*" as a major category. Their weights are between 12.5% and 15%, and their percentages of items are between 8% and 25%. In reviewing their intents, they generally aspire to minimize the environmental impacts through the building life cycle, whereas the economic and social sustainability are not explicit except for LBC.

On the other hand, material-related items do not exist within the "*Material*" category, but are spread over multiple categories. The ratio of their number ranges from 31% to 40%, which is rather high. This shows that material is not an isolated criterion but is related to diverse issues, such as site, waste, energy, pollution, health, wellbeing, etc.; the material criteria of sustainability has complexity.

All listed material-related items were analyzed based on a broadly adopted framework: the triple bottom line of sustainability. Many items belong to multiple dimensions. For example, "*EPD*" is related to life-cycle impacts (environmental) as well as to transparent information (social). "*Regional Sourcing*" deals with the local economy (economy) as well as locality and harmony (social). This indicates how integrated different dimensions of sustainability have the possibility of synergistic benefits.

This paper has reviewed the current features in a material assessment. The material-related items under the categories of pollution, energy, resource, IEQ, and waste share similar perspectives. In addition, the important new trends show some commonality. They are life-cycle perspectives, such as LCA or LCC, as well as transparent information and responsibility. On the other hand, there are significant differences in their scope to cover the social and economic aspects beyond the environmental aspect. LBC is the most balanced tool with its simplicity, while G-SEED shows weakness in this sense. CASBEE has the most items with details and diversity, and covers three sustainability dimensions.

The assessment tools were developed, focusing mainly on the environment; the importance of economic and social values emerged later. For this reason, in the interpretation of sustainability, environmental concerns often attract more attention than social or economic factors [30]. Actually, in the analysis, the number of environmental items is much larger with more detail than the social and economic items. The social dimension is also large because IEQ is related to the life quality and all tools cover comfort extensively. On the other hand, with the exception of IEQ, the assessment of social dimension varied according to the tools in terms of their contents and intensity. The economic dimension contains the fewest items. Because it is not the weight but the number of items that matter; it does not represent the importance of each item necessarily. Rather, a single item can intend the intensity, such as BREEAM's LCC or LBC's "*Living Economy Sourcing*". Nevertheless, less attention has been paid to economic values compared to the environmental dimension. This has highlighted the limits of current assessment tools, which appear to focus mainly on the environment. For comprehensive sustainability assessment purposes, the triple bottom line of building materials should be improved and there is a need to ensure adequate attention to all three factors.

In this manner, this paper has proposed the indicators under three dimensions from an analysis of all material-related items. They are environmental (ecology, energy, and resource), economic (life cycle cost, durability and adaptability, and local economy), and social (justice, wellbeing, and diversity).

The findings of this study provide several insights for further studies. First, all tools highlight the need for third party certification to ensure independence, credibility, and consistency of the label. Nevertheless, the social and economic sustainability measurements are still difficult to obtain [6] because they are complex and relative [48]. By paying attention to social or economic values, a future study can investigate how to measure those. Second, tools are being updated constantly, which takes advantage of new research to reflect the changing priorities in regulations and in the market place, to build on the experience gained, and generally keep them up to date. While this paper examined the current items related to materials, a further study may look at those items chronologically. This type of study will highlight the emphasizing aspects by looking into the evolution of each tool.

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