

Article

Not peer-reviewed version

---

# A Multi-Criteria Approach to Sustainable Building Material Selection: A Case Study in a Japanese Context

---

[Atsushi Takano](#)<sup>\*</sup> and Masashi Aiki

Posted Date: 24 February 2025

doi: 10.20944/preprints202502.1934.v1

Keywords: Sustainable building design; Material selection; LCA; Costs; multi-criteria approach



Preprints.org is a free multidisciplinary platform providing preprint service that is dedicated to making early versions of research outputs permanently available and citable. Preprints posted at Preprints.org appear in Web of Science, Crossref, Google Scholar, Scilit, Europe PMC.

Copyright: This open access article is published under a Creative Commons CC BY 4.0 license, which permit the free download, distribution, and reuse, provided that the author and preprint are cited in any reuse.

Article

# A Multi-Criteria Approach to Sustainable Building Material Selection: A case study in a Japanese Context

Atsushi Takano <sup>1,\*</sup> and Masashi <sup>2</sup>

<sup>1</sup> Department of Architecture and Architectural Engineering, Graduate School of Science and Engineering, Kagoshima University, 8900065 Kagoshima, Japan

<sup>2</sup> Building Construction Management Division, Kajima Corporation, 1078348 Tokyo, Japan

\* Correspondence: takano@aae.kagoshima-u.ac.jp; Tel.: +81-(0)99-285-8313

**Abstract:** With the aim of reducing the environmental impact of buildings, the appropriate selection of building materials is significant, as a building is complex system composed of various materials. With this background, a multi-criteria decision-making approach has recently been paid attention. This study examined the impact of building material selection on both environmental and economic parameters of a building in a context of Japan. A comparative analysis of five structural frame options was conducted utilizing a reference building model to assess the implication of material choices. The objective was to illustrate the characteristics of various building materials from multiple perspectives in order to facilitate multi-criteria decision-making for professionals in the construction sector. The findings revealed that the value of alternative materials is contingent on the aspects. Furthermore, it was highlighted which building elements and components should be preceded to enhance the sustainability of a building from a material perspective. No single material is optimal in all respects; therefore, it is crucial to select appropriate materials based on their intended use and features on a case-by-case basis. In addition, to expand the range of material selection, it is essential to develop a market system that integrates economic consideration with other relevant aspects, allowing for a more balanced approach in the decision-making process.

**Keywords:** Sustainable building design; Material selection; LCA; Costs; multi-criteria

## 1. Introduction

The building sector plays a substantial role in contributing to global environmental challenges [1]. Therefore, minimizing the environmental impact of a building throughout their life cycle is a crucial objective in the pursuit of sustainable development. In this context, considerable research efforts have been dedicated over the past few decades to investigate the life cycle impacts associated with buildings. In the effort to reduce the environmental impact of buildings, most of the attention has thus far been focused on operational energy use. As a result of advancements in this area, such as enhancements in the thermal insulation performance of the building envelope [2, 3], the environmental impact during the operation phase has been effectively reduced and the significance of other life cycle stages (embodied impacts) has increased [4].

To mitigate the embodied impacts of buildings, the careful selection of building materials is essential since a building is complex system composed of various materials. However, a dilemma arises in a building Life Cycle Assessment (LCA). During the design phase, there is a discrepancy between the flexibility in selecting design parameters and the quality and quantity of information available for the LCA [5]. Although the life cycle impacts of a building can vary considerably based on decisions made in the early design phase [6, 7], designers are often forced to make significant decisions at this initial design stage with insufficient information.

In this context, numerous researchers have explored indices of building materials to assist designers in achieving optimal design solutions for a sustainable building. For instance, Kerr et al. [8] compared Environmental Products Declarations (EPDs) of structural stone, concrete products and steel products focusing on their Global Warming Potential (GWP). The findings indicated that utilizing structural stone can significantly reduce the embodied CO<sub>2</sub> emissions of a building, with being 45-75% lower than those of concrete products and over 99% lower than those of steel products. Thormark [9] investigated the effects of material selection on both the embodied energy and recycling potential within an energy efficient apartment block in Sweden. He noted that a simple alternation in material choice could lead to a reduction in embodied energy by approximately 17% or an increase of about 6%. Tavares et al. [10] studied the embodied energy and greenhouse gas (GHG) emissions of a prefabricated house with alternative structural materials (steel, concrete, timber and light steel framing (LSF)). The result indicated that the material production phase is dominant and LSF or timber yield the lowest impacts, resulting in a reduction of approximately 10-20% in embodied energy and 20-40% in GHG emissions compared to steel and concrete. Takano et al. [11] studied the impact of material choice on the life cycle energy balance of a building in Finland. It was revealed that differences in material selection are quite visible at the production stage. For example, substituting the gypsum board with plywood as the sheathing material increased the renewable primary energy in the production stage by nearly 50% compared to the original configuration. Whereas, changing the gypsum board to MDF only increased by a few percent. These studies provided valuable insights to proper building material selection mainly from the aspects of energy performance and GWP, which are the most influential impacts categories.

Meanwhile, there is a growing interest in a multi-criteria decision-making approach [7, 12, 13]. Chen et al. [14] conducted a cradle-to-gate LCA on the eight-story residential building in China, focusing on the environmental impacts associated with two structural frame options: Cross Laminated Timber (CLT) and concrete, across 13 categories. It was reported that environmental performance of the two frame options varies depending on the categories. For instance, the timber frame shows about 25% less GWP than the concrete frame, however, on the other hand, it also leads about 70% higher Acidification potential of soil and water sources (AP) and Formation potential of tropospheric ozone (SFP). Geß et al. [15] analysed environmental impacts of insulation materials derived from four renewable resources (pasture grass, seaweed, reed and recycled jute fibres) on eight indicators in comparison with conventional non-renewable insulation materials such as mineral wool. The results demonstrated that the renewable insulation materials had lower environmental impacts in all indicators than their conventional counterparts and advantages regarding GWP was particularly highlighted. Takano et al. [16] illustrated the impact of building material selection on both environmental and economic parameters of a building in a context of Finland, revealing that the choice of frame material had the most substantial impact. In addition, it was noted that inner components, such as insulation and sheathing, also exert certain influences and should be carefully considered, even though they are not visible at the end. Balasbaneh et al. [17] studied the sustainability performance of four different flooring systems using a multi-criteria assessment method. It was revealed that, for instance, the concrete flooring is the best option in terms of economic aspect, whilst wood flooring shows the lowest environmental impacts because of fewer CO<sub>2</sub> emissions than the others. Balasbaneh et al. [18] evaluated the GWP, ozone layer depletion (OLD), life cycle cost (LCC) and social life cycle assessment (S-LCA) of five retaining wall materials used in a typical Malaysian residence. The results showed that stone walls are about one-third lower than concrete walls in terms of GWP and OLD. However, in terms of LCC, the cantilever reinforced concrete wall is the best option which is about 14% less than the second-best option. In terms of S-LCA, the rubble masonry wall is the best option, showing a 10% cost advantage over the second option. These studies underlined the significance of a multi-criteria approach for decision-making in building design, as a comprehensive perspective is essential in determining optimal solutions.

In such background, the objective of this study was to demonstrate the impact of material selection on various indicators in the material production phase of a building in a Japanese context. The indicators examined include:

- Greenhouse gas emissions (GHG)
- Embodied energy (EE)
- Resource use (RU)
- Ozone depletion potential (ODP)
- Acidification potential (AP)
- Carbon storage (CS)
- Energy content (EC)
- Material Cost (MC)

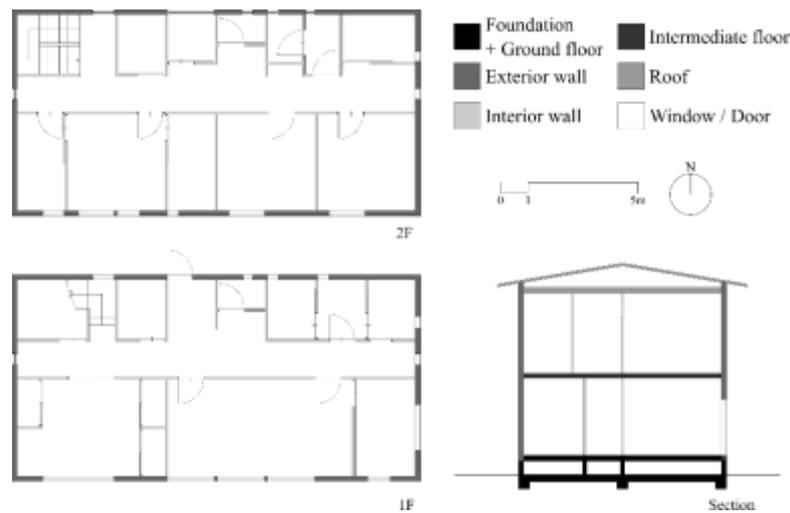
The analysis focused on the effects of five different structural frame alternatives on these indicators and the dominance of each building element (e.g. exterior wall) and material (e.g. Concrete) depending on the options were investigated comparatively on a reference building. Secondly, the effects of alternative building element use were quantified in order to observe the contribution of partial changes of the building constitution to the end results. Given the scarcity of similar research in Japan, this study aims to facilitate informed decision-making among professionals in the construction sector, thereby promoting enhanced sustainability in building design.

## 2. Materials and Methods

### 2.1. Reference Building Model And Building Materials Compared

The reference building was a hypothetical two-story building model, as exemplified in reference [19]. Figure 1 presents the basic plan and section of the building, indicating each building element, whilst Table. 1 shows the floor area of the building and the surface area of each building element used in the calculation. This study employs a comparative analysis of five alternative structural frames: wooden Post and Beam frame (P&B), Cross Laminated Timber frame (CLT), Massive Holz frame (MH), Reinforced Concrete frame (RC) and Steel frame (Steel)), based on the building materials commonly used in Japan [19]. Table. 2 outlines the selected structures for each building element corresponding to the five frame options. To observe the differences resulting from the selection of the frame materials, other building components, such as thermal insulation and finishing, were maintained as constant as possible. In addition, irrespective of the frame materials, all building elements adhered to identical specifications across all cases (e.g. U-value; Exterior wall =  $0.53\text{W/m}^2\text{K}$ , Floor =  $0.34\text{W/m}^2\text{K}$ , Roof =  $0.24\text{W/m}^2\text{K}$ ) in accordance with the Building Energy Efficiency Act [20]. The building was assumed to be of the lowest fire protection class as per the Japanese building code. Thus, structural fire protection was not considered.

In addition to examining the structural frame materials, alternative frame combinations were also studied. In general, the structural frame tends to consist of a single material due to, for instance, construction and cost efficiencies. Here, however, the aim was also to demonstrate how the sustainability performance changes when different structural frame materials are combined in a building. The reference building with the CLT frame served as the case study model. In this analysis, it was assumed that the interior wall, floor (both ground and intermediate) and roof elements of the CLT frame would be substituted with the elements from the P&B frame. The original specifications of the CLT described in Table 2 were utilized as a benchmark, and the impact of the alternative elements was assessed in relation to this reference. The comparative study was conducted for each category of building elements, and the contribution of these elements to the end results was examined. The performance of the building (e.g. U-value) remained constant in all cases.



**Figure 1.** Basic plan and section of the reference building with the indication of building elements.

**Table 1.** Floor area of the reference building and surface area of each building element used in the calculation (m<sup>2</sup>).

Building element	Area (m <sup>2</sup> )
Gross floor area	212
Foundation + Ground floor	106
Exterior wall	251
Interior wall	265
Intermediate floor (including Staircase)	106
Roof	151
Window / Door	82

**Table 2.** Structure of each building element with the five frame materials (t=mm).

Frame	Foundation		Exterior wall		Interior wall		Ground floor		Intermediate floor		Roof	
	Material	t	Material	t	Material	t	Material	t	Material	t	Material	t
P&B	Concrete slab	120	Wood cladding	18	Gypsum board	12.5	Wooden Flooring	15	Wooden Flooring	15	Roof tile	8
	Concrete footing	80	Batten: 30×30	30	Post: 105×105	105	Plywood	15	Plywood	9	Waterproof sheet	-
			Waterproof sheet	-	Stud: 30×105	105	Joist: 45×105	105	Joist: 30×105	105	Cedar board	15
			Post: 105×105	105	Gypsum board	12.5	Glass wool	50	Beam: 105×300	300	Rafter: 45×45	45
		Glass wool	50			Joist: 105×105	105	Joist: 45×30	30	Glass wool	50	

	Airtight sheet	-				Cedar board	9	Joist: 45×30	3 0
	Batten: 30×45	3 0						Gypsum board	9. 5
	Cedar board	1 2							

Table 2. Cont.

CL T	Concrete slab	1 5 0	Wooden cladding	1 8	CLT	9 0	Wooden Flooring	1 5	Wooden Flooring	1 5	Roof tile	1 8
	Concrete footing	6 1 0	Batten: 30×30	2 0			Plywood	1 5	Plywood	9	Waterproof sheet	-
			Waterproof sheet	-			Joist: 45×75	7 5	Joist: 45×45	4 5	Cedar board	1 5
			Glass wool	4 0			Glass wool	7 5	CLT	1 0 5	Rafter: 45×45	4 5
			CLT	1 0 5			CLT	1 0 5			Glass wool	1 4 0
M H	Concrete slab	1 5 0	Wooden cladding	1 8	Post: 105×105	1 0 5	Wooden Flooring	1 5	Wooden Flooring	1 5	Roof tile	1 8
	Concrete footing	6 1 0	Batten: 60×90	6 0	Massive Holz	9 0	Plywood	1 5	Plywood	9	Waterproof sheet	-
			Waterproof sheet	-			Joist: 45×105	1 0 5	Joist: 30×105	1 0 5	Cedar board	1 5
			Glass wool	5 0			Glass wool	1 0 5	Beam: 105×300	3 0 0	Rafter: 45×45	4 5
			Massive Holz	1 0 5					Joist: 45×30	3 0	Glass wool	1 5 0
								Cedar board	9	Joist: 45×30	3 0	
										Gypsum board	9. 5	



## 2.2. Indicators

### 2.2.1. Greenhouse gas emissions (GHG, Unit: kgCO<sub>2eq</sub>)

Greenhouse gas (GHG) emissions associated with the material production phase of the building, from the extraction of raw materials through to the completion of a product ready for delivery at the factory gate, were evaluated as embodied GHG using the IDEA database [21]. Emissions from the combustion of biogenic fuels were considered to be zero, in accordance with the principle of biogenic carbon neutrality [22]. Thus, in this study, GHG refers to only emissions arising from the combustion of fossil fuels.

### 2.2.2. Embodied energy (EE, Unit: MJ)

Primary energy consumed in the material production phase of the building was calculated as embodied energy with IDEA. Embodied energy originating from renewable (EE-R) and non-renewable resources (EE-NR) were presented separately.

### 2.2.3. Resource use (RU, Unit: kg)

The mass of the renewable and non-renewable resources utilized as the raw materials in the production of building components was quantified as an index of resource use (RU-R and RU-NR).

### 2.2.4. Ozone depletion potential (ODP, Unit: kgCFC<sub>11eq</sub>)

Ozone-depleting substances (chlorofluorocarbons, halon and methyl bromide) emitted in the material production phase of the building were assessed with IDEA.

### 2.2.5. Acidification potential (AP, Unit: kgSO<sub>2eq</sub>)

Anthropogenic air pollutants (SO<sub>2</sub> and NO<sub>x</sub>) emitted in the material production phase were assessed with IDEA.

### 2.2.6. Carbon storage (CS, Unit: kgCO<sub>2eq</sub>)

As previously noted, biogenic GHG is considered to have a net-zero impact throughout the life cycle of wood products. In this context, the carbon storage in wood products may be perceived as a virtual value. However, it is advantageous to sequester carbon in a product that postpones the release of CO<sub>2</sub> for a defined duration. Therefore, the temporal carbon storage in utilized wood products is recognized as an environmental benefit of the building, in accordance with EN16449 [23].

### 2.2.7. Energy content (EC, Unit: MJ)

According to the specifications outlined in EN 16485, the energy content of the materials used in the building is considered as an inherent property and is factored into the building's potential for energy recovery. This value was quantified with IDEA and literature [24].

### 2.2.8. Material cost (MC, Unit: JPY)

Cost constitutes a primary criterion for material selection in practice; therefore, it should be taken into account in conjunction with the environmental attributes of products. Initial material cost was determined based on the data provided in reference [25].

## 2.3. Calculation

According as the indicators, the reference building was assessed by multiplying the unit values, which are the values derived from one square meter of the building elements (kg-CO<sub>2eq</sub>-, MJ-, kg-, kg-CFC-11eq-, kg-SO<sub>2eq</sub>-, JPY/m<sup>2</sup>), and the surface area of each building element (m<sup>2</sup> shown in Table 1). As mentioned before, this study was carried out with the IDEA database and Japanese literature.

Thus, although the results shown are Japanese specific information, they are also discussed in comparison with the previous study in order that the trend of the results can be understood in different context.

#### 2.4. Analyssi techniques

The results were presented and analysed in a relative manner due to the application of a simplified calculation method. The differences among the frame materials were quantified in relation to the average of all alternatives, utilizing a metric referred to as “difference index (DI)”, as established by Takano et al [16]. A DI value of 3, 2 and 1 indicates that the result associated with a particular frame material is 3 times, 2 times and equal to the average, respectively. When a DI value expressed as a decimal, such as 0.5, the result from the frame material is one-half of the average. Furthermore, a DI of 0 denotes that the frame material holds no value concerning that specific indicator.

For the comparative study of alternative frame material combinations, the percentage relative differences (PRD) were used. The original specification of the CLT frame (Table 2) was set as the reference value and PRD in the result of the alternative frame combinations which were determined using Equation (1).

$$\text{PRD} = (\text{Value}_x - \text{Value}_{\text{ref}}) / \text{Value}_{\text{ref}} \times 100 \quad (1)$$

where: PRD is Percentage of relative differences (%).  $\text{Value}_x$  is the value calculated with element  $x$  (kg-CO<sub>2</sub>eq, MJ, kg-CFC<sub>11</sub>eq or kg-SO<sub>2</sub>eq).  $\text{Value}_{\text{ref}}$  is the value calculated with the original specification (kg-CO<sub>2</sub>eq, MJ, kg-CFC<sub>11</sub>eq or kg-SO<sub>2</sub>eq).

This method allows for the identification of both positive and negative deviations in relation to the reference case, thereby enabling a comparative analysis of an index. For instance, PRDs of 100%, 50% and 0% indicate that the results from the alternative building element are 2 times, 1.5 times and equivalent to those of the reference case, respectively. PRDs with negative values, such as -66.6% and -50%, indicate that the results from the alternative element are, respectively, one-third and one-half of the results arose from the reference case.

### 3. Results

#### 3.1. Comparison of Structural Frames

Table 3 presents the assessment results of the reference building with the five structural frame alternatives. This table shows the correlation among the frame options and highlights the predominance of each building element in accordance with the indicators. Additionally, Fig. 2 illustrates the relative relationship between the frame options as the difference index (DI).

First of all, it is important to note that there is a considerable variation in the results. The magnitude of differences among the frame options varies depending on the indicators. But at the same time, a general tendency can also be seen in the results. For instance, the wooden frame options (P&B, CLT and MH) are below average in the impacts, except EE-R and RU-R of the CLT frame and RU-R of the MH frame. Since RU-R indicates the mass of renewable resources used in the building, it is in proportion to CS and EC. Thus, the CLT and MH show the largest CS and EC, which are higher than GHG and EE. On the other hand, the CLT frame is identified as the least favourable option concerning MC. This would indicate that the CLT frame may entail higher initial cost, but it may yield the greatest environmental benefits in the end, contingent upon the end of life (EoL) scenario for the material, such as energy recovery through thermal recycling. The P&B frame appears to represent a well-balanced option, exhibiting the lowest values for nearly all the indicators while maintaining an adequate amount of CS and EC. The MH frame may also be considered a favourable option, as it is practically equivalent to the P&B frame in terms of environmental impacts and MC, but it has higher CS and EC.

The non-wooden frames (RC and Steel) are notable in the environmental impacts. The RC frame exhibits the worst option regarding GHG, RU-NR, ODP and AP, particularly RU-NR is about 2.5 times greater value than the average of all options. Conversely, the Steel frame is the worst option in terms of EE (both R and NR); however, the differences between the RC and Steel are relatively minor across many indicators. In short, the large quantity of non-renewable resource use (for both energy and material) would be a clear weakness of the non-wooden frames. In terms of MC, the RC and Steel frames are almost the average as they are a common frame option.

**Table 3.** The assessment results of the reference building according as the five alternative frame materials: categorized by the building elements (Functional unit is gross floor area).

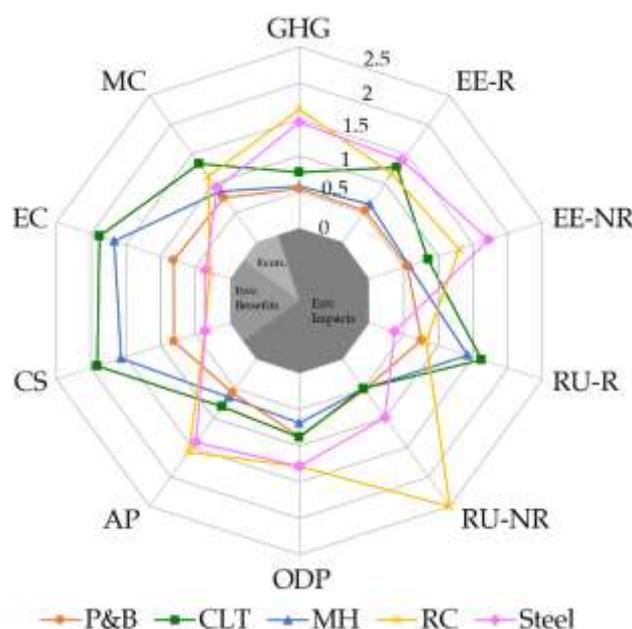
Frame	Element	GHG		EE-R		EE-NR		RU-R		RU-NR	
		kgCO <sub>2</sub> e q	%	MJ	%	MJ	%	kg	%	kg	%
P&B	Foundation + Ground floor	80	55	73	45	650	42	20	21	374	86
P&B	Exterior wall	8	5	12	8	102	7	23	25	3	1
	Interior wall	16	11	16	10	243	16	6	6	21	5
	Intermediate floor	8	5	16	10	114	7	23	24	0	0
	Roof	26	18	34	21	318	21	19	20	37	9
	Window/Door	8	6	12	7	113	7	3	3	1	0
	Total	146		163		1,540		94		435	
CLT	Foundation + Ground floor	93	45	110	28	820	34	38	19	380	91
	Exterior wall	31	15	86	22	443	19	57	28	2	0
	Interior wall	26	13	78	20	377	16	45	22	0	0
	Intermediate floor	16	8	42	11	231	10	27	14	0	0
	Roof	32	15	60	15	406	17	31	15	34	8
	Window/Door	8	4	12	3	113	5	3	1	1	0
	Total	206		388		2,391		202		417	
MH	Foundation + Ground floor	82	53	76	39	659	40	19	11	380	91
	Exterior wall	25	16	41	21	332	20	71	40	0	0
	Interior wall	7	4	17	9	92	6	42	24	0	0
	Intermediate floor	8	5	16	8	114	7	23	13	0	0
	Roof	26	17	34	17	318	20	19	11	37	9
	Window/Door	8	5	12	6	113	7	3	2	1	0
	Total	156		196		1,628		176		419	
RC	Foundation + Ground floor	94	21	77	22	795	22	14	14	474	22
	Exterior wall	82	19	56	16	637	17	24	24	465	22
	Interior wall	78	18	63	18	595	16	25	25	373	18
	Intermediate floor	80	18	74	21	680	19	23	23	365	17

	Roof	97	22	73	21	842	23	13	13	431	20
	Window/Door	7	2	10	3	96	3	3	2	1	0
	Total	438		353		3,645		102		2,109	
Steel	Foundation + Ground floor	75	19	71	17	693	14	14	30	424	51
	Exterior wall	76	20	110	26	1,110	23	9	20	63	8
	Interior wall	36	9	32	7	523	11	0	0	24	3
	Intermediate floor	85	22	120	28	1,080	22	14	29	70	8
	Roof	110	28	82	19	1,329	27	7	15	252	30
	Window/Door	8	2	11	3	108	2	3	5	1	0
	Total	390		426		4,843		46		835	

Frame	Element	ODP		AP		CS		EC		MC	
		kgCFC1 1eq	%	kgSO <sub>2</sub> e q	%	kgCO <sub>2</sub> eq	%	MJ	%	JPY	%
P&B	Foundation + Ground floor	2.8.E-06	21	4.0.E-02	47	-25	6	-212	6	12,8	2
	Exterior wall	6.7.E-07	5	4.5.E-03	5	-43	7	-340	6	12,5	2
	Interior wall	2.8.E-06	21	1.3.E-02	15	-11	7	-93	7	1,52	3
	Intermediate floor	7.9.E-07	6	3.7.E-03	4	-42	6	-345	6	5,88	1
	Roof	2.4.E-06	18	1.6.E-02	19	-33	1	-282	1	9,78	2
	Window/Door	4.0.E-06	30	8.0.E-03	9	-6	3	-48	4	1,86	4
	Total	1.4.E-05		8.6.E-02		-160		1,320		44,5	05
CLT	Foundation + Ground floor	3.3.E-06	24	4.8.E-02	39	-63	7	-517	7	17,9	2
	Exterior wall	1.8.E-06	13	2.0.E-02	16	-111	9	-878	9	22,1	2
	Interior wall	1.3.E-06	9	1.7.E-02	14	-88	3	-707	3	13,5	1
	Intermediate floor	1.1.E-06	8	9.6.E-03	8	-53	4	-426	4	8,84	1
	Roof	2.3.E-06	17	2.0.E-02	16	-58	5	-473	6	14,0	1

	Window/Door	4.0.E-06	29	8.0.E-03	7	-6	1	-48	2	1,867	2
	Total	1.4.E-05		1.2.E-01		-379		3,048		78,356	
MH	Foundation + Ground floor	2.8.E-06	26	4.1.E-02	41	-25	8	-212	8	12,147	24
	Exterior wall	4.9.E-07	5	2.6.E-02	26	-128	41	1,163	43	15,198	30
	Interior wall	2.0.E-07	2	3.4.E-03	3	-76	25	-653	24	5,454	11
	Intermediate floor	7.9.E-07	7	3.7.E-03	4	-42	13	-345	13	5,888	12
	Roof	2.4.E-06	23	1.6.E-02	17	-33	11	-282	10	9,787	19
	Window/Door	4.0.E-06	37	8.0.E-03	8	-6	2	-48	2	1,867	4
	Total	1.1.E-05		9.8.E-02		-311		2,703		50,342	
RC	Foundation + Ground floor	2.8.E-06	14	4.9.E-02	20	-14	20	-115	25	12,985	20
	Exterior wall	2.3.E-06	11	4.3.E-02	18	-24	33	-80	17	12,728	19
	Interior wall	5.1.E-06	26	4.8.E-02	20	0	0	-2	0	12,372	19
	Intermediate floor	3.1.E-06	16	4.2.E-02	17	-22	31	-174	37	14,326	22
	Roof	3.2.E-06	16	5.2.E-02	22	-7	9	-56	12	11,811	18
	Window/Door	3.5.E-06	17	6.8.E-03	3	-5	6	-39	8	1,578	2
	Total	2.0.E-05		2.4.E-01		-71		-467		65,801	
Steel	Foundation + Ground floor	2.5.E-06	13	3.8.E-02	18	-21	30	-171	30	10,216	19
	Exterior wall	3.0.E-06	15	4.4.E-02	21	-16	23	-124	22	15,191	28
	Interior wall	3.3.E-06	16	2.3.E-02	11	0	0	0	0	2,173	4
	Intermediate floor	3.3.E-06	17	4.2.E-02	20	-25	35	-202	35	14,793	27

Roof	3.7.E-06	19	5.9.E-02	27	-4	6	-35	6	9,99	1
Window/Door	4.1.E-06	21	7.9.E-03	4	-5	7	-39	7	1,57	3
Total	2.0.E-05		2.1.E-01		-70		-571		53,9	42



**Figure 2.** Difference index of the reference building with the five frame materials on the indicators.

### 3.1.1. Dominance of building elements

Figs. 3 highlights the predominance of each building element as determined by the indicators. The results depend on the indicators, but there is a clear trend. In terms of the environmental impact indicators except ODP, the foundation is significantly the most influential element in the wooden frame options (P&B, CLT and MH), whilst the exterior wall, intermediate floor and roof exhibit substantial contributions in the case of non-wooden frames (RC and Steel). In terms of ODP, the interior wall and window/door emerges as the predominant elements in many cases due to the amount of glass and gypsum used as the surface material. In terms of CS and EC, the exterior wall and interior wall are the primary elements in the massive wooden frames (CLT and MH) because of the large surface area of the elements and the volume of wood product used. In the P&B frame, the exterior wall, intermediate floor and roof share equivalent contributions. In terms of MC, the foundation, exterior wall and roof correctively represent approximately 60-80% of the total. These assessment results indicate that the building envelope (foundation, exterior wall and roof) has the priority across several aspects.

### 3.1.2. Dominance of building materials

Fig. 4 and Table 4 present the assessment results of the reference building concerning the structural frame options in terms of GHG, EE-R/NR, ODP and AP, indicating the dominance of each building material according to the indicators. The environmental indicators where a single material becomes dominant (RU-R/NR, CS, EC,) and MC are excluded in this case. Naturally, the materials used as the structural components have a significant share and concrete and steel are major materials

in many cases. However, wood bears high share in the case of the massive wooden frames (CLT and MH). As discussed before, the use of large amount of wood may bring the environmental benefits (CS and EC), but at the same time, it would cause the higher impacts. Therefore, the impacts and benefits caused using wood should be considered concurrently. Gypsum also shows relevant share especially in the case of the lightweight frames (P&B and Steel). The lightweight frame requires sheathing materials and gypsum board is often used because of its reasonable function and cost. But the result would indicate that the environmental parameter should be considered more in the selection of sheathing materials. Glass, plastic and mineral fibre used as the surface and inner components are minor materials in general, but their impacts are notable in terms of ODP.

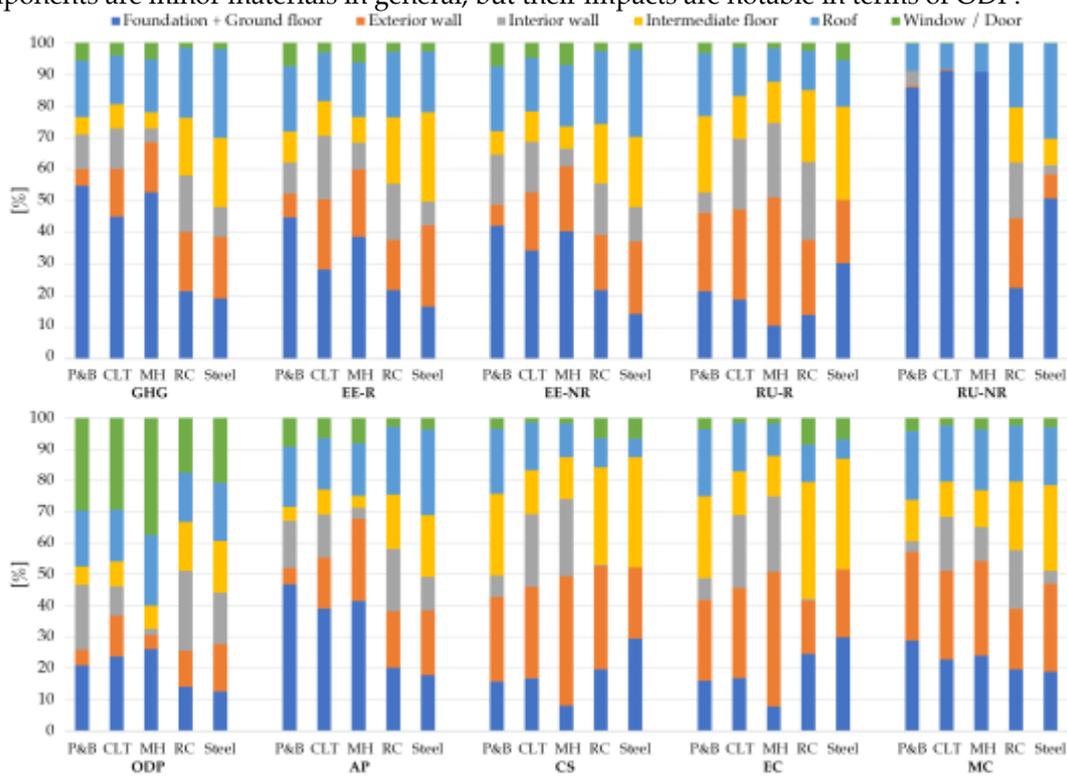


Figure 3. Dominance of the building elements with the five frame materials on the indicators.

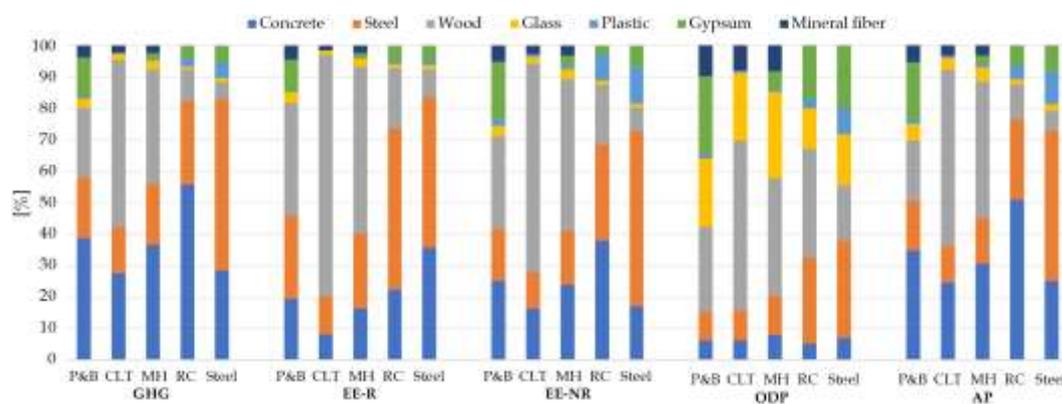


Figure 4. Dominance of the building materials with the five frame materials on the indicators.

Table 4. The assessment results of the reference building according as the five alternative frame materials: categorized by the materials (Functional unit is gross floor area).

Frame	Element	GHG		EE-R		EE-NR		ODP		AP	
		kgCO <sub>2</sub> e	%	MJ	%	MJ	%	kgCFC11e	%	kgSO <sub>2</sub> e	%
		q						q		q	

P&B	Concrete	57	3 9	32	2 0	389	2 5	8.7.E-07	6	3.0.E-02	3 5
	Steel	28	1 9	43	2 6	258	1 7	1.2.E-06	9	1.3.E-02	1 6
	Wood	32	2 2	58	3 6	451	2 9	3.6.E-06	2 7	1.7.E-02	1 9
	Glass	4	3	5	3	51	3	2.9.E-06	2 2	4.6.E-03	5
	Plastics	1	1	0	0	33	2	1.4.E-07	1	1.4.E-03	2
	Gypsum	18	1 2	17	1 0	281	1 8	3.4.E-06	2 5	1.5.E-02	1 8
	Mineral fiber	6	4	7	4	78	5	1.3.E-06	1 0	4.6.E-03	5
	Total	146		16 3		1,54 0		1.4.E-05		8.6.E-02	

Table 4. Cont.

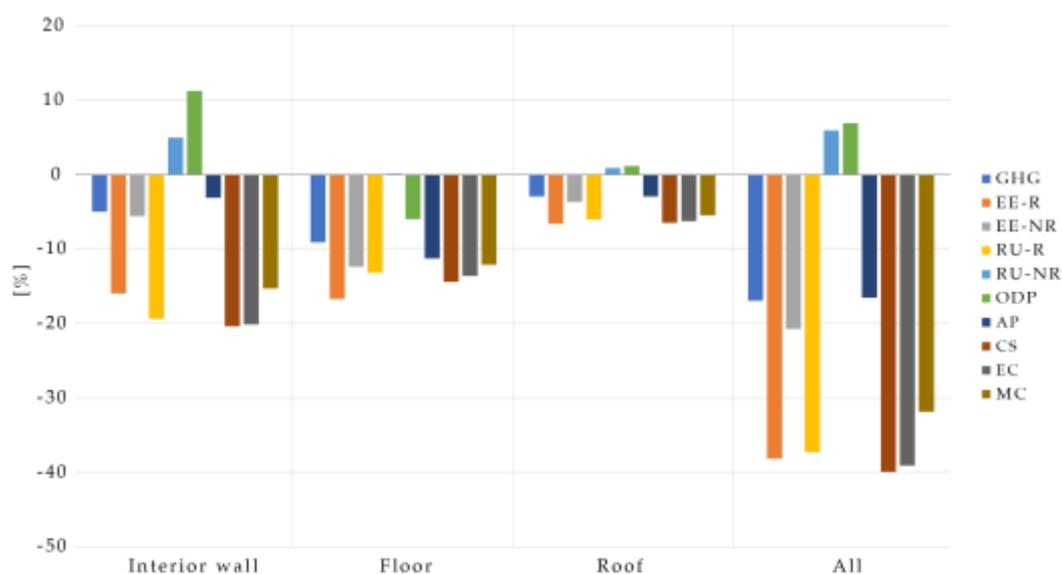
CLT	Concrete	57	2 8	32	8	392	1 6	8.7.E-07	6	3.0.E-02	2 5
	Steel	30	1 5	47	1 2	275	1 2	1.3.E-06	9	1.4.E-02	1 2
	Wood	110	5 3	29 7	7 7	1,58 5	6 6	7.4.E-06	5 4	6.9.E-02	5 6
	Glass	4	2	5	1	51	2	2.9.E-06	2 1	4.6.E-03	4
	Plastics	1	0	0	0	22	1	9.8.E-08	1	9.6.E-04	1
	Gypsum	0	0	0	0	0	0	0	0	0	0
	Mineral fiber	5	2	6	2	65	3	1.1.E-06	8	3.9.E-03	3
	Total	206		38 8		2,39 1		1.4.E-05		1.2.E-01	
MH	Concrete	57	3 7	32	1 6	392	2 4	8.7.E-07	8	3.0.E-02	3 1
	Steel	30	1 9	47	2 4	275	1 7	1.3.E-06	1 2	1.4.E-02	1 4
	Wood	57	3 6	10 4	5 3	786	4 8	4.0.E-06	3 8	4.3.E-02	4 3
	Glass	4	3	5	3	51	3	2.9.E-06	2 7	4.6.E-03	5
	Plastics	1	0	0	0	20	1	8.8.E-08	1	8.7.E-04	1
	Gypsum	3	2	3	2	51	3	6.2.E-07	6	2.8.E-03	3
	Mineral fiber	4	2	5	2	52	3	8.7.E-07	8	3.1.E-03	3
	Total	156		19 6		1,62 8		1.1.E-05		9.8.E-02	

RC	Concrete	245	5	79	2	1,38	3	1.0.E-06	5	1.2.E-01	5
			6		2		6				
	Steel	116	2	18	5	1,11	3	5.4.E-06	2	6.2.E-02	2
			6	1	1		3				
	Wood	45	1	68	1	693	1	6.9.E-06	3	2.6.E-02	1
			0		9		9				
	Glass	4	1	5	1	45	1	2.6.E-06	1	4.0.E-03	2
Plastics	11	2	3	1	304	8	6.1.E-07	3	1.1.E-02	5	
Gypsum	18	4	17	5	104	3	3.4.E-06	1	1.5.E-02	6	
											7
Mineral fiber	0	0	0	0	0	0	0	0	0	0	
Total	438		35		3,64		2.0.E-05		2.4.E-01		
			3		5						
Steel	Concrete	111	2	15	3	833	1	1.4.E-06	7	5.4.E-02	2
			9	3	6		7				
	Steel	211	5	20	4	2,69	5	6.1.E-06	3	1.0.E-01	4
			4	3	8		7				
	Wood	23	6	38	9	362	7	3.5.E-06	1	1.3.E-02	6
	Glass	5	1	6	1	57	1	3.2.E-06	1	5.0.E-03	2
Plastics	19	5	7	2	566	1	1.6.E-06	8	2.2.E-02	1	
						2					
Gypsum	21	5	20	5	328	7	4.0.E-06	2	1.8.E-02	8	
											0
Mineral fiber	0	0	0	0	0	0	0	0	0	0	
Total	390		42		4,84		2.0.E-05		2.1.E-01		
			6		3						

### 3.2. Comparison of Alternative Frame Material Combinations

Fig. 5 illustrates the PRD in the assessment results of the reference building, which incorporates three alternative building elements in comparison to the original CLT frame elements. The objective of this analysis was to examine the differences among the individual building elements while simultaneously assessing their contributions to the overall results. Overall, MC and the environmental impacts except RU-NR and ODP decrease by about 15-40%, but at the same time, the environmental benefits (CS and EC) decline by about 40% too. The greater influence can be seen in the interior wall and floor because of their substantial surface area (quantity) used. In the case of interior wall, RU-NR and ODP increase by about 5% and 11% respectively, whilst the other indicators decrease by about 5-20%. In the case of floor, every indicator decreases by about 5-15%, except RU-NR, which was equivalent to the reference. These results mainly arise from the replacement of the large amount of massive wood (CLT) used in the elements with smaller wood components, such as timber post and joist, along with sheathing materials. The sheathing material has great influence because of the large quantity of material used. In this case, gypsum board used as the sheathing

material led significant impacts in terms of RU-NR and ODP. Although this study acknowledges certain limitations, such as the number of combinations analysed, it effectively demonstrates that the combination of different structural frame significantly influences the overall assessment results.



**Figure 5.** Percentage relative differences in the assessment results of the reference building caused by the alternative frame material combinations (Reference is the CLT frame).

#### 4. Discussion

The comparison of structural frame alternatives reveals that the interpretation of the results pertaining to the wooden frame options is significant. Especially the massive wooden frames (CLT and MH) have distinct advantages and disadvantages related to the other life cycle stages, as described above. Understanding the characteristics of these materials is crucial for informed decision-making. In general, the difference among the frame materials is very minor in the use phase of a building, since the maintenance mainly pertains to the surface components. On the other hand, the recycling aspect is critical for mitigating the environmental impacts of buildings, particularly concerning wooden frames [26, 27]. For instance, the repurposing of wood as secondary products and its recycling for thermal energy generation will lead different impacts and benefits. This underlines the necessity of effective design methods, such as ensuring disassemblability and reversibility of the frame materials, as well as developing scenarios for the EoL management of these materials. Although this study only dealt with the material production phase of the building, the influence of the EoL of the materials on the environmental and economic performance of buildings is an important topic that should be investigated further. In addition, the findings suggest that environmental consideration should take precedence over economic factors in decision-making, since MC did not exhibit significant variation among the alternative frame options analysed. This finding aligns with trends reported in previous studies [16, 28].

In terms of the building elements, in principle, the envelope (foundation, exterior wall and roof) would have higher environmental and economic impacts due to its complex composition in response to the functions required. To mitigate these impacts, simplification of the composition of the element would be a solution. For instance, the use of massive wooden frame like CLT as a structural component can effectively take advantage of the physical properties of wood (e.g. structural strength, low thermal conductivity, thermal/moisture buffering property, fire retardancy). By optimizing these properties, massive wood may have the potential to rationalize the composition of a building by integrating multiple functions into a single component. If advancements are made to ensure that massive wood meets relevant building regulations, such as fire safety and thermal performance, it

could serve as a unitary and multi-functional component for the exterior wall. Such developments would contribute to enhance the environmental and economic sustainability of buildings.

The dominance analysis of each building material revealed the importance of both surface and inner components in the multi-criteria decision making. Although structural frame materials tend to be the priority in terms of GHG and EE, which are considered as the main environmental indicators, glass, plastic and mineral fibre used as the surface and inner components exhibit considerable effects on ODP, as previously discussed. Therefore, adopting a broader perspective is essential for sustainable building design based on appropriate material selection. Furthermore, it is important to consider both quantitative (e.g. environmental impacts, cost) and qualitative (e.g. appearance, durability) factors in the process of selecting building materials [16].

From the comparison of frame material combinations, at least, three insights would be found. First, the combination of building elements should be carefully designed rather than constructing a building with a single structural frame material, which is common in reality though. Second, building elements with large quantities need to be considered carefully. Third, the selection of building elements and materials should be done in such a way as to minimize weaknesses (impacts) and maximize strength (benefits) of a building in terms of sustainability. For instance, as shown in this study, it would be reasonable to use CLT in the building envelope by utilizing its structural stiffness and low thermal conductivity. On the other hands, the lightweight frame (e.g. P&B, steel) which makes a building lighter and gives a flexibility to room arrangement may be better for inner elements such as interior wall and floor. The implications of different frame material combinations warrant further investigation from multiple perspectives, including constructivity, aesthetical quality and psychological perception throughout the building's life cycle.

The selection of materials for sustainable construction presents a multifaceted challenge. A basic approach would be to select materials based on their intended use and specific features on an individual basis. Since there is no universally ideal material, it is essential to handle all materials fairly. The principle of "the right material in the right place" should be a guiding consideration. However, it is often observed that cost considerations take precedence over the other factors. Currently, it remains challenging to weight the environmental impacts on par with material costs during the selection process. Therefore, it is crucial to establish a framework that integrates economic factors with other relevant aspects, allowing for a more balanced decision-making process. For instance, implementing a discount system that correlates with the environmental impacts of products available in the market could expand the range of choice. Additionally, initiatives such as green procurement and a tax system for building materials, including a carbon tax, may serve as effective measures. Furthermore, adopting a post-use material purchasing strategy could enhance recycling efforts, as evidenced by practices in the automotive industry.

## 5. Conclusions

This study demonstrated the effect of building material selection on the embodied environmental impacts, environmental benefits and material cost associated with a building in a Japanese context. The influences of the selection were studied on the five structural frame options in a comparative manner using a reference building model. Even though the results relating to the material costs are specific to Japanese buildings, the other results can be used and extrapolated in wider context.

A primary aim of this study was to objectively and quantitatively describe the features of each building material from multiple perspectives. This paper indicates the significance of expressing and understanding the diversity of the materials. In addition, the findings indicate which building elements and components should be prioritized to improve the sustainability of a building from a material standpoint. It is acknowledged that no single material is ideal in all respects. Therefore, it is crucial for sustainable building design to select appropriate materials based on their intended use and specific features on a case-by-case basis. Additionally, to expand the range of selection, it is important to develop the market system.

The goal of this research is to enhance the multi-criteria decision-making processes for stakeholders in the construction sector. To achieve this goal, however, this study is constrained by the limited number of case studies that encompass specific material types and sustainability indicators. Consequently, conducting additional case studies would be essential for generalizing the findings and fostering a more thorough understanding of building materials in sustainable construction. For a more diverse understanding of the interplay between material selection and sustainable building design, it would be imperative to consider a broad range of factors, including other building life cycle phases (e.g. end-of-life), different building types, scales, geometries, a wider array of materials, different material combinations and additional sustainable indicators.

**Author Contributions:** Conceptualization, A.T.; methodology, A.T.; software, A.T. and M.A.; validation, A.T. and M.A.; formal analysis, A.T. and M.A.; investigation, A.T. and M.A.; resources, A.T. and M.A.; Data curation, A.T.; writing—original draft preparation, A.T. and M.A.; writing—review and editing, A.T.; visualization, A.T. and M.A.; supervision, A.T.; project administration, A.T.; funding acquisition, A.T. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## References

1. AR6 Climate Change 2021: The Physical Science Basis. IPCC. **2021**. Available online: <https://www.ipcc.ch/report/ar6/wg1/#FullReport> (accessed 09 November 2023).
2. Llantoy, N.; Chàfer, M.; Cabeza, F.L. A comparative life cycle assessment (LCA) of different insulation materials for buildings in the continental Mediterranean climate. *Energy Build.* **2020**, *225*, 110323. [<https://doi.org/10.1016/j.enbuild.2020.110323>]
3. Schiavoni, S.; D'Alessandro, F.; Bianchi, F.; Asdrubali, F. Insulation materials for the building sector: A review and comparative analysis. *Renew. Sustain. Energy Rev.* **2016**, *62*, 988-1011. [<https://doi.org/10.1016/j.rser.2016.05.045>]
4. Nwodo, M. N.; Anumba, C.J. A review of life cycle assessment of buildings using a systematic approach. *Build Environ.* **2019**, *162*, 106290. [<https://doi.org/10.1016/j.buildenv.2019.106290>]
5. König, H.; Kohler, N.; Kreißig, J.; Lützkendorf, T. *A life cycle approach to buildings: Principles, calculations, design tools*. Institut für internationale Architektur-Dokumentation GmbH & Co. KG: Munich, Germany, 2010.
6. Kotaji, S.; Schuurmans, A.; Edwards, S. *Life-cycle assessment in building and construction: a state-of-the-art report of SETAC-Europe*. Society of Environmental Toxicology & Chemist (SETAC): Brussels, Belgium, 2003.
7. Hu, M. Building impact assessment-A combined life cycle assessment and multi-criteria decision analysis framework. *Resour. Conserv. Recycl.* **2019**, *150*, 104410. [<https://doi.org/10.1016/j.resconrec.2019.104410>]
8. Kerr J.; Rayburg S.; Neave M.; Rodwell J. Comparative Analysis of the Global Warming Potential (GWP) of Structural Stone, Concrete and Steel Construction Materials. *Sustainability.* **2022**, *14*, 9019. [<https://doi.org/10.3390/su14159019>]
9. Thormark, C. The effect of material choice on the total energy need and recycling potential of a building. *Build Environ.* **2006**, *41*, 1019-1026. [<http://dx.doi.org/10.1016/j.buildenv.2005.04.026>.]
10. Tavares, V.; Lacerda, N.; Freire, F. Embodied energy and greenhouse gas emissions analysis of a prefabricated modular house: The “Moby” case study. *J. Clean. Prod.* **2021**, *212*, 1044-1053. [<http://dx.doi.org/10.1016/j.buildenv.2005.04.026>.]
11. Takano, A.; Pal, S.K.; Kuittinen, M.; Alanne, K.; Hughes, M.; Winter, S. The effect of material selection on life cycle energy balance: A case study on a hypothetical building model in Finland. *Build Environ.* **2015**, *89*, 192-202. [<https://doi.org/10.1016/j.buildenv.2015.03.001>.]
12. Feng, H.; Zhao, J.; Hollberg, A.; Habert, G. Where to focus? Developing a LCA impact category selection tool for manufactures of building materials. *J. Clean. Prod.* **2023**, *405*, 136936. [<https://doi.org/10.1016/j.jclepro.2023.136936>]

13. Invidiata, A.; Lavagnab, M.; GhisiE. Selecting design strategies using multi-criteria decision making to improve the sustainability of buildings. *Build Environ.* **2018**, *139*, 58-68. [<http://doi.org/10.1016/j.buildenv.2018.04.041>.]
14. Chen, C.X.; Pierobon, E.; Jones, S.; Maples, L.; Gong, Y.; Ganguly, I. Comparative Life Cycle Assessment of Mass Timber and Concrete Residential Buildings: A case study in China. *Sustainability.* **2022**, *14*, 144. [<https://doi.org/10.3390/su14010144>]
15. Geß, A.; Lorenz, M.; Tolsdorf, A.; Albrecht, S. Environmental impacts of Renewable Insulation Materials. *Sustainability.* **2021**, *13*, 8505. [<https://doi.org/10.3390/su13158505>]
16. Takano, A.; Hughes, M.; Winter, S. A multidisciplinary approach to sustainable building material selection: A case study in a Finnish context. *Build Environ.* **2014**, *84*, 526-535. [<https://doi.org/10.1016/j.buildenv.2014.09.026>.]
17. Balasbaneh, A.T.; Yeoh, D.; Juki, M.I.; Gohari, A.; Abidin, A.R.Z.; Marsono, A.K.B. Applying three pillar indicator assessments on alternative floor systems: life cycle study. *Int. J. Life Cycle Assess.* **2021**, *26*, 1439-1435. [<https://doi.org/10.1007/s11367-021-01881-6>.]
18. Balasbaneh, A.T.; Marsono, A.K.B. Applying multi-criteria decision-making on alternatives for earth-retaining walls: LCA, LCC, and S-LCA. *Int. J. Life Cycle Assess.* **2020**, *25*, 2140-2153. [<https://doi.org/10.1007/s11367-020-01825-6>.]
19. Iwashita, Y.; Hurumoto, K.; Okuya, K.; Isono, S. *Architectural structure and construction method*. Inoue Shoin: Tokyo, Japan, 2016.
20. Overview of the Act on the improvement of energy consumption performance of buildings. Institute for Building Environment and Energy Conservation (IBEC). **2016**. Available online: <https://www.mlit.go.jp/common/001134876.pdf> (accessed 26 September 2023).
21. The National Institute of Advanced Industrial Science and Technology. *Inventory Database for Environmental Analysis (IDEA)*, v3.3. Japan, 2024.
22. CEN. *EN 16485: Round and sawn timber - Environmental Product Declarations - Product category rules for wood and wood-based products for use in construction*. European Committee for Standardization: Brussels, Belgium, 2014.
23. CEN. *EN 16449: Wood and wood-based products – calculation of the biogenic carbon content of wood and conversion to carbon dioxide*. European Committee for Standardization: Brussels, Belgium, 2014.
24. Suzuki, Y. Material and energy utilization of forest resource, *J. Jpn. Forest Eng. Soc.* **2012**, *27* (1), pp.69-80
25. Economic Research Association. *Price Data for Construction Cost Estimating*. Economic Research Association: Tokyo, Japan, April 2021.
26. Blay-Armah, A.; Mohebbi, G.; Bahadori-Jahromi, A.; Fu, C.; Amoako-Attah, J.; Barthorpe, M. Evaluation of Embodied Carbon Emission in UK Supermarket Constructions: A Study on Steel, Brick, and Timber Frameworks with consideration of End-of-Life Processes. *Sustainability.* **2023**, *15*, 14978. [<https://doi.org/10.3390/su152014978>.]
27. Dodoo, A.; Gustavsson, L.; Sathre, R. Effect of thermal mass on life cycle primary energy balances of a concrete- and a wood-frame building. *Appl Energ.* **2012**, *92*: 462-472. [<https://doi.org/10.1016/j.apenergy.2011.11.017>]
28. Yasantha, A.U.G.; Babel, S.; Gheewala, S. A matrix in life cycle perspective for selecting sustainable materials for buildings in Sri Lanka. *Build Environ.* **2009**, *44*: 997-1004. [<https://doi.org/10.1016/j.buildenv.2008.07.005>]

**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.