

Article

Reducing Environmental Impact of Buildings Based on Actual Building Analyses: A Multi-Criteria Study of Frame and Finish Materials

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Abstract

The building sector has a significant environmental impact throughout the life cycle of a building. Reducing the environmental load of the building sector is essential for creating a sustainable society. Many current reports focus on carbon emission, while other environmental impacts remain insufficiently evaluated. Furthermore, buildings serve different functions depending on the region, and the types and quantities of primary materials used vary accordingly. Under these circumstances, little research has focused specifically on Japan. This study conducted a life cycle assessment (LCA) covering the life cycle of material inputs (structural and finishing materials) for 95 buildings in Japan. In addition to greenhouse gas emissions, multi-criteria analysis, including characterization and integration (characterization such as acidification, ozone layer destruction, and photochemical ozone; damage assessment; and integration using LIME2 and LIME3), was conducted. Based on analyses of numerous buildings, the objectives were to clarify trends in environmental impact emissions by building use, conduct an environmental impact analysis that could serve as a future benchmark, and discuss for reducing these environmental impacts. First, the analysis of trends such as maximum, median, and minimum values across six building types revealed that the environmental impact per square meter tended to be lower for production and logistics facilities and higher for offices, government buildings, schools, hospitals, hotels, and condominiums across many indicators. However, significant variations were observed between individual buildings within each category. These results can serve as a benchmark for the environmental impact of future buildings in Japan. Next, GHG emissions and integration (LIME2, LIME3) were quantitatively identified for materials with high emissions, and the factors were considered. Furthermore, processes with high environmental impacts associated with the material were analyzed and identified. Ready-mixed concrete, reinforcing bars, and steel frames showed high values across quantitative indicators, whereas wood and other materials varied by indicator. Finally, based on these findings, perspectives for reducing the environmental impact of key materials are proposed for each stakeholder group.

Keywords: life cycle assessment; greenhouse gas emissions; characterization; integration

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1. Introduction

1.1. Background

Buildings are indispensable to human life. The building sector has a large environmental impact throughout the life cycle of a building and is responsible for reducing this impact to create a sustainable society. For example, 40% of global GHG emissions can be attributed to construction [1], and the consumption of natural resources for the production of building materials accounts for 50% of all materials extracted from the Earth [2]. This trend holds in Japan, where 40% of GHG emissions are attributable to construction [3]. Thus, measures have been taken to reduce the environmental impact of these buildings. For example, in Japan, considerable efforts have been made to reduce the amount of energy consumed for heating, cooling, and hot water during the life cycle of a building. The web program developed by the Building Research Institute to study reductions in energy consumption during operational processes is part of these efforts [4]. However, the reduction in load related to building embodied emissions is insufficient, and addressing this issue is becoming increasingly important.

To realize buildings with a low environmental impact, it is essential to conduct a life cycle assessment (LCA), which enables a comprehensive, quantitative evaluation of environmentally hazardous substances. However, LCAs for buildings require a large number of parts and a wide range of evaluations, making the evaluation process labor-intensive. Thus, capturing approximate numbers early in the design stage, rather than after detailed design, will lead to a better building design process. Therefore, it is important to evaluate past buildings and use the results in the early design stage to gain knowledge that can serve as a benchmark for future designs and to summarize perspectives on reducing environmental impacts. In addition, the functions required of buildings vary by country and region; for example, earthquake-resistant measures are required in Japan. Owing to differences in required functions and material availability, the materials used may vary across countries and regions. Therefore, it is essential to enhance knowledge and consider reduction measures for each country and region.

1.2. Previous Studies

Numerous studies have analyzed the environmental impact of embodied buildings. Among these, several studies have evaluated multiple buildings and analyzed their variability. Gervasio et al. [5] examined the variability of the assessment results for individual buildings to develop benchmarks. They examined the variability of CO₂ emissions and energy consumption in residential buildings in the EU. Dong et al. [6] reviewed the literature from the past 10 years and conducted a comprehensive analysis of 105 building assessment cases to develop benchmarks and clarify variability, GHG emissions and seven other environmental impacts. Furthermore, Julie et al. [7] conducted case studies on approximately 50 offices, apartment buildings, and other structures in the Czech Republic to explore the development of benchmarks.

Although the study was not intended to create a benchmark, Sartori and Hestnes [8] analyzed GHG emissions from 60 buildings in nine countries and the impact of differences in building lifespans on the results. Roberts et al. [9] reviewed 108 studies and discussed developing the challenges of benchmarks for use in the early stages of construction. Lotteau et al. [10] reviewed the analytical results of 21 urban development projects from 14 papers, focusing on GHG emissions.

Some studies have focused on specific processes, such as the analysis of renovations—particularly the effects of energy efficiency improvements on GHG emissions—of 23 real buildings by Zimmermann et al. [11].

Other relevant studies include those by Vilches et al. [12], Goulouti et al. [13], and Mesa et al. [14], who focused on demolition and disposal. Another report by Nwodo and Anumba [15] systematically reviewed numerous building analysis cases and discussed the challenges of comparing multiple results. Specifically, limitations of comparative analysis using the diverse literature were noted, including inconsistencies in functional units, building lifespans, and system boundaries. Additionally, some studies have compared analysis results using various inventory data (Atsushi et al. [16] and Yue [17]). Specifically, they pointed out that comparing results across different databases revealed significant variations. Furthermore, Ganga et al. [18] highlighted the uncertainties in the evaluation. Specifically, they pointed out that early design decisions, input data and data quality issues, future stages (service life of building components, reference study period of buildings, end-of-life stage choices, and climate change), and LCA methods (type of life cycle inventory technique and impact assessment methods) are important.

Many of the environmental impacts assessed in these reports appear to focus on GHGs, for example, the studies by Gervasio et al. [5] and Sartori and Hestnes [8]. Examples of assessments of environmental impacts other than GHGs include those by Yahong Dong [6] and Ma et al. [19]; however, such reports are rare. In a study on high-rise buildings, Ma et al. [19] analyzed hotspot materials using multiple criteria and found that concrete and steel frames had a considerable impact. Focusing on life cycle energy, Thil-laigovindhan et al. [20] analyzed 73 cases across 13 countries. Rahman and Narjes [21] reviewed data and methodologies on embodied energy and presented key strategies for its reduction. Additionally, Chi et al. [22] reviewed assessments of LCA, LCE, and LCCO₂, highlighting challenges in evaluating these metrics for decision-making. Ana et al. [23] analyzed Portuguese retail buildings, incorporating not only CO₂ and energy but also material flow perspectives.

Additionally, a case study comparing individual buildings examined the environmental impacts of cross laminated timber (CLT) and reinforced concrete mid-rise apartment buildings across 18 impact categories (Julie et al. [24]). Similarly, another study analyzed a residential tower in Denmark across 12 impact categories (Licia et al. [25]).

Violeta et al. [26] conducted multi-criteria evaluations and cost assessments for single-family homes, aiming to support decision-making from multiple perspectives. Additionally, evaluation methods incorporating changes in intensity have been proposed for multi-criteria decision analysis (Aydin et al. [27]). These methods have also been applied in studies targeting tall buildings and bridges (Aydin et al. [28,29]). Roman et al. [30] analyzed the relationship between building shape and structure and environmental impact emissions, and investigated methods for evaluating environmental indicators based on building shape. Furthermore, as a more advanced development, Peter et al. [31] developed a procedure called the Decision Choices Procedure (DCP) to improve LCA as an effective tool for decision support concerning design alternatives when less information is available. There is also research by Holger and Lisa [32] that proposes creating benchmarks that take into account LCA and life cycle costs.

Research on simplifying assessments has been conducted. For example, Bernardette et al. [33] proposed strategies for simplifying LCA based on a review of single-family homes. Tove et al. [34] examined guidelines designed to simplify the sequence of LCA implementation tasks.

The number of buildings analyzed also varies, such as those by Yahong Dong [6], Sartori and Hestnes [8], Zimmermann [11], and Lavagna et al. [35] with 105, 60, 20, and 30 buildings, respectively. Therefore, most studies have analyzed fewer than 100 buildings. Regarding the countries and regions of the reported cases, some studies have focused on Europe or specific European countries, such as Sartori and Hestnes [8], Lavagna et al. [35], and Moschetti et al. [36], who analyzed buildings in nine countries, European residential

buildings, and Italian residential buildings, respectively. For example, Joanna et al. [37] analyzed 11 buildings in Poland. Many studies have focused on North America or specific countries within North America, such as Ma [19], who examined buildings in the Chicago metropolitan area, while Arvizu-Piña [38] examined buildings in Latin America. However, few studies have focused on Japan.

Large-scale analyses have also been conducted by industry associations and other organizations rather than by academic research papers. The International Energy Agency [39] analyzed the energy consumption and CO₂ emissions of multiple buildings. The assessment covered the embodied life cycle, including process-specific analysis. Participants from 14 countries conducted a comparative analysis of 80 case studies, which not only examined variability in assessment results but also considered issues related to the assessment methodology examined. However, only a few Japanese buildings were included. The Leadership analysis [40] focused on 1007 buildings in North America. It analyzed the variability in carbon emissions across factors such as building area and floor count for each building type (offices, schools, and hospitals). The Joint Research Centre [41] focused on developing a benchmark for life cycle performance in Europe and analyzed variability in carbon emissions across countries and building components. The Towards embodied carbon benchmarks for buildings in Europe report [42] focused on Europe and included 769 case studies, but was heavily biased towards France (486). The analysis focused on carbon emissions and variations according to building use.

In summary, most current reports have focused on evaluating carbon emissions, with other environmental impacts inadequately assessed. While research papers often cover <100 buildings, project reports often cover >1000 buildings, and only a few studies have focused on Japan. Most analyses used m² as the functional unit, but in some cases, the evaluations were based on useful life, such as m²-yr. Furthermore, the useful life varied from the expected life of each building at the time of design to a uniform 50 years estimate; in many cases, it was assessed at 60 years. While some studies have analyzed the overall embodied environmental impact of a building, others have analyzed it by processes or components. However, few studies have examined more detailed aspects, such as material inputs.

1.3. Objective

Based on the above, this study aims to build a database serving as a benchmark for the environmental impacts of buildings from a multi-criteria perspective, targeting the embodied framework and finishing materials (excluding equipment) of 95 buildings in Japan. Moreover, based on the analysis results, this study aims to clarify the dominant factors by material and process and to consider measures to reduce them.

This study is characterized by its examination of a large number of cases—95 in total—reflecting Japan's actual conditions compared to past studies. Based on this, the novelty of this research lies in its multifaceted evaluation, presentation of benchmarkable indicators, and proposal of reduction measures.

2. Method of Analysis

2.1. Target Buildings and System Boundaries

In this study, all buildings—designed after 2015—were actual buildings for which cost estimates were conducted by the company of the authors, and the authors owned all materials used in the buildings. Most buildings have already been completed; however, some are currently under construction or scheduled for construction (Table 1). This study focused on the structural framework and finishing materials of construction work, excluding temporary structures, equipment, exterior structures, and ancillary work. Although it

is important to include equipment and related materials, the available data are limited. However, many important insights can be gained by analyzing only the embodied framework and finishing materials; therefore, this study focused on these. The building lifespan was set at 65 years, which is the expected service life of these buildings at the time of design. The design process, as defined by the Japanese building standard stands for the Japanese Architectural Standard Specification 5 and structural design documents, requires that the planned service life of each component be clearly stated within the structural performance requirements to ensure its durability.

This study considered six facility types: logistics facilities, production facilities (factories), offices/government buildings, schools, hospitals, and residential. Many statistics published in Japan (for example, construction statistics) are often categorized. Therefore, this classification was adopted. Although the target number of buildings was 95, when divided by use, it ranged from 10 to 23, which is insufficient to draw a universal conclusion. However, we believe we can obtain a glimpse of some trends; therefore, we decided to use these data for analysis. Furthermore, the proportions of steel and reinforced concrete buildings for each use were approximately the same as the proportions of construction that began in Japan.

This study was conducted in Japan. Therefore, its geographic scope was Japan. The buildings in this study are located throughout Japan and are not limited to specific regions. Although regional variations in environmental emissions are possible, the analysis accounted for these fluctuations.

Table 1. Use and number of buildings examined.

Types of Buildings	Types of Structure			Total
	Steel	Reinforced Concrete	Hybrid Structure	
01_Logistics	11	1	7	19
02_Factory	18	4	1	23
03_Office	11	3	4	18
04_School	3	4	3	10
05_Hospital	4	7	3	14
06_Hotel and Residence	5	5	1	11
Total	52	24	19	95

2.2. Basic Methods

The assessment concept was based on International Organization for Standardization 21930 [43], which sets out rules for environmental declarations for buildings. Japan has also published LCA Guidelines for Buildings [3], which are based on ISO 14040 [44], 140044 [45], and ISO 21930, and include additional considerations for assessing Japanese buildings. This study was also based on the guidelines.

In this study, the environmental impacts of the main disclosure items required by ISO 21930 were calculated. Furthermore, calculations based on this alone would lead to results for many impact areas, such as climate change, acidification, and photochemical ozone. Therefore, considering that it would be difficult to efficiently grasp the environmental impacts of buildings, a single indicator (weighting) was also evaluated.

This section describes the background of the database used for the assessment. For the inventory analysis, we used inventory database for environmental analysis (IDEA) ver. 3.4.1 [46], which is one of the largest databases in Japan. IDEA is an inventory database primarily targeted at Japan. Since version 3.4, IDEA has published inventory data compatible with ISO 21930.

We used the life cycle impact assessment method based on endpoint modeling 2 (LIME2) and LIME3 (the latest version at the time of the study) [47] to calculate the impact and weighting (integration). LIME2 can conduct impact assessments within Japan. Characterization, damage assessment, and integration coefficients were established, and various assessments can be performed using the inventory analysis results from IDEA. However, LIME3 is globally compatible, and damage assessments and integration coefficients for each country have been established; the characterization results of LIME3 are not publicly available. Therefore, characterization was performed using the coefficients from LIME2. Damage assessment and integration were analyzed using LIME2 and LIME3.

2.3. Target Processes

Based on the classification of ISO 21930, this study focused on nine processes: A1–3 (production), A4 (transportation), A5 (installation), B3 (repair), B4 (replacement), C1 (demolition), C2 (transportation), C3 (waste processing), and C4 (disposal of waste). Operational processes B1 (use), B2 (maintenance), B6 (energy use), and B7 (water use) were excluded from this study. Furthermore, renovations to B5 (refurbishment) were not anticipated. This study focuses on the building structure and finishing materials, but not on facilities. Therefore, the energy and water consumption during operation were also excluded.

2.4. Data Sources

Table 2 lists the data sources used here. For A1–3, the amount of construction material used in each building was determined using estimated data for each building. The environmental impact was calculated by multiplying the amount of input material by the background data. For A4, the Logistics Census and statistical data published by the Ministry of Land, Infrastructure, Transport, and Tourism of Japan [48] were used to estimate the transport distance for each material type. For example, the distances of wood, ceramic, and metal building materials were 170, 72, and 228 km, respectively. For A5, energy consumption data from 19 buildings constructed by a construction company were utilized; specifically, electricity was 10.19 kWh/m², kerosene 0.4 L/m², diesel 13.49 L/m², and heavy oil A 0.0005 MJ/m². For B3 and B4, the number of repairs and renewals was calculated using the building life cycle management data collection (BELCA) [49], which includes repair rates and useful lives for building materials. The number of repairs and renewals over the life cycle of buildings was calculated using these data and the useful life data of buildings.

For C1 to C4, the construction by-product survey published by the Ministry of Land, Infrastructure, Transport, and Tourism of Japan [50] was used, which lists the average transport distances for waste in Japan. For example, concrete blocks are 15.5 km, scrap metal 23.9 km, wood chips 27.9 km, and other waste (landfill) 26.2 km. Calculations were performed assuming loading rates of 100 and 0% for the outbound and return journeys, respectively. The separate collection and recycling rates were set as 0.99 for concrete blocks (roadbed material), 0.99 for scrap metal (metal resources), 0.9 for wood chips (incineration), and 0 for other waste (landfill). For gypsum board, for which sufficient information was not available in this statistic, a value of 0.5 was set based on the Gypsum Board Handbook [51].

Table 2. Data sources used.

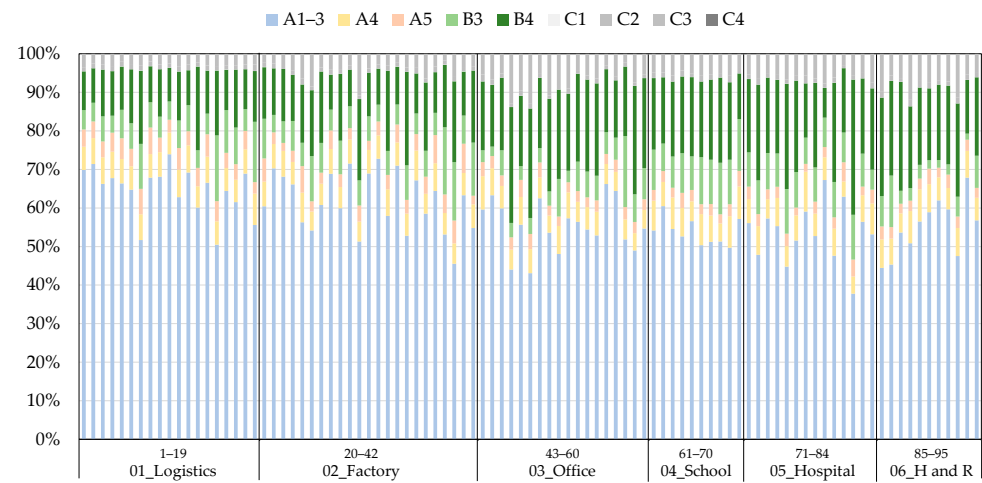
		Stage	Condition
A	Production	A1 Extraction and upstream production	Set input material data based on actual building calculation data.
		A2 Transport to factory	
		A3 Manufacturing	
	Construction	A4 Transport to site	Set by material based on statistical data (logistics census)
		A5 Installation	Set based on the average value of past performance data (19 cases)
B	Use	B1 Use	Not included
		B2 Maintenance	Not included
		B3 Repair	Set based on literature (BELCA)
		B4 Replacement	Set based on literature (BELCA)
		B5 Refurbishment	No renovations will be carried out.
		B6 Operational energy use	Not included
		B7 Operational water use	Not included
C	End of life	C1 Deconstruction/Demolition	Extract energy consumption associated with demolition based on literature values (IDEA standard units) and set energy consumption per square meter.
		C2 Transport to waste processing or disposal	Set transportation distances for each type of waste based on statistics (survey of construction by-products).
		C3 Waste processing	Based on statistics (survey of construction by-products), set waste separation and recycling rates for each type of material.
		C4 Disposal of waste	

Note: BELCA (building life cycle management data collection).

3. Results and Discussions

3.1. Breakdown Analysis by Life Cycle Process

Figures 1–3 show the results of the analysis for the entire target area, including GHG emissions and integration using LIME2 and LIME3. Marked variations were observed in each case. For GHG emissions (Figure 1), A1–3 and B4 accounted for 50–70 and 10–20%, respectively. For the integration using LIME2 (Figure 2), A1–3, B4, and C1–4 accounted for 30–40, 20–30, and 20–40%, respectively. For integration using LIME3 (Figure 3), A1–3 and C1–4 accounted for 40–60 and 10%, respectively. The results for C1–4 were markedly affected by the recycling rate, and the impact of landfilling C4 was particularly notable.



"H and R" means Hotel and Residence.

Figure 1. GHG by building.

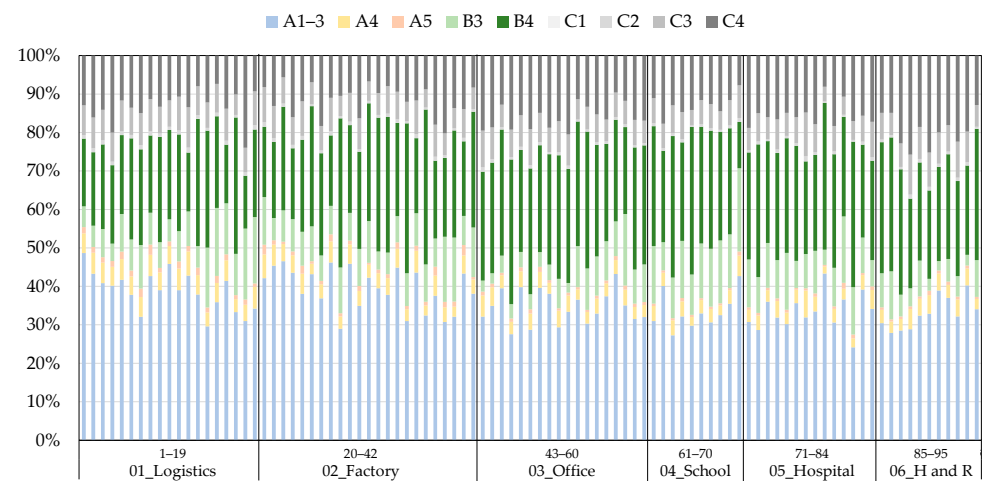


Figure 2. Integration (LIME2) by building.

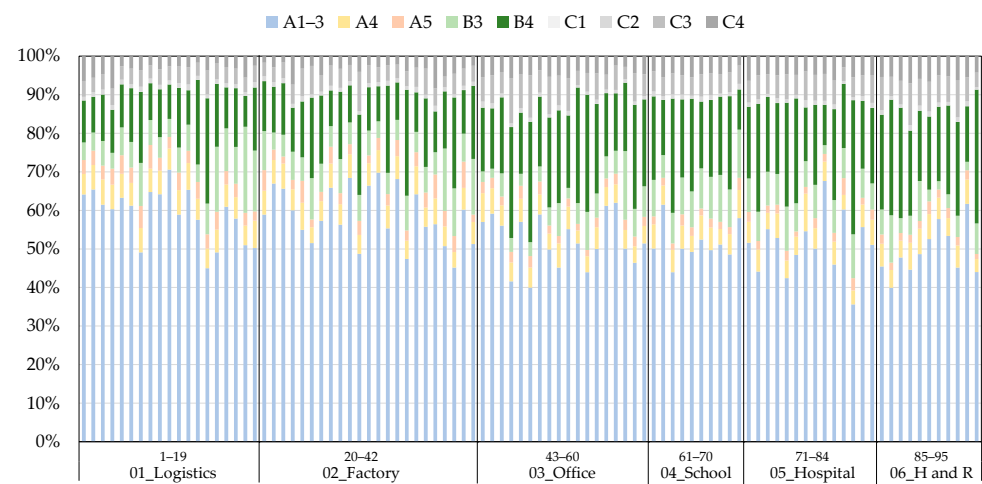
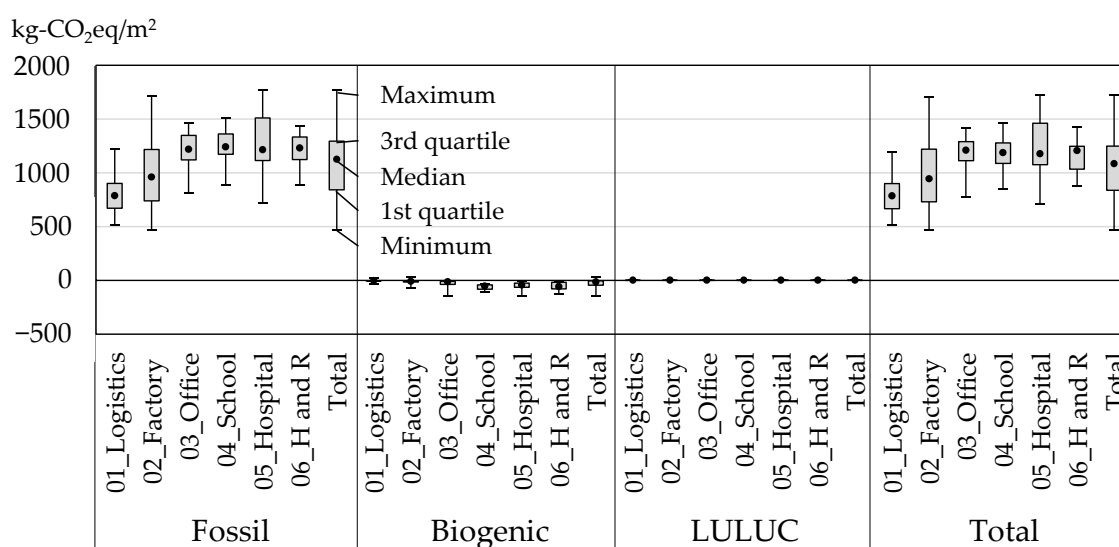


Figure 3. Integration (LIME3) by building.

3.2. Variation Analysis by Application

3.2.1. LCIA (Life Cycle Impact Assessment) Results

The results in Section 3.1 revealed considerable variations among the buildings. Based on this, we examined the variations in the use of each environmental load substance, environmental impact assessment, and damage assessment/integration. First, we present the results of the environmental impact assessment by characterization (Figures 4–8). Because the characterization coefficients are only available for LIME2, we present them. We present the results for climate change, ozone layer destruction, acidification, photochemical ozone, and eutrophication as required by ISO 21930. Overall, logistics and factories tended to be small. We also confirmed that the variations among buildings were substantial. These results can serve as a benchmark for the environmental impacts of buildings in Japan.



“LULUC” means Land Use, Land Use Change.

Figure 4. Greenhouse gas emissions by building type.

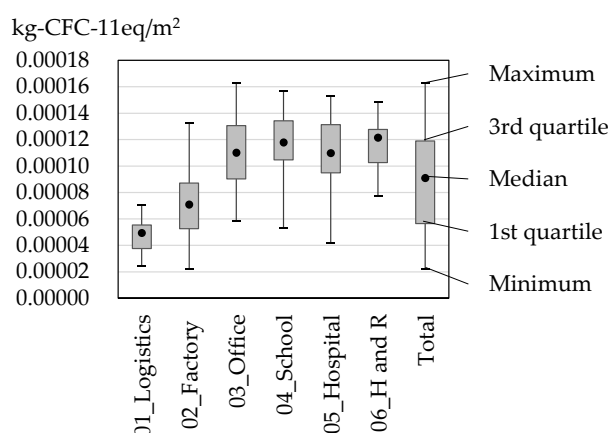


Figure 5. Ozone layer destruction.

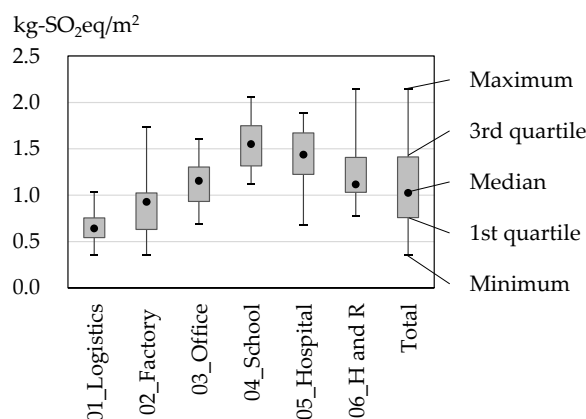


Figure 6. Acidification.

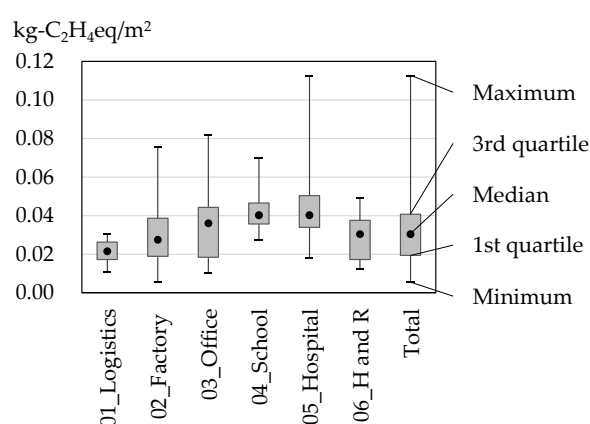


Figure 7. Photochemical ozone.

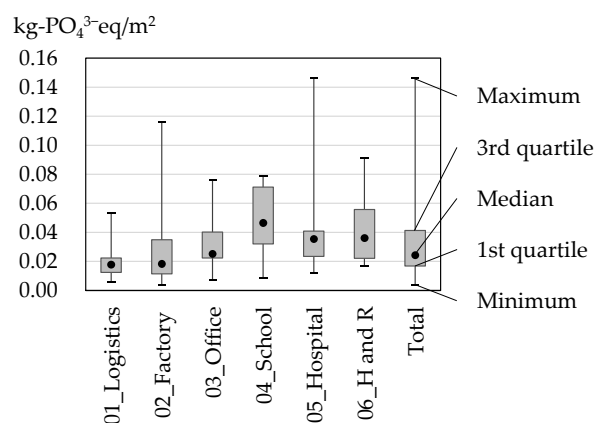


Figure 8. Eutrophication.

(1) Climate change (GHG)

Figure 4 shows the climate change results, including factors such as fossil fuels, bio-fuels, and land use, land use change (LULUC). Our analysis revealed that fossil fuels had an overwhelmingly significant impact. Furthermore, biofuels consider variations in the balance of emissions from biomass fuel use, temporary absorption from wood, and emissions from wood waste incineration. If emissions and absorption are accounted for separately, the impact may not be negligible. LULUC was used to assess the impact of raw materials and energy production factory construction, and the results indicated a small impact, suggesting that reducing fossil fuel usage is essential.

The results for the use, logistics, and factories tended to be smaller overall. One possible reason for this is that these facilities have fewer partitions and require less input for interior and exterior materials than other facilities. Based on these results, we provide a detailed analysis of climate change in Section 3.3 and the subsequent sections.

(2) Other impact categories

Figure 5 shows the results for ozone layer destruction, Figure 6 for acidification, Figure 7 for photochemical ozone, and Figure 8 for eutrophication. These results demonstrate notable variations among the buildings. Furthermore, logistics and factories tend to have a smaller impact.

Ozone layer destruction (Figure 5) is influenced by chlorofluorocarbons and halons. This study also found that the impact of major raw materials and interior materials, such as aluminum sashes, ready-mix concrete, gypsum board, and steel frames, was greater than that of other materials. Furthermore, when examining the causes of ozone layer destruction for these materials, one example is grid-based electricity. Further reductions could include reducing material inputs and, where possible, extending the lifespan of input materials. Moreover, reducing electricity consumption in manufacturing processes could be an important perspective for further mitigating the impact of ozone layer destruction.

Acidification (Figure 6) was notably affected by SO_x and NO_x emissions, particularly those emitted during fuel combustion. The results also showed that ready-mix concrete, gypsum board, steel frames, and aluminum building materials had a significant impact. When examining the causes of acidification in these materials, we found that some, but not all, acidification was caused by coal and electricity. In some cases, the use of fuels that generate SO_x and NO_x was a contributing factor. Further reduction can be achieved by reducing the amount of material used and extending its lifespan. Reducing the use of fossil fuels and electricity in the material manufacturing process is also important. Procurement from facilities with highly efficient desulfurization and denitrification equipment is also an important approach.

Photochemical ozone (Figure 7) is influenced by compounds such as benzene and xylene. This study also found that metal products, such as steel frames, sashes, and shutters, tend to have a greater impact. Further reductions could include reducing the number of materials used and extending their lifespan.

Eutrophication (Figure 8) can be influenced by NH₄⁺, NO₂, and PO₄³⁻. This study found that products that use agricultural products in their production process tend to have a greater impact. For example, there were cases where agricultural products, such as vegetable oils, were used in small portions of resin products. However, the input amount was very small compared with that of the entire building; therefore, it may not have a notable impact.

3.2.2. LCI (Life Cycle Inventory) Results

The results showed that the use of primary and secondary resources and water consumption are major environmental load factors. These items must be disclosed according to the ISO 21930 standard.

(1) Use of primary and secondary resources

As shown in Figures 9 and 10, resource use is divided into primary and secondary resources, and each is further divided into renewable, non-renewable, non-raw materials, and raw materials. Items other than secondary materials (Figure 9) are expressed in MJ-NCV (lower heating value) units. Overall, consistent with the results of the environmental impact assessment, logistics and factories had a low environmental impact.

Regarding energy (non-raw materials), this study did not evaluate operational use; therefore, it only considered the energy used during material manufacturing, construction, and demolition and disposal. The results show that non-renewable energy sources, such as coal, oil, and gas, are overwhelmingly dominant. This is particularly true for materials that consume large amounts of energy when used in construction, such as steel frames, ready-mix concrete, and ordinary steel light rebar. There are also a considerable number of renewable primary energy sources (bio-based fuels, hydropower, solar power, and wind power). This refers to the renewable energy used in the production of building materials. These findings highlight the importance of reducing the use of non-renewable energy and transitioning to renewable energy sources. Additionally, although only a small amount, the use of renewable secondary fuels and recovered energy was observed.

The use of renewable primary resources (such as wood) is thought to depend on the amount of wood used. Non-renewable primary resources (such as plastic products) are thought to depend on the amount of plastic used in their production. The secondary materials (Figure 10) included scrap metal, concrete debris, glass waste, plastic, and wood. Here, the use of secondary materials in steel and aluminum building materials had a significant effect. The use of recycled materials is also important.

(2) Water resource consumption and waste

Figure 11 shows the water consumption results associated with the manufacturing, demolition, and disposal of building materials, but does not include water consumption during the use of B7. As a result, there were notable differences between buildings. Wood consumes large amounts of water, and water consumption during the growth process of trees may have a considerable impact. There were marked differences between buildings that used a large amount of wood for the interior and exterior materials and those that did not.

Figure 12 shows the results for non-hazardous waste that ultimately goes to the landfill after intermediate treatment with ready-mix concrete and gypsum board, notably impacting waste. It was assumed that 99% of the ready-mix concrete was recycled, and although only a small proportion was landfilled, the large amount generated indicated that the impact was considerable. It was also assumed that 50% of the gypsum board was landfilled. Improving this would lead to a marked reduction in environmental impact.

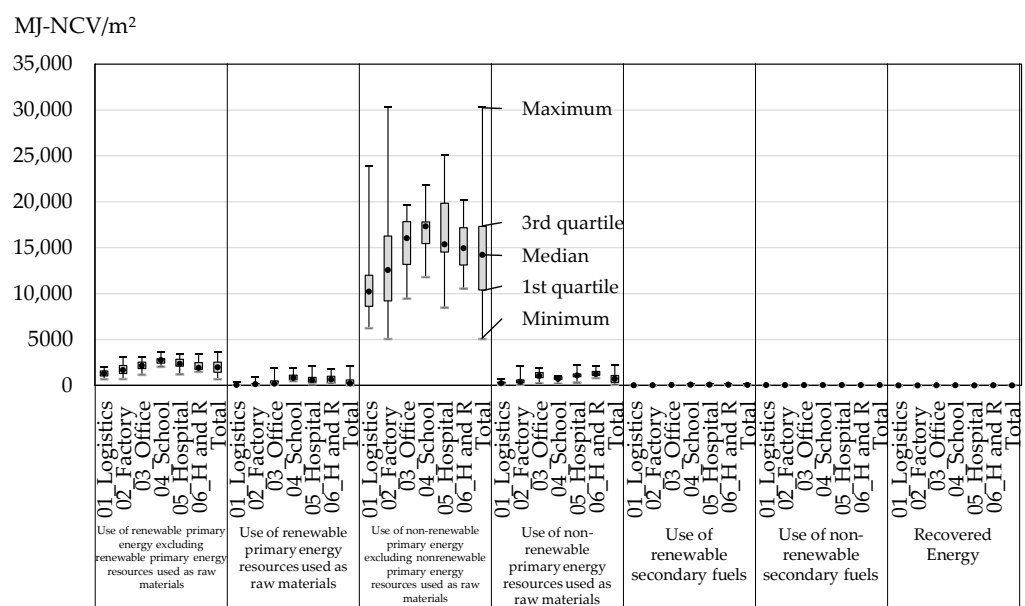


Figure 9. Use of primary and secondary resources.

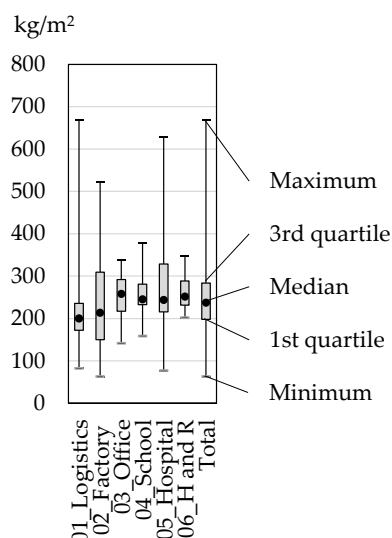


Figure 10. Use of secondary material.

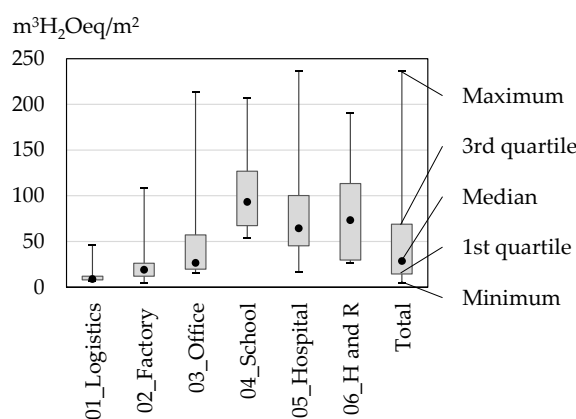


Figure 11. Water resource consumption.

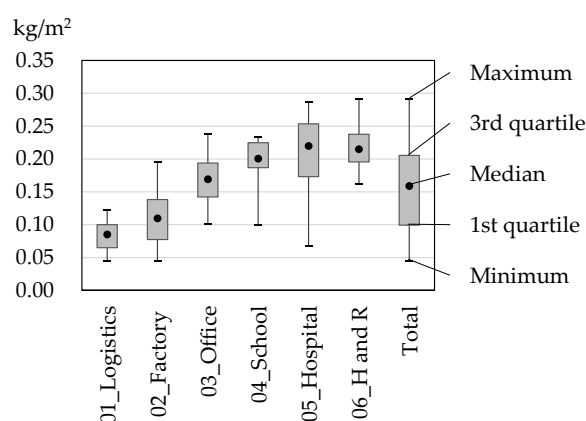


Figure 12. Waste.

3.2.3. Integration

In the previous section, we focused on the items that must be disclosed in accordance with ISO 21930. However, even among these, there are numerous environmental factors, and we believe it is essential to identify the dominant ones with the greatest overall impact. Therefore, we conducted a weighting using LIME, which is the most commonly used impact assessment method in Japan. This is a damage calculation method that weights and

integrates four protected areas—human health, social assets, biodiversity, and primary production.

Figures 13 and 14 show the results of the damage assessment and integration using LIME2 and LIME3. Note that while LIME3 can assess countries around the world, this analysis focused on “consumption country: Japan.” We confirmed that each of the protected areas—human health (climate change, air pollution, acidification, and photochemical ozone), social assets (resource consumption and waste), biodiversity (climate change, land use, resource consumption, and waste), and primary production (land use, resource consumption, and waste)—contributed notably to the integration results. The LIME2 results indicated a relatively large impact on biodiversity. One reason for this increase in biodiversity is climate change and waste. In LIME3, the impact on human health and social assets was significant. Human health is presumed to be affected by factors such as climate change, whereas social assets are thought to be affected by factors such as waste landfilling. In addition, the environmental load per floor area was generally low in logistics and production facilities. It was also confirmed that there was considerable variation between the buildings for each type of use. Based on these results, a detailed analysis is presented in Section 3.3.

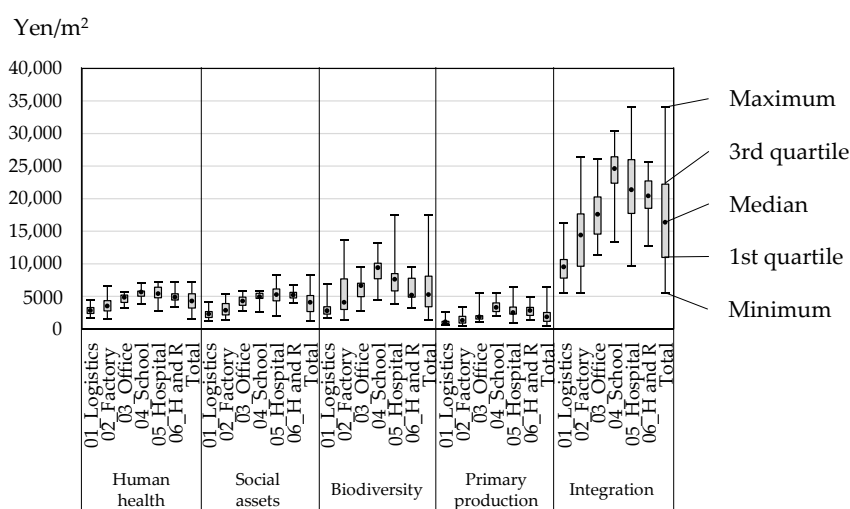


Figure 13. Integration (LIME2) by building type.

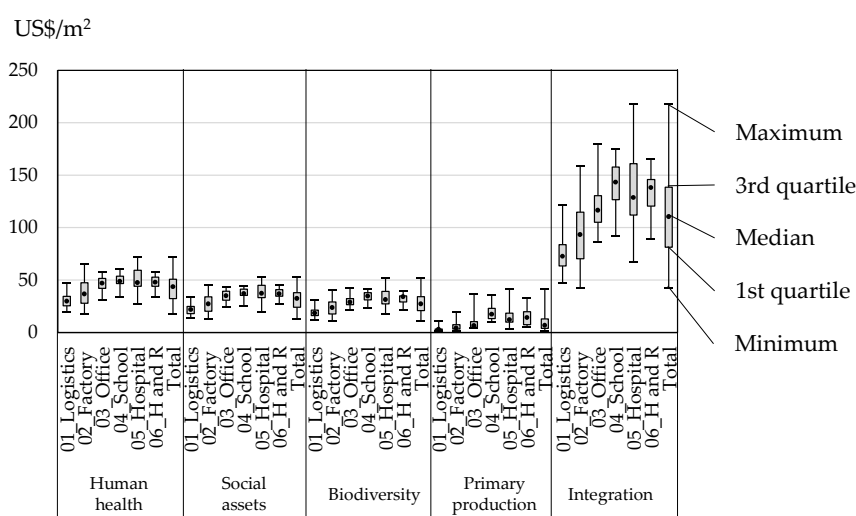


Figure 14. Integration (LIME3) by building type.

3.3. Analysis by Application and Material

To explore the causes of the variability noted in Section 3.2, the environmental impact of each material was analyzed. Therefore, we conducted a variability analysis of the major materials based on the application type. Figures 15–32 show the results for all processes by material type. This analysis focused on greenhouse gases (Figures 15–20), which are of particular social concern, and integrated indicators that combine various environmental impacts into a single index (LIME2; Figures 21–26 and LIME3; Figures 27–32). Materials with a contribution rate of 1% or more to the total emissions are shown.

From the perspectives of GHG emissions and integrated indicators (LIME2 and LIME3), we analyzed the materials with the highest contribution rates across all applications. The materials with particularly large environmental impacts include steel frames, ready-mix concrete, gypsum board, and ordinary steel light rebar. The results showed that the variability in the environmental impact of the material was extremely large for all applications. The large variation in steel, ready-mix concrete, and ordinary steel light rebar is likely due to the analysis including steel-framed, reinforced concrete, and mixed structures. In steel-framed structures, the environmental impact of ready-mix concrete and reinforcing bars can be small, whereas in reinforced concrete structures, the impact of the steel frame can be minimal.

Materials with large variations depending on their use were also analyzed. Shutters were relatively large in logistics and factories but were rarely seen in hospitals, hotels, and residences. This is considered to be a characteristic of building use. Sash doors and openings were also large in offices, schools, hospitals, hotels, and residences, but small in logistics and factories. Consequently, the amount of material input per unit area is reduced, which is believed to have lowered the environmental impact. Furthermore, because these partition walls are frequently replaced, they have a significant environmental impact throughout their life cycles. Additionally, these are often replaced, resulting in a large environmental impact over their life cycles.

Materials with large variations depending on the building were also analyzed. In particular, finishing materials tended to vary widely because the materials used depended on the building. Among these, wood products such as lumber and plywood have been cited as having a particularly large impact. In some cases, the impact on the integration results was particularly notable. Integration has a considerable effect on wood products through reforestation [52]. Here, calculations were based on the average reforestation rate in Japan (50%), and the impact was found to be extremely large.

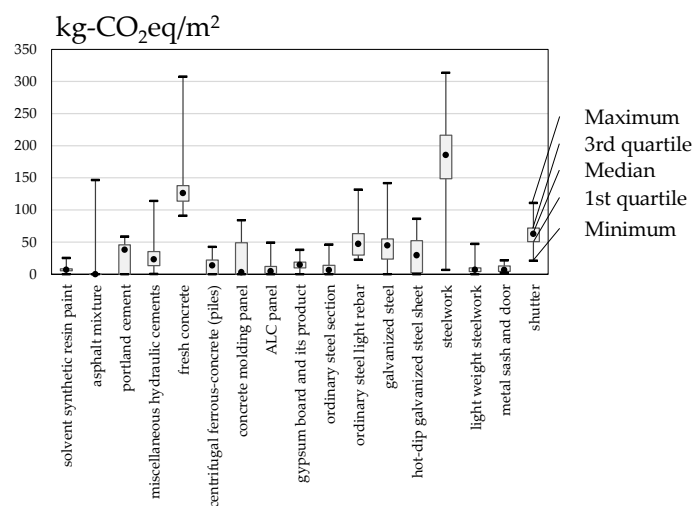


Figure 15. GHG in logistic.

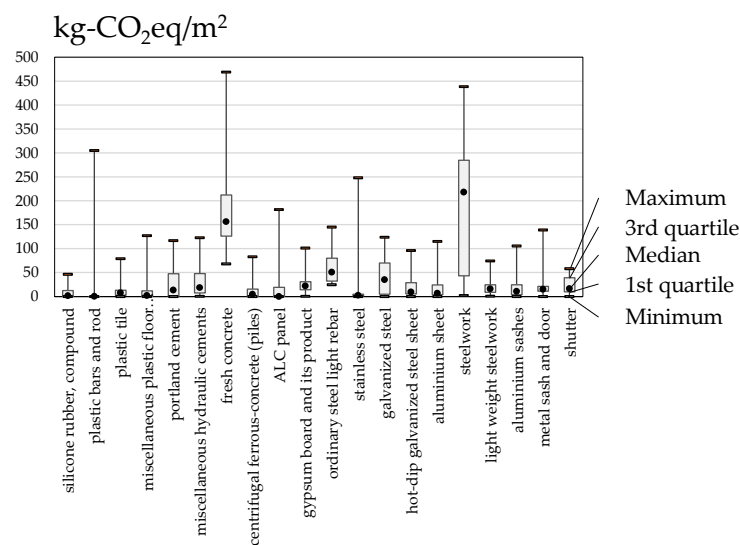


Figure 16. GHG in factories.

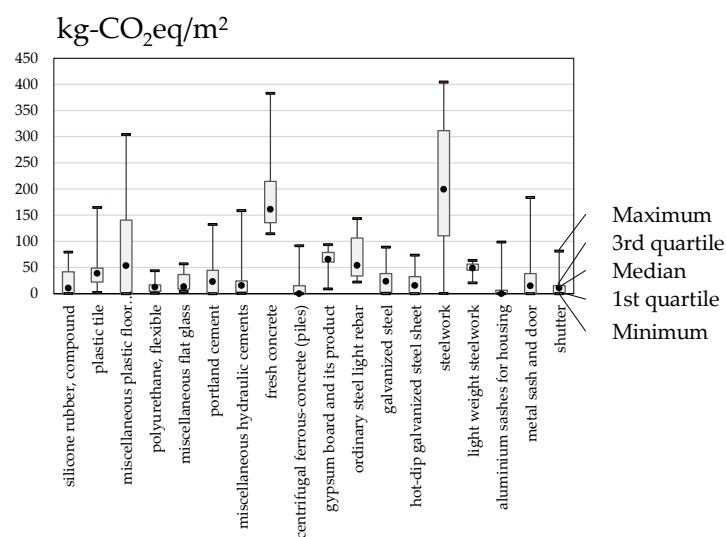


Figure 17. GHG in offices.

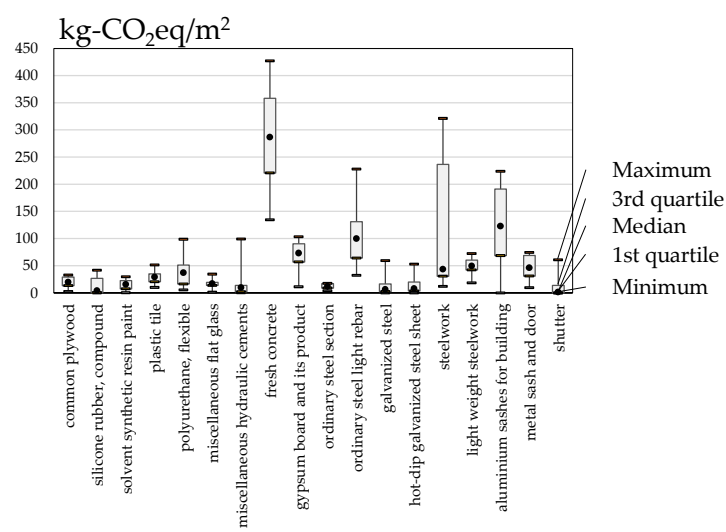


Figure 18. GHG in schools.

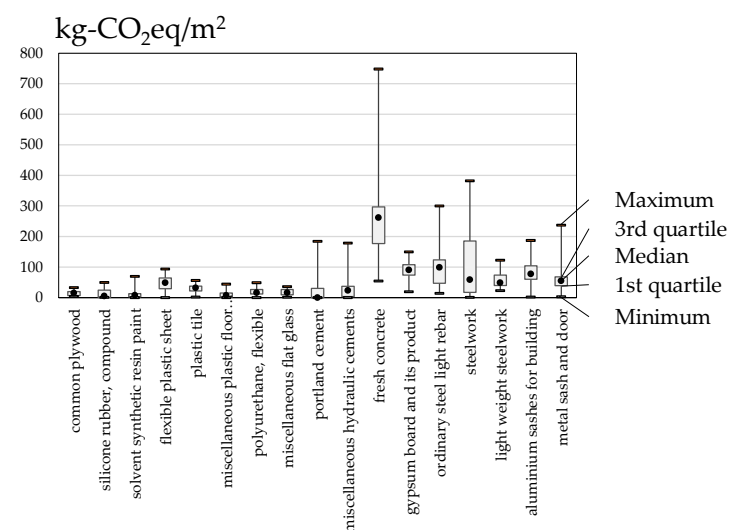


Figure 19. GHG in hospitals.

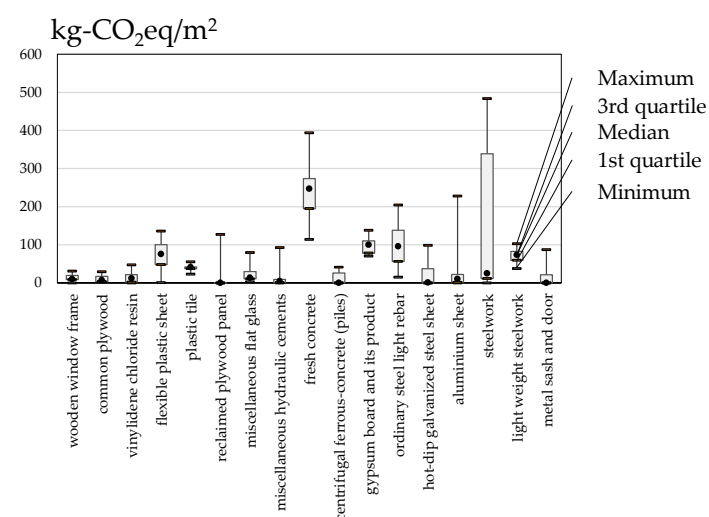


Figure 20. GHG in hotels and residence.

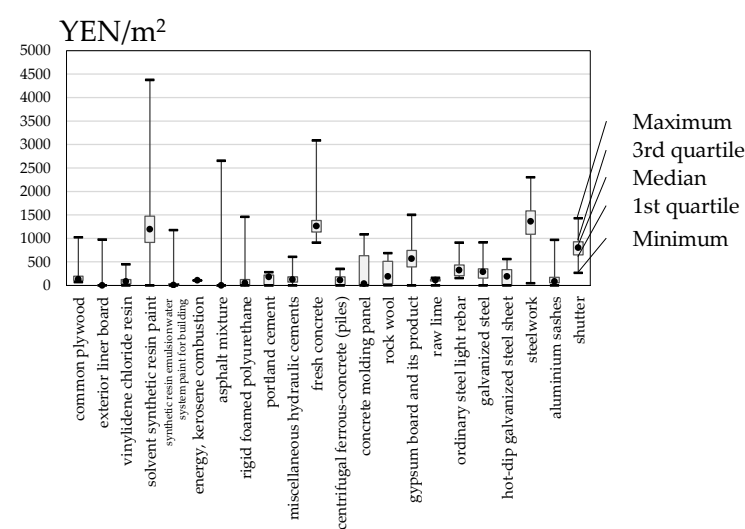


Figure 21. Integration (LIME2) in logistics.

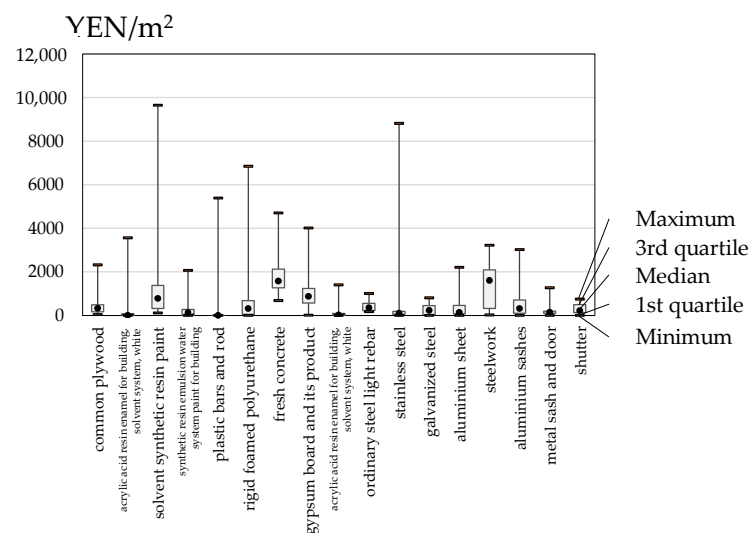


Figure 22. Integration (LIME2) in factories.

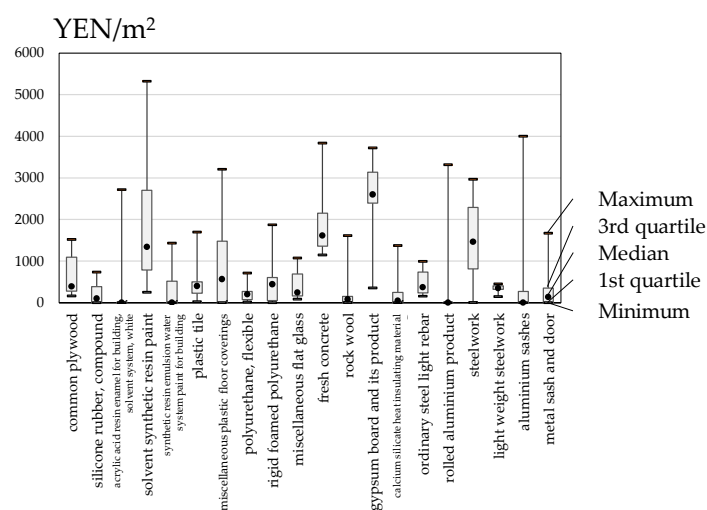


Figure 23. Integration (LIME2) in offices.

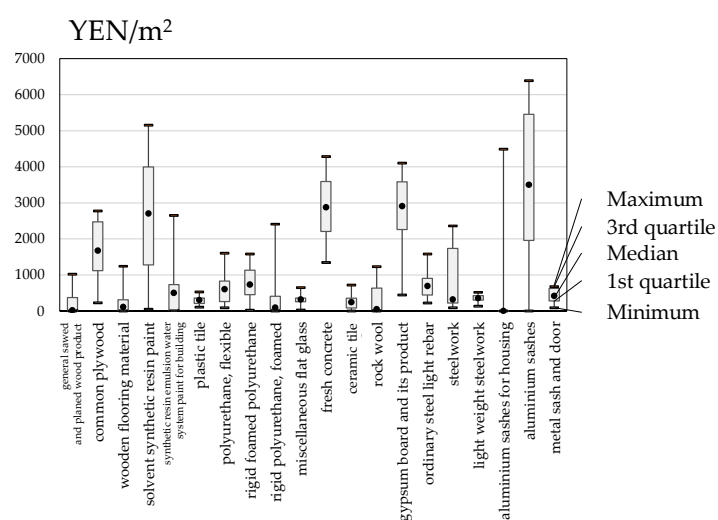


Figure 24. Integration (LIME2) in schools.

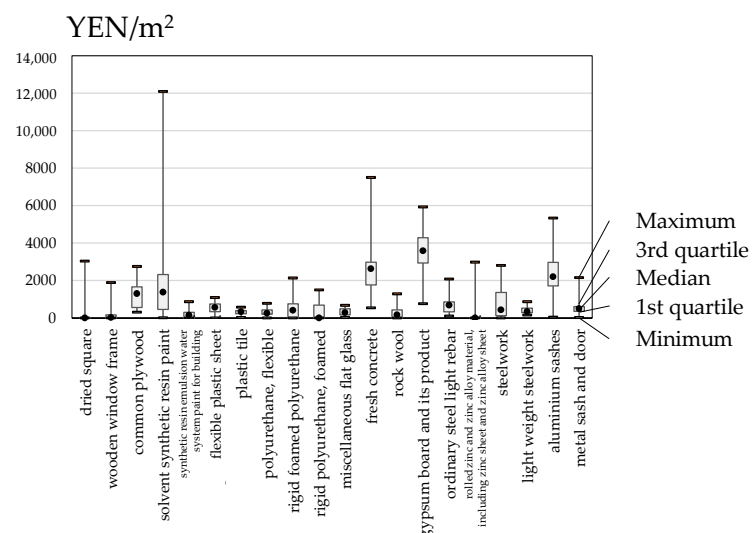


Figure 25. Integration (LIME2) in hospitals.

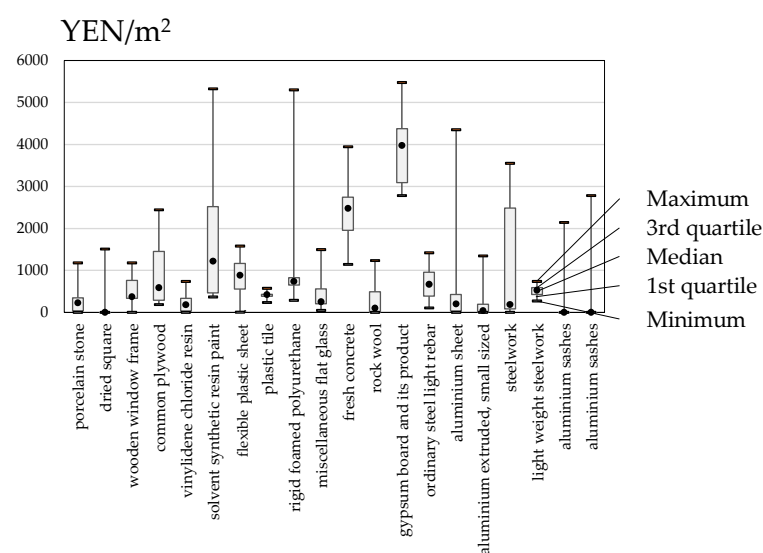


Figure 26. Integration (LIME2) in hotels and residence.

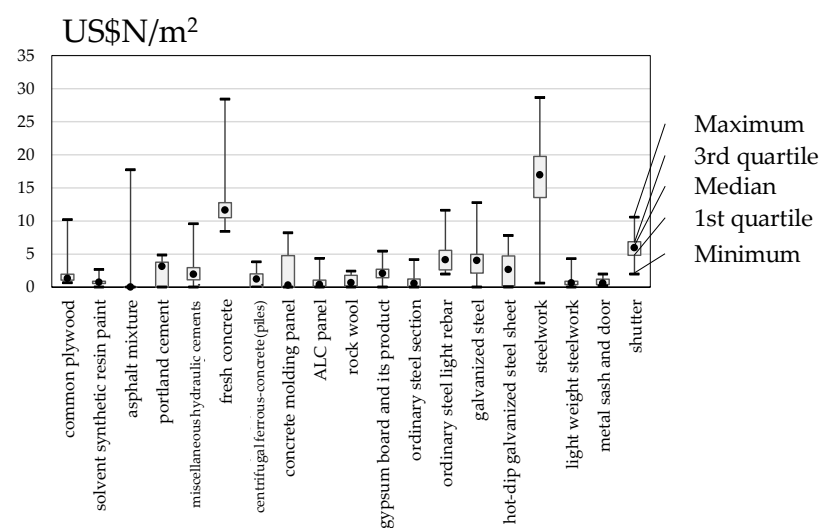


Figure 27. Integration (LIME3) in logistics.

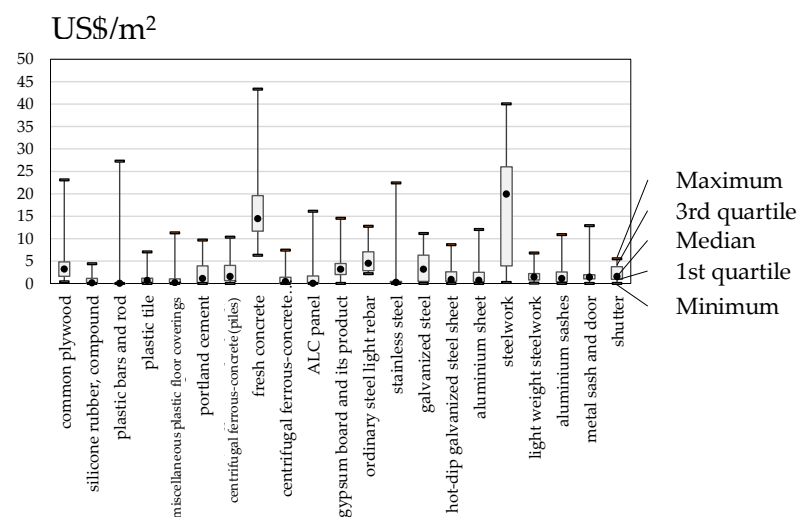


Figure 28. Integration (LIME3) in factories.

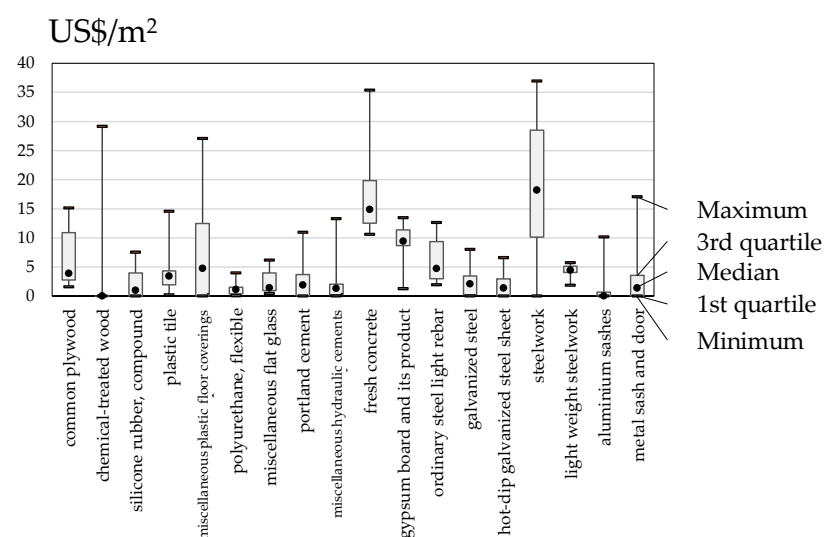


Figure 29. Integration (LIME3) in offices.

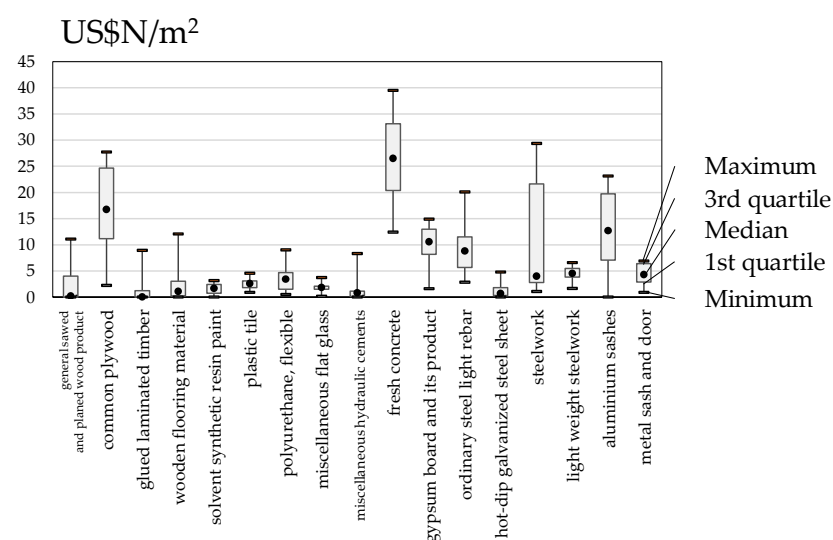


Figure 30. Integration (LIME3) in schools.

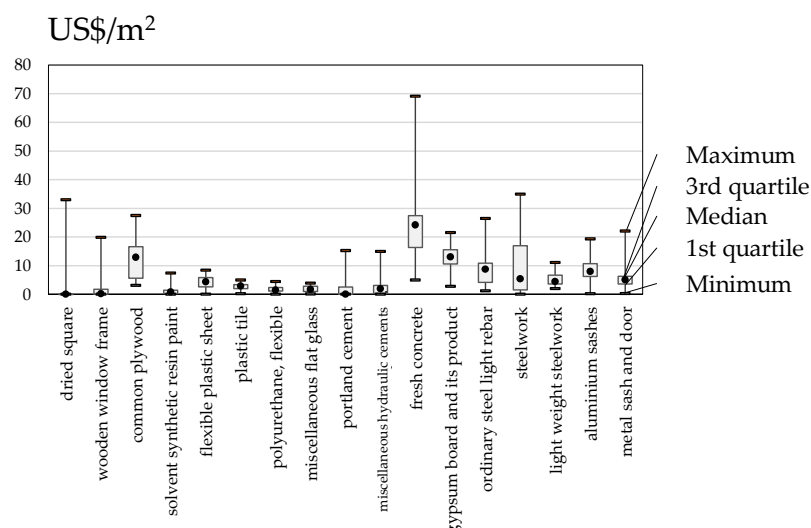


Figure 31. Integration (LIME3) in hospitals.

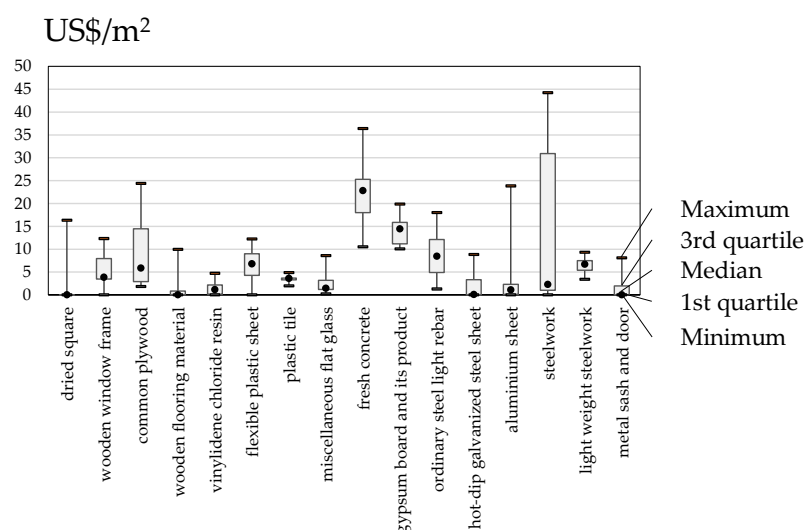


Figure 32. Integration (LIME3) in hotels and residence.

4. Analysis by Material and Process

Here, materials that had a notable impact on the analysis of GHG emissions and integration in LIME2 and LIME3 were analyzed using the life cycle process. In this analysis, we examined each IDEA product category rather than individual products. Therefore, when multiple product types were included in each category, the average was calculated.

In terms of GHG emissions (Figure 33), steel frames, ready-mix concrete, and ordinary steel light rebar contributed significantly to A1–B3, whereas shutters and sashes, which are frequently repaired and replaced, contributed significantly to B3 and B4. Therefore, it is important to reduce the environmental impact during the manufacturing stage and the amount of material input by extending the material life and improving yield.

In terms of integration (Figures 34 and 35), many materials showed similar results for both LIME2 and LIME3. Steel frames, small ordinary steel bars, and plywood were categorized as A1 to 3, shutters and sashes as B3 and B4, and items with a high proportion of landfill waste, such as gypsum board (assumed to be 50% landfilled) and plastics (assumed to be almost entirely landfilled), were categorized as C3 and C4. The impact of waste disposal is low, as it has a small impact on GHG emissions, although the trends differ slightly between LIME2 and LIME3. For steel frames, ordinary steel bars, plywood,

shutters, and sashes, it is important to reduce environmental impact during manufacturing and material input by extending product life and improving yield. For plywood, it is important to use timber to guarantee that reforestation occurs. For items such as gypsum boards, a design that considers recycling (ease of disassembly) is also important.

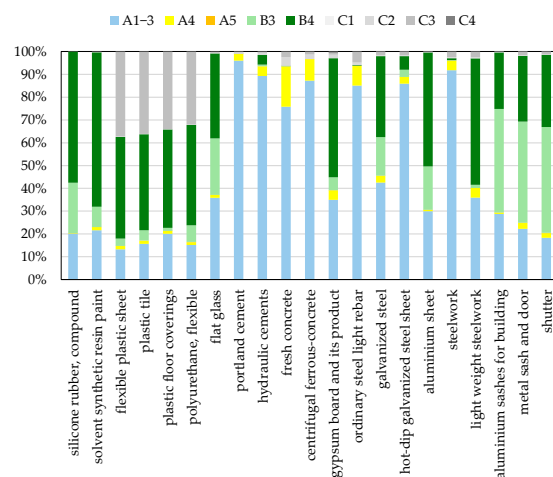


Figure 33. GHG by process.

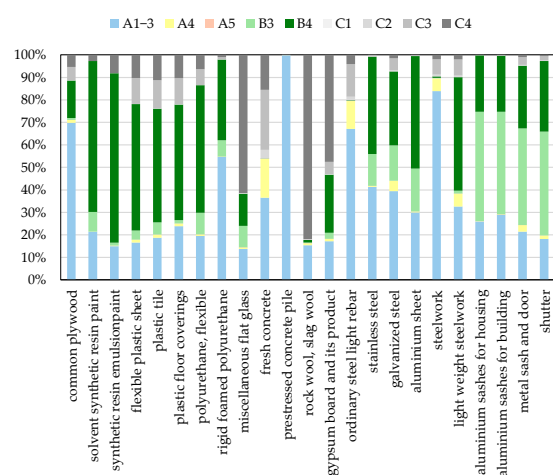


Figure 34. Integration (LIME2) by process.

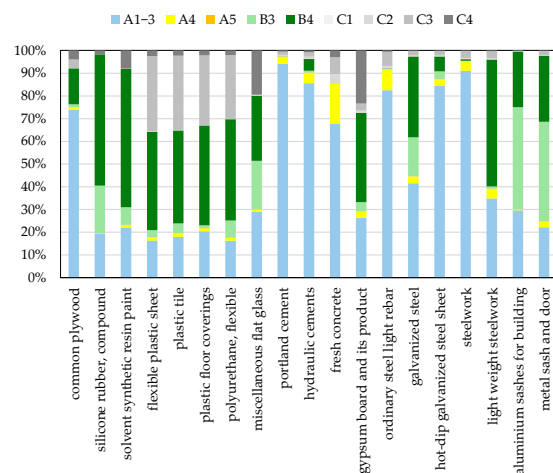


Figure 35. Integration (LIME3) by process.

5. Materials with Considerable Impact by Application and Process

Table 3 shows the top 10 items by average contribution rate to GHG emissions by application and the results of integration (LIME2 and LIME3). The materials with the highest contribution rates to GHG emissions across all applications included ready-mix concrete, steel frames, and ordinary steel light rebar. The integration of LIME2 and LIME3 showed high contribution rates for ready-mix concrete, steel frames, plywood, and gypsum boards across all end-use categories. By specific end use, shutters had a marked impact on logistics and factories; sashes in offices, schools, and hospitals; and wooden window frames in hotels and residences.

Table 3 underlines items that did not rank among the top 10 for GHG emissions but were included for the integrated analysis of LIME2 and LIME3. The high contribution rate of wood products, such as plywood, across all integrated analyses compared to GHG emissions, is likely due to insufficient reforestation. This is thought to have a notable impact on biodiversity and primary production, which are the targets of conservation. Furthermore, a tendency was observed for materials such as gypsum board to contribute more to the integration. This is because gypsum board and other materials notably contribute to C4 landfills. Therefore, the impact of consolidation is expected to be reduced by separating and collecting waste gypsum boards and other materials for recycling.

Table 3. Contribution rate of environmental impact by process (top 10 items).

Type	GHG Emissions	Contribution Ratio (%)	Integration (LIME2)	Contribution Ratio (%)	Integration (LIME3)	Contribution Ratio (%)
01_Logistics	Portland cement	3.6	<u>common plywood</u>	2.2	<u>common plywood</u>	3.1
	miscellaneous hydraulic cements	3.7	<u>solvent synthetic resin paint</u>	20.6	miscellaneous hydraulic cements	3.2
	fresh concrete	17.6	fresh concrete	13.1	fresh concrete	16.8
	concrete molding panel	2.8	concrete molding panel	2.7	concrete molding panel	2.8
	gypsum board and its products	2.2	<u>rock wool, slag wool, and its product</u>	2.6	gypsum board and its products	3.2
	ordinary steel light rebar	6.5	gypsum board and its products	6.4	ordinary steel light rebar	5.9
	galvanized steel	5.5	ordinary steel light rebar	3.4	galvanized steel	5.1
	hot-dip galvanized steel sheet	4.0	galvanized steel	2.7	hot-dip galvanized steel sheet	3.8
	steelwork	22.2	steelwork	12.1	steelwork	21.0
	shutter	8.5	shutter	8.1	shutter	8.4
02_Factories	Portland cement	2.6	<u>common plywood</u>	1.6	<u>common plywood</u>	3.6
	miscellaneous hydraulic cements	2.2	<u>solvent synthetic resin paint</u>	6.3	Portland cement	2.2
	fresh concrete	14.6	<u>rigid foamed polyurethane</u>	4.0	miscellaneous hydraulic cements	1.8
	gypsum board and its products	2.6	fresh concrete	6.6	fresh concrete	13.6
	ordinary steel light rebar	5.4	gypsum board and its products	4.6	gypsum board and its products	3.7
	galvanized steel	4.9	ordinary steel light rebar	1.7	ordinary steel light rebar	4.8
	steelwork	20.4	<u>stainless steel</u>	2.4	galvanized steel	4.4
	lightweight steelwork	1.8	steelwork	6.8	steelwork	18.7

03_Offices	metal sash and door	1.9	<u>aluminum sashes for buildings</u>	2.0	metal sash and door	1.8
	shutter	3.7	shutter	2.2	shutter	3.6
	plastic tile	3.2	<u>common plywood</u>	5.0	<u>common plywood</u>	7.2
	miscellaneous plastic floor coverings	5.3	<u>solvent synthetic resin paint</u>	7.9	plastic tile	2.7
	Portland cement	2.2	miscellaneous plastic floor coverings	3.7	miscellaneous plastic floor coverings	4.5
	fresh concrete	18.2	<u>rigid foamed polyurethane</u>	3.3	fresh concrete	16.2
	centrifugal ferrous-concrete (piles)	4.1	fresh concrete	12.2	centrifugal ferrous-concrete (piles)	3.6
	gypsum board and its products	4.3	centrifugal ferrous-concrete (piles)	2.3	gypsum board and its products	5.9
	ordinary steel light rebar	6.8	gypsum board and its products	11.3	ordinary steel light rebar	5.8
	steelwork	13.8	ordinary steel light rebar	3.2	steelwork	12.2
04_Schools	lightweight steelwork	3.1	steelwork	6.8	lightweight steelwork	2.8
	metal sash and door	2.2	<u>aluminum sashes for housing</u>	2.8	metal sash and door	2.0
	common plywood	1.7	<u>common plywood</u>	6.7	<u>general sawed and planed wood product</u>	1.9
	plastic tile	2.3	<u>solvent synthetic resin paint</u>	11.9	<u>common plywood</u>	12.4
	polyurethane, flexible	3.2	polyurethane, flexible	2.4	polyurethane, flexible	2.5
	fresh concrete	23.5	<u>rigid foamed polyurethane</u>	2.8	fresh concrete	18.7
	gypsum board and its products	5.5	<u>rigid polyurethane, foamed</u>	10.3	gypsum board and its products	6.8
	ordinary steel light rebar	8.9	fresh concrete	10.9	ordinary steel light rebar	6.7
	steelwork	9.2	gypsum board and its products	10.1	steelwork	7.2
	lightweight steelwork	3.9	ordinary steel light rebar	2.9	lightweight steelwork	3.0
05_Hospitals	aluminum sashes for buildings	9.7	steelwork	3.1	aluminum sashes for buildings	8.6
	metal sash and door	4.5	aluminum sashes for buildings	12.8	metal sash and door	3.6
	flexible plastic sheet	3.9	<u>common plywood</u>	5.8	<u>common plywood</u>	9.3
	Portland cement	2.7	<u>solvent synthetic resin paint</u>	9.9	<u>flexible plastic sheet</u>	3.2
	miscellaneous hydraulic cements	2.8	<u>flexible plastic sheet</u>	2.5	miscellaneous hydraulic cements	2.2
	fresh concrete	21.7	<u>rigid foamed polyurethane</u>	2.3	fresh concrete	18.2
	gypsum board and its products	7.4	fresh concrete	12.1	gypsum board and its products	9.7
	ordinary steel light rebar	8.1	gypsum board and its products	16.5	ordinary steel light rebar	6.5
	steelwork	8.6	ordinary steel light rebar	3.1	steelwork	7.1
	lightweight steelwork	4.9	steelwork	3.5	lightweight steelwork	4.0
05_Hospitals	aluminum sashes for buildings	6.7	aluminum sashes for buildings	10.7	aluminum sashes for buildings	6.3

06_Hotels and Residence	metal sash and door	5.2metal sash and door	2.6metal sash and door	4.4
	flexible plastic sheet	4.5% <u>wooden window frame</u>	2.3 <u>wooden window frame</u>	3.7
	plastic tile	3.9 <u>common plywood</u>	5.2 <u>common plywood</u>	7.9
	rigid foamed plastic thin sheet	1.9 <u>solvent synthetic resin paint</u>	7.5 <u>chemically treated wood</u>	2.7
	fresh concrete	18.5flexible plastic sheet	3.0flexible plastic sheet	3.5
	concrete molding panel	3.0rigid foamed polyurethane	6.0plastic tile	3.0
	gypsum board and its products	7.4fresh concrete	10.4fresh concrete	14.8
	ordinary steel light rebar	7.7gypsum board and its products	16.6gypsum board and its products	9.3
	aluminum sheet for building material	2.0ordinary steel light rebar	3.0ordinary steel light rebar	5.9
	steelwork	13.5steelwork	5.6steelwork	10.7
	lightweight steelwork	5.5 <u>aluminum sashes for buildings</u>	2.6lightweight steelwork	4.3

Note: rebar (reinforced bar).

6. Environmental Impact Reduction Measures

Based on the results of our previous study, we attempted to organize perspectives for reducing the environmental impact of materials through life cycle processes (material manufacturing, design, construction, repair/renewal, and demolition/disposal). Although various countermeasure perspectives are possible, the results shown in Table 4 are merely examples, and we believe that one important perspective is also important.

Cement and concrete tend to have high environmental impacts on all buildings. This is significant in terms of GHG emissions and integration. By process, GHG emissions were notable during manufacturing (especially cement manufacturing), whereas disposal/processing was notable during integration (especially LIME2). From the perspective of material manufacturers, this suggests that alternative fuels (switching from thermal coal) should be considered for cement clinker production. Furthermore, from a design perspective, extending the lifespan of buildings and switching to Class B or blast furnace cement are important. Regarding demolition and disposal, although concrete mass is almost recycled entirely in Japan, the small amount of waste that is landfilled, owing to the high volume of waste generated, has a marked impact. Therefore, further recycling (avoiding landfills) is important.

Steel products, such as steel frames and small ordinary steel-reinforced bars, tend to have a high environmental impact on buildings. Furthermore, the environmental impact of product manufacturing is significant, including GHG emissions and product integration. From the perspective of steel production, alternative fuel sources for in-house power generation and renewable energy sources should be considered. From a design perspective, the extension of the lifespan of buildings and, where possible, switching to steel produced in electric furnaces should also be considered.

Gypsum boards tended to have a high environmental impact on all buildings. Furthermore, the environmental impacts of new construction and renovation are substantial in terms of both GHG emissions and integration. Based on this, in gypsum board manufacturing, the selection of low-impact gypsum raw materials (such as waste gypsum) and the increased use of waste gypsum boards should be considered where possible. From a design perspective, it is important to extend the lifespan of components and use dry construction methods to facilitate separation and recovery during demolition. Furthermore,

reducing scrap wood during repair and renovation (improving the yield) is important for new construction and retrofitting projects.

The environmental impacts of wood materials, such as lumber, plywood, and wooden building materials, vary greatly from building to building, with some cases resulting in extremely large environmental impacts. This is particularly true when wooden building materials are used as finishing materials. Furthermore, the impact was notably greater as a result of consolidation burden to the impact of reforestation. Therefore, the most important aspect from the perspective of producers is appropriate management (appropriate reforestation), and from the perspective of design and construction, timber must be properly managed. Furthermore, in production, the use of renewable energy in natural and artificial drying processes and construction and reducing the use of scrap wood are also important considerations.

Table 4 is merely an example, and it is important to discuss how reduction measures can be implemented based on these results and further analyses.

Table 4. Examples of measures to reduce environmental impacts.

Material Type	Material Manufacturer	Design	Construction	Repair and Replacement	Demolition and Disposal
Cement and Concrete	- Fuel change during cement clinker production (change from thermal coal)	- Extending the lifespan - Switching to Class B cement, blast furnace cement, etc., where possible - Saving design information (transmitting it so that the situation at the time of demolition can be understood)	- Reduction in leftover concrete (improvement of yield) - Improvement of procurement methods (reduction in transportation load)		- Further sorting and recycling (especially avoiding landfills)
Steel products	- Use of alternative fuels and renewable energy sources to the extent possible - In some products, making it easier to decompose impurities (products other than steel)	- Extending the lifespan - Where possible, use of steel produced in electric furnaces - Saving design information (transmitting information so that the input status can be understood when demolishing)	- Reduction in offcuts during construction (improvement of yield) - Improvement of procurement methods (reduction in transportation load)		- Further sorting and recycling (especially avoiding landfills)
Gypsum board	- Selection of gypsum raw materials to the extent possible (natural, desulfurized, by-produced phosphate) - Further utilization of waste gypsum board	- Extending the lifespan - Saving design information (transmitting information so that the input status can be known when dismantling)	- Reduction in offcuts during construction (improvement of yield) - Improvement of procurement methods (reduction in transportation load)	- Reduction in scrap materials for repairs and renewals (improvement of yield)	- Further sorting and recycling (especially avoiding landfills); Select dry construction methods
Aluminum building materials	- Use secondary ingots to the extent possible - Select facilities that have implemented environmental measures such as low GHG and desulfurization- Make it easy to decompose impurities (such as screws)	- Extending the lifespan - Saving design information (transmitting information so that the input status can be known when dismantling)	- Improving procurement methods (reducing transportation burden)		- Further sorting and recycling (especially avoiding landfills)

Wood (form-work)	- Use of properly managed timber (forestry businesses should reforest properly) - Use of natural drying in the drying process- Use of renewable energy for artificial drying	- Selecting products with a lower environmental impact (changing the type of material)	- Reduction in offcuts during construction (improvement of yield) - Improvement of procurement methods (reduction in transportation load)	- Further sorting and recycling (especially avoiding landfills)
Wood (general building material)	- Use of properly managed wood (forestry businesses should reforest appropriately) - Use of natural drying in the drying process- Use of renewable energy for artificial drying- Efficient use of adhesives (Note: GHG emissions during incineration are also affected) - Improvement of yield during product manufacturing	- Extending the lifespan - Saving design information (transmitting information so that the input status can be known when dismantling) - Selecting products with a lower environmental impact	- Reduction in offcuts during construction (improvement of yield) - Improvement of procurement methods (reduction in transportation load)	- Reduction in scrap materials for repairs and renewals (improvement of yield) - Further sorting and recycling (especially avoiding landfills)
Plastic materials	- Improved yield during product manufacturing	- Extending the lifespan - Saving design information (transmitting information so that the input status can be known when dismantling) - Selecting products with a lower environmental impact	- Reduction in offcuts during construction (improvement of yield) - Improvement of procurement methods (reduction in transportation load)	- Reduction in scrap materials for repairs and renewals (improvement of yield) - Further sorting and recycling (especially avoiding landfilling and simple incineration)

7. Conclusions

Here, we conducted an LCA on the embodied structure and finishing materials (excluding equipment) of 95 buildings in Japan and considered measures to reduce their environmental impact. Specifically, we conducted a multifaceted analysis focusing not only on GHG emissions but also on their characterization and integration. Based on the analysis results, we identified the dominant factors and considered the reduction measures. The following findings were obtained:

(1) Environmental loads for key environmental indicators by use

Each key environmental indicator was analyzed based on its use. The results quantitatively confirmed that analysis by use reduced the variance in environmental load per total floor area compared with when use was not limited. However, the analysis also confirmed that the variance was not small for any indicator. Furthermore, the environmental load per total floor area tended to be lower for production and logistics facilities. It tended to be larger in offices, schools, hospitals, hotels, and residences, likely due in part to their greater use of interior partitions and interior and exterior materials.

In the characterization analysis, GHG emissions were overwhelmingly dominated by fossil-fuel emissions. Ozone layer destruction, acidification, and photochemical ozone are frequently and significantly affected by the major construction materials used. However, eutrophication is considerably affected by specific materials.

Damage assessment and integration were performed using LIME2 and LIME3 models. In both cases, no indicators showed extremely small impacts on human health, social assets, biodiversity, or primary production; all had some degree of impact. LIME2 had a relatively large impact on biodiversity, possibly due to climate change and waste. In LIME3, the impact on human health and social assets was large, with human health presumably affected by climate change and social assets affected by factors such as waste landfills.

These results can serve as a benchmark for the environmental impact of buildings in Japan.

(2) Environmental load by material

This study identified materials with a tendency toward higher GHG emissions and integration, and examined the factors behind these increases. Major structural materials such as steel frames, ready-mix concrete, and ordinary steel light rebar tend to exhibit high emissions across all applications. However, there was considerable variation between the buildings. Furthermore, metal sashes and doors, which are frequently replaced, have a notable impact as interior and exterior materials have a greater impact.

(3) Environmental impact by process

Processes with high environmental impacts by material were quantitatively identified, focusing on GHG emissions and integration.

Regarding GHG emissions, steel frames, ready-mix concrete, and ordinary steel light rebar were classified as A1–3, while shutters and sashes, which require frequent repair and replacement, were classified as B3 and B4.

Regarding integration, steel frames, ordinary steel light rebar, and plywood were classified as A1–3; shutters and sashes were classified as B3 and B4; and gypsum board (assumed to be 50% landfilled) and plastics (assumed to be almost entirely landfilled), with a high percentage of landfill waste, were classified as C4.

(4) Consideration of measures to reduce environmental impacts

Based on the results, perspectives for reducing the environmental impact of materials throughout the life cycle process are proposed. Although various measures are possible, the contents proposed in Table 4 are only one example and are considered an important perspective. Specifically, we provide examples of measures for cement/concrete, steel products, gypsum board, aluminum products, and wood products for each life cycle process: manufacturing, design/construction, repair/renewal, and demolition/disposal.

Buildings create a significant environmental burden, both in Japan and globally. Buildings are constructed globally using a combination of materials and technology. The factors that cause environmental burdens are diverse. Based on the results of this study, it is essential that stakeholders from across the building life cycle communicate and have deep discussions on ways to reduce environmental burdens.

This study proposes countermeasures for each stakeholder based on an environmental impact analysis. However, it is essential to identify the priority order of countermeasures to be implemented through optimization and sensitivity analyses. Furthermore, a comprehensive decision-making perspective that accounts for environmental factors and costs (e.g., using AECIE) is crucial.

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Abbreviations

The following abbreviations are used in this manuscript:

BELCA	Building and Equipment Long-life Cycle Association
CLT	Cross Laminated Timber
DCP	Decision Choices Procedure
IDEA	Inventory Database for Environmental Analysis
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LIME	Life Cycle Impact Assessment Method based on Endpoint modeling
LULUC	Land use, land use change

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