


Article

Environmental Impacts of Building Construction Using Cross-laminated Timber Panel Construction Method: A Case of the Research Building in Kyushu, Japan

Katsuyuki Nakano ^{1,*} , Masahiko Karube ² and Nobuaki Hattori ^{3,*}

¹ College of Policy Science, Ritsumeikan University, Ibaraki 567-8570, Japan

² Department of Wood Engineering, Forestry and Forest Products Research Institute, National Research and Development Agency of Forest Research and Management Organization, Tsukuba 305-8687, Japan; karube@ffpri.affrc.go.jp

³ Faculty of Agriculture, Tokyo University of Agriculture and Technology, Fuchu 183-8509, Japan

* Correspondence: nakanok@fc.ritsumeai.ac.jp (K.N.); hattori@cc.tuat.ac.jp (N.H.)

Received: 20 February 2020; Accepted: 11 March 2020; Published: 12 March 2020



Abstract: In Japan, there has been an increase in the number of buildings built using cross-laminated timber (CLT) in order to utilize the abundant forest resources in the country. However, no studies have evaluated the environmental impact of the construction of CLT buildings in Japan. This study evaluates the environmental impacts from the start of construction to the completion of a real CLT building in Kumamoto city, Kyushu region, southern Japan. We investigated the input of the materials and energy used in the construction of the building. The environmental impact categories evaluated include climate change, ozone layer depletion, eutrophication, acidification, and photochemical oxidation. We found that the concrete used for the foundations, and the cement-based soil stabilizer used for ground reinforcement accounted for 42% of the greenhouse gas (GHG) emissions. The construction site was previously used as a seedbed field, necessitating ground reinforcement. Furthermore, the large foundations were designed in order to raise the low height of the wooden structure from the ground level. Developing and applying methods with lower environmental impacts for ground reinforcement and building foundations is recommended. In addition, we found that by using biomass-derived electricity in CLT manufacturing, the environmental impacts of CLT manufacturing could be reduced, thus reducing the environmental impacts of the entire building. The biogenic carbon fixed in the wooden parts during the building usage accounted for 32% of the total GHG emissions of the building construction. Since this biogenic carbon will be released to the atmosphere at the end-of-life stage of the building, a long-term usage of the CLT buildings and/or reuse of the CLT is recommended.

Keywords: life cycle assessment (LCA); cross-laminated timber (CLT); cradle-to-installation; wooden building; environmentally conscious design; biogenic carbon; construction

1. Introduction

Wooden buildings are a common part of architecture in Japan. Wooden buildings account for 42% of the floor area of new housing and buildings in Japan [1]. In 2010, the government introduced the “Act for Promotion of Use of Wood in Public Buildings”, which aims to establish a practice of using timber for building widely in society. Under the Act, the government and related organizations take initiatives for using wood for public buildings, etc. The main policy of the Act states that “the Government to construct all the public buildings of three stories or lower with wood structure in principle” [2].

Until recently, timber was used for the construction of low-rise buildings, typically detached houses. In recent years, the number of mid- and high-rise timber buildings has increased, especially in Europe and North America, due to the growing interest in the environment. For example, the student dormitory (Brock Commons-Tallwood House, 18 stories, 53 m high) completed in 2017 in Vancouver, Canada, has a mixed structure with reinforced concrete; however, the walls and floors are mostly made of engineered wood, such as cross-laminated timber (CLT). In 2019, an 18-story building with a height of 85.4 m was completed in Brumundal, Norway, where all structural components (posts, beams, floors and walls) are made of wood. In Japan, construction of an 11-story seismic isolation structure (fire-resistant building) made entirely of wood will begin in March 2020.

The increase in the number of the high-rise wooden buildings is due to the improvements and dissemination of new technologies such as glued laminated timber. The strength of these materials is guaranteed and, being made of wood, these construction materials are relatively long and large in size. Since these materials are manufactured by laminating and bonding dried wood using an adhesive, they have a higher strength and stability, in both dimension and shape, than lumber. Hence, these materials can meet more generic needs when designing and constructing new buildings. However, there are concerns about the environmental impacts of the engineered wood production compared to lumber because of the complexity of the production processes, and the use of adhesives [3–7].

Life-cycle assessment (LCA) has been conducted to evaluate the environmental performance of buildings using CLT. Liu, Guo, Sun, et al. [8] and Guo, Liu, Meng, et al. [9] showed that, in cold regions of China, CLT buildings emit less greenhouse gases (GHG) than concrete and reinforced concrete (RC) buildings. Robertson, Lam and Cole [10] performed an LCA of the construction of a five-story CLT building in North America. Leskovar [11] discussed the influence of the building shape on the building's environmental performance. Dodoo, Gustavsson and Sathre [12] studied the primary energy consumption of the life cycle of CLT buildings in Sweden. Takano, Pal, Kuittinen, et al. [13] evaluated the energy consumption in the life cycle of hypothetical CLT building models in Finland buildings. Hafner and Schäfer [14] argued that the impact of carbon sequestration on CLT buildings is significant in the total GHG emissions during the life cycle.

Most of the LCA research of buildings has mainly focused on the efficiency and associated emissions of the operational phase; however, research interest is shifting to the construction phase due to energy-efficient operations [15]. Not only full life cycle (cradle-to-grave) assessment, but also cradle-to-gate or cradle-to-installation assessments of buildings, contribute to clarifying directions for environmentally conscious design [10,16,17].

The requirements for the fire-resistance and earthquake-resistance of buildings vary greatly from country to country. In Japan, the fire resistance required for structural materials differs depending on the location and scale of the building, and the presence of fire extinguishing equipment such as sprinklers is not included in the judgment of the fire-resistance ability of a building [18]. Hence, when constructing a building using engineered wood such as CLT, it is necessary to ensure fire resistance by, for example, covering the surface of the interior with gypsum board. Further, the required level of earthquake resistance in Japan is necessarily stricter than in other countries. The climate in Japan differs across the country. The climate in Kumamoto city in the Kyushu region of Japan is classified as humid subtropical climate and not subarctic like the climate in the Hokkaido region; the latter is similar to the climatic conditions in Canada and Sweden, where buildings should be able to withstand large loads of heavy snowfall. The timber buildings in the Kyushu region need appropriate protective measures in order to withstand a hot and humid climate. Due to these requirements, the environmental impacts of CLT buildings constructed in Japan may be greater than those of other countries and caused by different factors.

However, the environmental impacts caused by the construction of Japanese CLT buildings have not been reported. Thus, the aim of this study is to quantify the environmental impacts of the construction of a real CLT building and, based on this, suggest directions for an environmentally conscious design of future CLT buildings.

The remainder of this paper is structured as follows. Section 2 presents Materials and Methods, including the description of the building, system boundaries, and the methodology used for the environmental impact assessment in this study, as well as data collection. Section 3 presents the Results, including the impacts associated with the various stages of the construction process. Discussion (including recommendations for environmentally conscious design) and Conclusions are presented in Sections 4 and 5.

2. Materials and Methods

2.1. Surveyed CLT Building

The evaluation target was a building intended for conducting research and experiments at the Kyushu branch of the Forestry Research Institute. Figure 1 shows the exterior and interior of the CLT building after completion, and Figure 2 shows the floor plan of the first and second floors. The first floor was mainly used as laboratories, and to accommodate experimental equipment. The second floor was mainly used as a library.

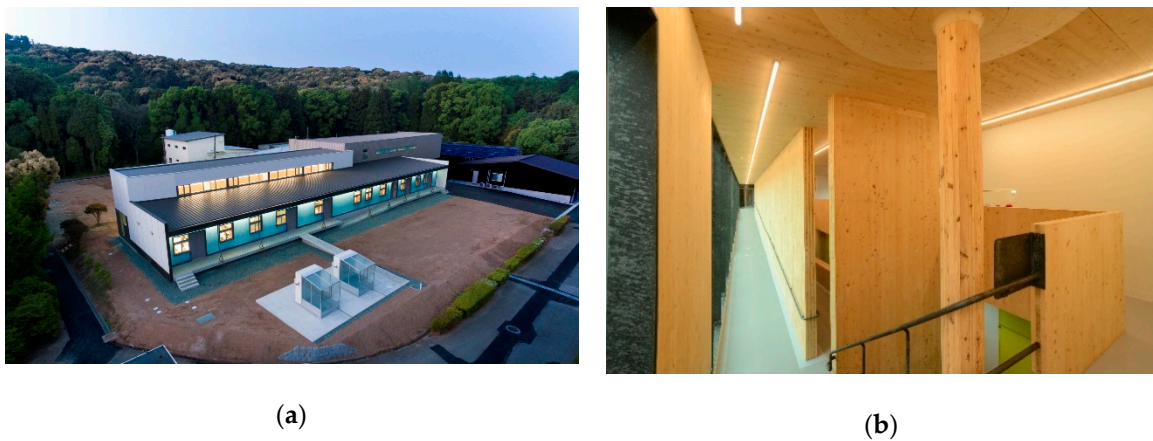


Figure 1. Images of the CLT building (a) exterior (photo by Nacása & Partners); (b) interior.

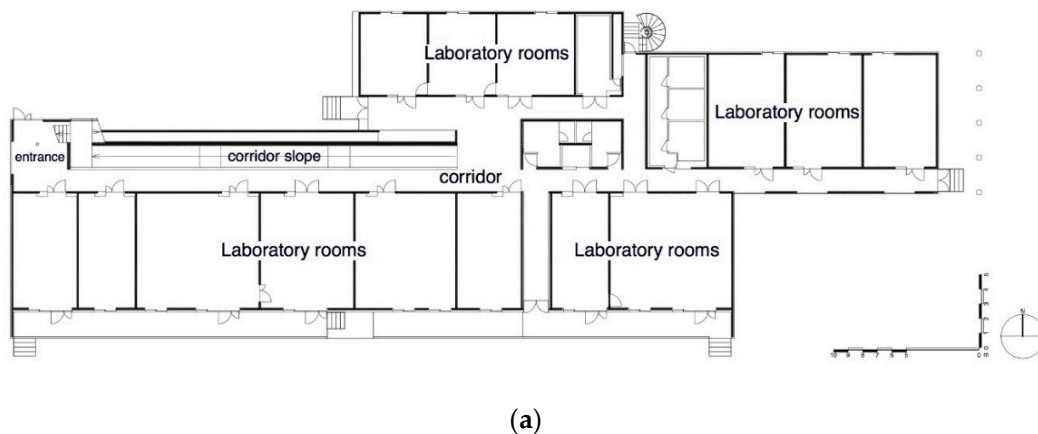
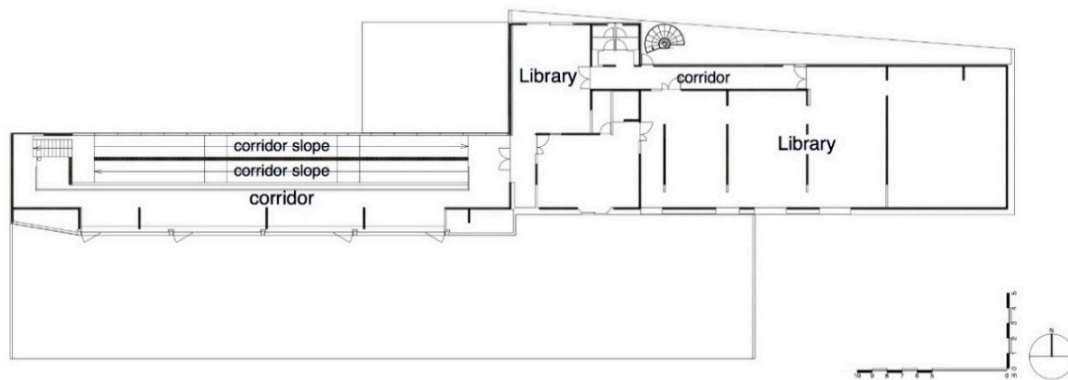


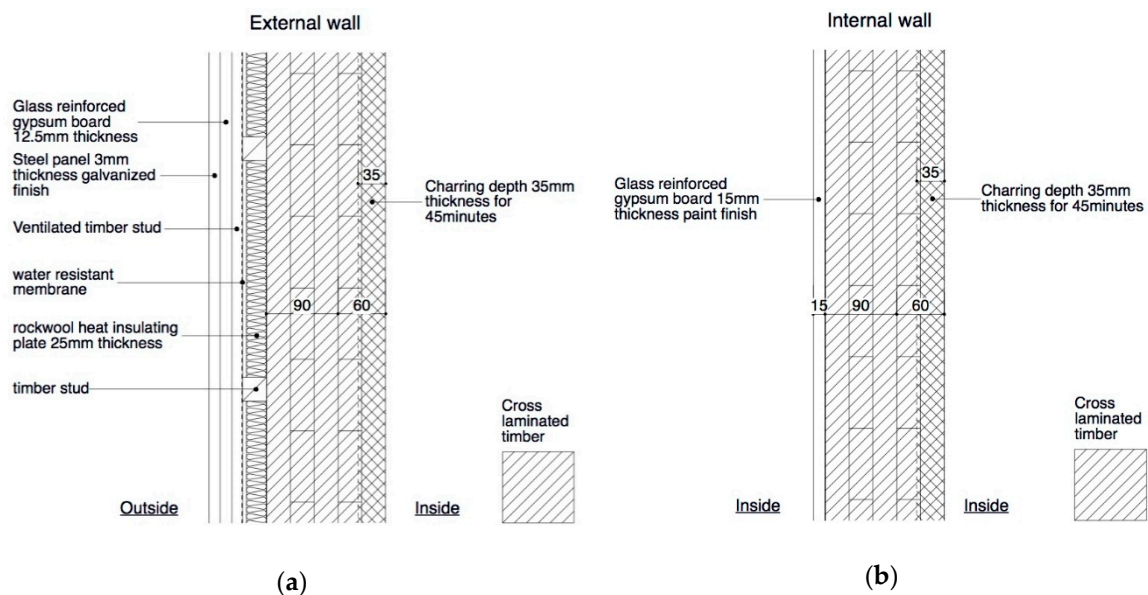
Figure 2. Cont.



(b)

Figure 2. Floor plan of the CLT building (a) first floor; (b) second floor.

The building was planned as a replacement for the old experimental building, which was damaged by the 2016 Kumamoto earthquake and became unusable. The construction of the building was started in 2017 and completed in 2018. The building has a total floor area of 1424.23 m². This was the first research and experiment building in Japan to use a CLT panel construction method. The interior of the passage inside the building was finished using CLT as a structural material. Examples of the cross section of the external and internal walls are shown in Figure 3. The CLT-exposed indoors was designed to be thicker than the necessary thickness for a structural material. This was done in order to prevent a fire and to ensure sufficient evacuation time considering the burning rate in case of a fire. The interior and the ceiling of the laboratory were finished with a gypsum board in order to prevent the spread of a fire indoors.



(a)

(b)

Figure 3. Examples of cross section of wall (a) external wall; (b) internal wall.

Table 1 summarizes the specifications of the building. The project cost amounted to approximately 670 million yen (approximately 6 million USD based on 111 JPY/USD), which was higher than that for regular Japanese houses. The thermal insulation and earthquake resistance of the building meet the Japanese building standards; therefore, the specifications of the building are considered to be stricter than those of other countries.

Table 1. Specification of the cross-laminated timber (CLT) building.

Category	Specification
Name	Joint experiment building of the Kyushu branch of the Forestry Research Institute.
Structure and construction method	CLT panel method
Building area	1037.90 m ²
Total floor area	1418.23 m ²
Floor	2 floors above ground
CLT usage	Wall: 219.8 m ³ (302 panels) Floor and roof: 331.2 m ³ (222 panels)
CLT dimensions and layer composition	90 mm (3-layer 3-ply) 150 mm (5-layer 5-ply) 210 mm (5-layer 7-ply)
Fireproof	Quasi-Fireproof 45 minutes construction
Intended application	Research and experiment building
Location	Kumamoto city, Kumamoto Pref., Kyushu, Japan.

2.2. System Boundary

The system boundaries in this study were defined as cradle-to-installation, from the production of the construction materials to up to the construction stage of the building (Figure 4). According to ISO21930:2017 [19], which is an international standard for building life-cycle assessment, the production stage consists of extraction and upstream production (A1), transport to factory (A2), and manufacturing (A3). All these were included in the system boundary. Since the construction stage consists of transport to site (A4) and installation (A5), both of these were also included in the system boundary. The installation included ground reinforcement work, concrete work, CLT work, and exterior work. ISO21930:2017 defines cradle-to-installation assessment as covering the mandatory production stage (A1 to A3), and both transport to construction site and construction installation on site (A4 and A5) [19], and this study adopted this definition.

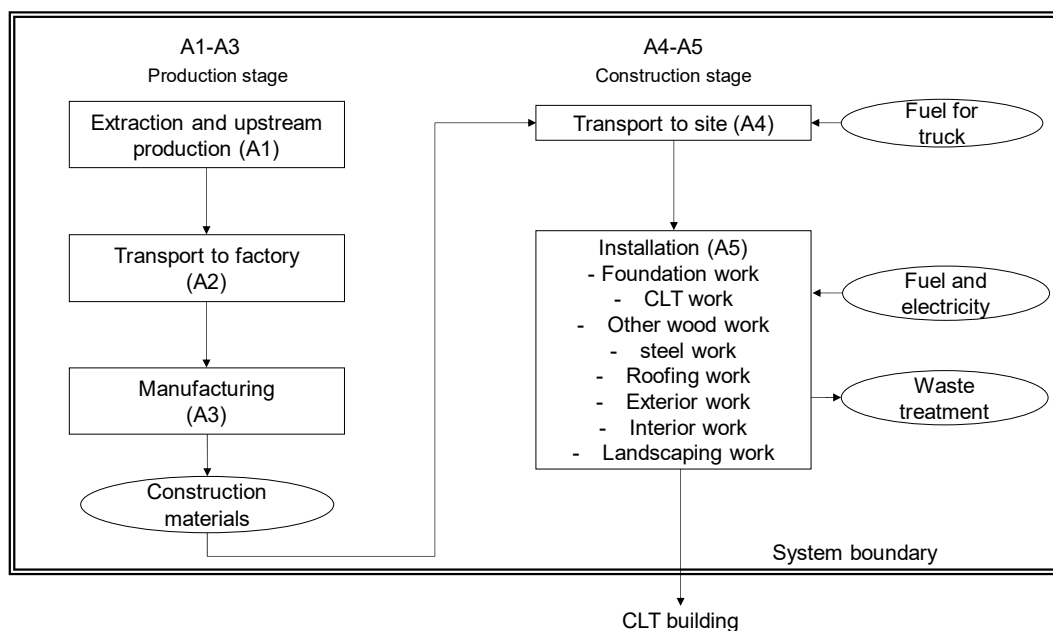


Figure 4. System boundary of the construction of the CLT building. The definition of A1 to A5 conformed to ISO21930:2017. Machines and electrical equipment installed in the building were excluded from the system boundary.

In the use stage of the building, energy is further consumed by using, for example, air conditioners, and luminaires. However, as the surveyed building was intended for conducting research and experiments, a variety of facilities and equipment will need be operated in the use stage. Hence, the environmental impacts of the use stage of the building will differ from those of regular office and apartment buildings. However, quantifying energy consumption for this building involved high uncertainties associated with the uncertainties surrounding the type of research to be carried out in the building. For this reason, this study focused on the environmental impacts of up to the construction stage, and other life-cycle stages were excluded from the system boundary. For the same reason, the production of machines and electrical equipment installed in the building was treated as being outside of the system boundaries. Further, environmental impacts from the commute of the construction workers were also excluded.

2.3. Environmental Impact Assessment Method

In this study, we assessed the environmental impacts of climate change, ozone depletion, eutrophication, acidification, and photochemical oxidation associated with constructing the CLT building. All of these impact categories are required by ISO21930:2017 [19]. Table 2 shows each impact category and the characterization model adopted in this study. The values of the 100-year factors of IPCC [20] were used as characterization factors of climate change. The impacts on ozone depletion were evaluated by the characterization factors of World Meteorological Organization (WMO) [21], widely adopted internationally.

Table 2. Environmental impact categories and impact assessment model.

Environmental Impact Category	Impact Assessment Method	Reference
Climate change	IPCC AR5	Myhre, Shindell, Bréon, et al. (2013) [20]
Ozone layer depletion	ODP ¹	WMO (1999) [21]
Eutrophication	EPMC ²	Itsubo (2012) [22]
Acidification	DAP ³	Itsubo (2012) [22]
Photochemical oxidation	OCEF ⁴	Itsubo (2012) [22]

¹ ODP: Ozone depleting potential; ² EPMC: Eutrophication potential by material circulation; ³ DAP: Deposition-oriented acidification potential; ⁴ OCEF: Ozone conversion equivalency factor.

Eutrophication, acidification, and photochemical oxidation are local or regional environmental issues. An environmental impact assessment method, LIME2 [22], is typically used in Japan to provide a characterization models for a variety of impact categories considering the local geographical and environmental situation. Therefore, characterization factors of LIME2 were used for environmental impact categories of eutrophication, acidification, and photochemical oxidation in this study.

2.4. Inventory Data Collection

2.4.1. Production Stage (A1–A3)

Data on the daily material delivery were collected at the construction site. This included not only the materials directly used for the construction of the building, but also materials consumed at the site and the excess materials ordered to avoid a potential material shortage. All of these were included in the inventory data, since they were prepared for the construction. Inputs less than 1% of the total weight were cut off. For the temporary materials (such as pipes for temporary scaffolding) that could be reused at other construction sites, only fuel consumption due to transportation was included in the inventory data.

Table 3 summarizes the amount of materials used. This corresponds to the production stage (A1–A3) in Figure 4. Our findings showed that the weights of reinforcing steel rod in concrete (deformed bar), the cement-based soil stabilizer used in the foundation work, and crusher-run stone

used in the external construction work, were large. Hot-dip galvanized steel sheet was used for the exterior, such as the roof.

Table 3. Inventory data of production stage (A1–A3) for the CLT building.

Item	Value
Crushed stone	7.39×10^5 kg
Soil stabilizer (cement)	2.23×10^5 kg
Fresh concrete	8.41×10^2 m ³
Concrete blocks	6.78×10^3 kg
Deformed bar	1.08×10^5 kg
Structural carbon steel	1.00×10^4 kg
Hot-dip galvanized steel sheet	4.23×10^4 kg
Other ordinary steel	3.30×10^3 kg
Expanded polystyrene (EPS)	1.10×10^3 kg
Sawn and planed wood	5.20×10 m ³
Common plywood (concrete form panel)	1.20×10^2 m ³
Special plywood (roof bed material)	2.56×10 m ³
CLT	5.51×10^2 m ³
Wooden window frame	3.00×10^3 kg
Lumber cement products	4.25×10^2 kg
Gypsum board	4.07×10^3 m ²
Polymer-modified asphalt	4.00×10^3 kg
Glass fiber (heat insulating)	9.61×10 kg
Rock wool (heat insulating)	8.01×10^2 kg
Calcium silicate (heat insulating)	2.57 m ³

2.4.2. Construction Stage (A4–A5)

Based on the above data, and on the maximum loading capacity of trucks and the loading site (material procurement location), the fuel consumption was calculated at the time of material delivery.

At the construction site, several machines were used. For example, heavy machinery was used for ground reinforcement works and lifting equipment was used for installing CLT panels. The environmental impacts caused by the fuel consumption in the heavy machinery were evaluated based on the amount of the fuel delivered to the construction site. The electricity consumed at the construction site was measured weekly by checking the specially installed power meter.

Table 4 shows the amount of materials transported to the construction site, the amount of energy consumed during construction, and the amount of waste to be disposed. This corresponds to the construction stage transport (A4) and building works (A5) in Figure 4. In terms of transportation volume, heavy trucks such as 10 t trucks accounted for the most significant volume. In terms of fuel consumption in Installation (A5), diesel oil was the most calorific in the calorie base. Diesel oil was mainly consumed by heavy machinery used in ground reinforcement works, foundation works, CLT construction works, and exterior construction works.

Table 4. Inventory data of the construction stage (A4–A5) for the CLT building.

Module	Item	Value
Transportation to site (A4)	10 t trucks	2.22×10^5 tkm
	4 t trucks	2.02×10^4 tkm
	2 t trucks	2.13×10^3 tkm
Installation (A5)	Heavy oil (type A)	4.12×10^4 L
	Diesel oil	1.20×10^5 L
	Electricity	7.95×10^3 kWh
	Residual soil treatment	3.06×10^2 m ³

2.5. Background Data

We used IDEA ver.2.3 (National Institute of Advanced Industrial Science and Technology; Sustainable Management Promotion Organization: Tsukuba and Tokyo, Japan, 2016) [23], a Japanese process-based inventory database, for the background data. Environmental impacts of roundwood production were adopted from Nakano, Shibahara, Nakai, et al. [24], and re-calculated using IDEA ver.2.3 for assessing all impact categories of this study, and maintaining the consistency of the background data. The environmental impacts of the CLT manufacturing and precutting processes were adopted from the Japanese representative LCA data [25]. The amount of biogenic carbon fixed in the CLT product was accepted as 585 kg-CO₂e/m³-CLT [25].

3. Results

3.1. Environmental Impacts of the CLT Building

Table 5 and Figure 5 show the calculation results for each impact category, and the breakdown by item. The total GHG emissions until completion (A1–A5) were 1.01×10^6 kg-CO₂e. As for the total floor area of the building (1424.29 m²), the GHG emissions amounted to 7.11×10^2 kg-CO₂e/m². The largest GHG emissions— 2.35×10^5 kg-CO₂e or 23%—were from the concrete used for building the foundations. The second largest GHG emissions— 1.91×10^5 kg-CO₂e or 19%—were associated with the soil stabilizer (cement). The GHG emissions during CLT production accounted for the third highest GHG emissions, at 17% (1.74×10^5 kg-CO₂e). The impact of on-site energy consumption and waste disposal due to on-site works (A5) was small, at 2% (1.87×10^4 kg-CO₂e). The impact of material transportation (A4) was also small (but not negligible), at 4% (4.29×10^4 kg-CO₂e).

Table 5. Environmental impacts of the CLT building construction.

Environmental Impact Category	Category Indicator
Climate change	1.01×10^6 kg-CO ₂ e
Ozone layer depletion	3.50×10^{-2} kg-CFC11e
Eutrophication	1.04×10 kg-PO ₄ ³⁻ e
Acidification	4.64×10^2 kg-SO ₂ e
Photochemical oxidation	1.53×10 kg-C ₂ H ₄ e

The impacts of the building construction on acidification showed the same breakdown as GHG emissions. However, the proportion of the impacts caused during CLT production (30% or 1.40×10^2 kg-SO₂e) was higher than the concrete (17% or 7.92×10 kg-SO₂e) and the soil stabilizer (14% or 6.53×10 kg-SO₂e). The impact on the ozone depletion was the greatest, with the contribution of other steel, mainly hot-dip galvanized steel sheet used for the exterior, at 24% (8.41×10^{-3} kg-CFC11e). In terms of impacts on eutrophication and photochemical oxidation, the contribution of plywood was the largest, at 68% (7.05 kg-PO₄³⁻e) and 32% (4.95 kg-C₂H₄e), respectively.

3.2. Environmental Impacts of the CLT-Related Structural Construction

We analyzed the environmental impacts of the CLT-related structural construction work, which were calculated based on the amount of materials delivered to the construction site during the building works (Figure 6). The results showed that 72% of GHG emissions were due to CLT panel manufacturing, with gypsum board and iron products accounting for 11% each. The pre-cut CLT panels were lifted and installed to their designated place one by one with a crane, which consumed diesel oil; however, the associated GHG emissions were as low as 2%. In other impact categories, the impact of diesel oil used for the lifting equipment was similarly small.

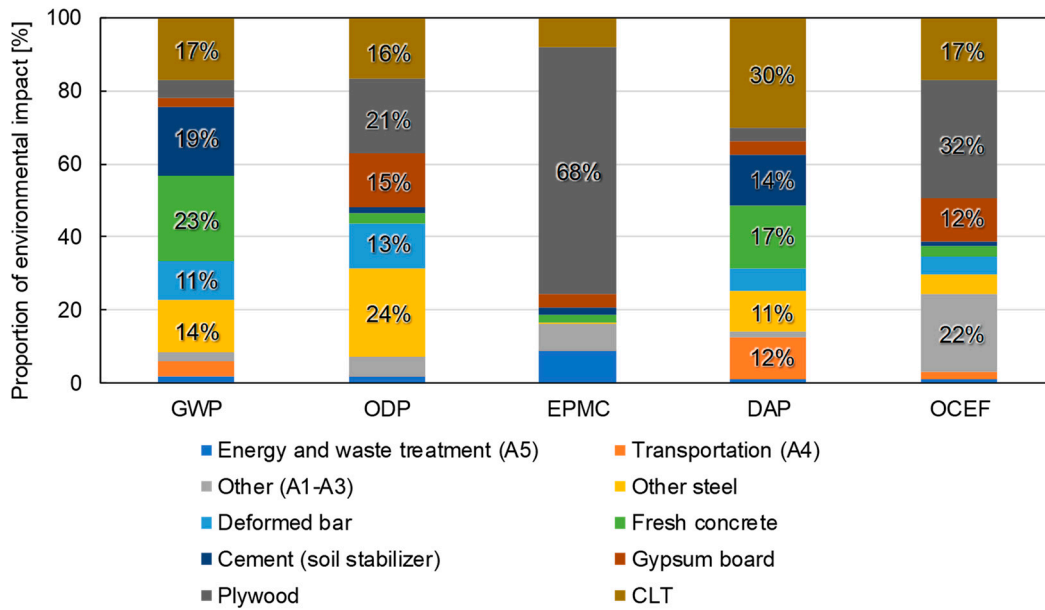


Figure 5. Composition of environmental impacts caused by the CLT building construction. GWP: global warming potential; ODP: ozone depleting potential; EPMC: eutrophication potential by material circulation; DAP: deposition-oriented acidification potential; OCEF: ozone conversion equivalency factor.

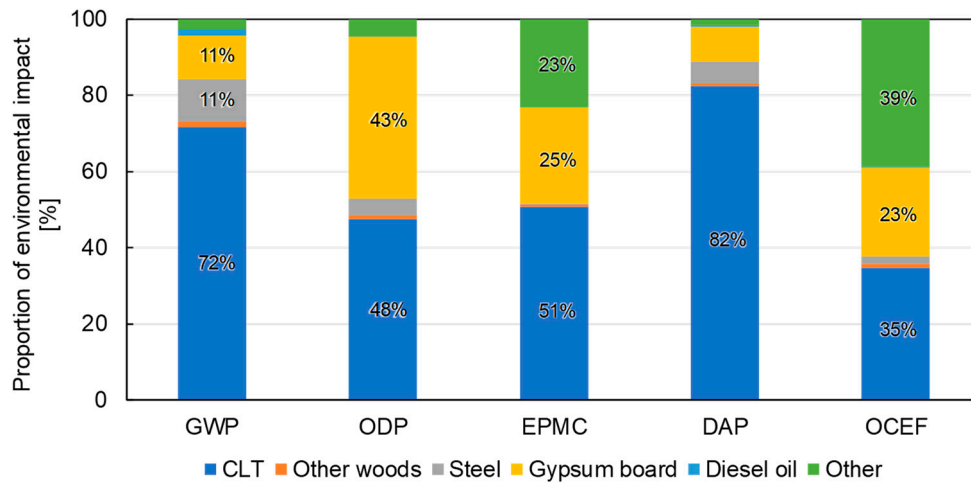


Figure 6. Environmental impacts of the CLT building construction. GWP: global warming potential; ODP: ozone depleting potential; EPMC: eutrophication potential by material circulation; DAP: deposition-oriented acidification potential; OCEF: ozone conversion equivalency factor.

In the acidification category, most of the impacts were caused by the CLT panel manufacturing, similar to the GHG emissions. The CLT manufacturing also resulted in major impacts on the ozone layer depletion, eutrophication and photochemical oxidation. However, the impacts of the gypsum board were also significant. In particular, the gypsum board accounted for 43% of the impact on the ozone layer depletion, and for 25% and 23%, of the impacts on eutrophication and photochemical oxidation, respectively.

4. Discussion

4.1. Environmentally Conscious Design of the CLT Building

In this study, the cement-based soil stabilizer used for ground reinforcement and concrete used for the foundation accounted for 34% of the GHG emissions associated with the construction of the CLT building, in total. By adding the impact of the deformed steel bars used during construction, this amount will be increased to 53%. The production of these materials also had a significant impact on the acidification category. The significance of these impacts was due to the following reasons. First, the construction site was formerly used as a seedbed field, hence ground reinforcement was necessary. Second, large foundations were designed in order to raise the low height of the wooden structure from the ground level. This was necessary for the stable installation of the research equipment and to comply with the requirement for raising the wooden structure to a height of 1 m above ground level in order to prevent decay or termite damage, as stipulated in the Housing Quality Assurance Act [26].

Using an alternative, non-cement based, ground reinforcement method, and an alternative design for the building foundation, has the potential to reduce these environmental impacts; hence, developing and applying these methods is recommended. In addition, plywood used as the concrete foundation formwork showed a certain contribution to the impact categories of the ozone layer depletion, eutrophication, and photochemical oxidation, hence plywood reuse should be considered to reduce the environmental impacts.

Note that this study focused on the production stage only; therefore, an alternative method to meet the above-mentioned recommendations must keep other performances, such as thermal insulation, to avoid an unintended shift in environmental impacts from the production stage to use and end-of-life stages.

4.2. Environmental Impact Reduction of CLT Manufacturing

GHG emissions from CLT manufacturing accounted for 17% of the entire building's impact. The environmental impact data of CLT manufacturing used in the study were based on the Japanese representative LCA data [25], with grid electricity and steam provided by biomass fuel used during the manufacturing process. However, there are currently CLT manufacturing plants in Japan that have introduced a cogeneration system using biomass fuel, so it is possible to manufacture CLT using biomass-derived electricity.

When using biomass-derived electricity in the CLT manufacturing process, the GHG emissions were reduced by 5% (Figure 7). The impact on acidification in this case was also reduced by 5%, and the impact on photochemical oxidation was reduced by 7%. Since the environmental impacts of the CLT manufacturing accounted for a large proportion of the impacts of the series of construction works considered in this study, it can be concluded that reducing the environmental impacts of the CLT manufacturing process is highly effective in reducing the overall environmental impacts of the CLT building construction.

4.3. Uncertainty Analysis

Fresh concrete must be changed to a mixing ratio and/or ingredient to maintain its mechanical properties, such as strength and fluidity, in the winter (daytime temperatures of 4 °C or less) and in the summer (daily average temperatures of 25 °C or more). In practice, it is usual to schedule the concrete laying work to avoid these seasons, to prevent a deterioration in concrete quality and an increase in cost. In this case, the foundational concrete laying work was carried out in September and October. However, owing to the limited construction period, the concrete laying work may be carried out in summer and winter. However, the environmental impacts may increase under these conditions.

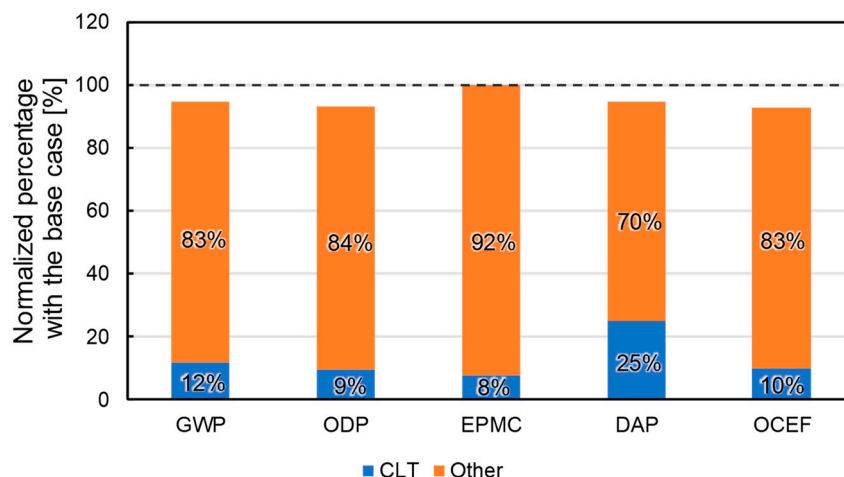


Figure 7. Environmental impact reduction by using bio-derived electricity for the CLT panel production. GWP: global warming potential; ODP: ozone depleting potential; EPMC: eutrophication potential by material circulation; DAP: deposition-oriented acidification potential; OCEF: ozone conversion equivalency factor.

Further, the environmental impacts caused by the use of electric furnace steel (e.g., deformed bars) mainly depend on the environmental impact of electricity used in the electric furnace. In this study, the electric furnace steel was evaluated assuming the use of grid electricity in 2017. In 2017, Japan's electricity mix was heavily fossil-fuel-based (81%) and most of the nuclear power plants were under temporary shutdown [27]. Renewable energy accounts for 16% of energy use, but the introduction of the Feed-in-tariff policy has increased the installation of renewable energy facilities, such as solar photovoltaics and wind power [27]. Therefore, the environmental impacts of these electric furnace products can be changed based on the operational status of nuclear power plants and the spread of renewable energy.

With regard to CLT, Japan is hot and humid in summer and cold in winter, with low humidity in some areas. Under high humidity conditions, wood swells, especially in the cross direction of the fibers, thus requiring time and energy to adjust the dimensions of the CLT panels when installing them at the construction site. The dimensions of the CLT panels, however, are adjusted considering the environmental conditions before shipping to the site. Therefore, this does not influence the results.

4.4. Biogenic Carbon Content

The amount of biogenic carbon fixed in the CLT product is 5.85×10^2 kg-CO₂e/m³-CLT [25]. Since the building used 5.51×10^2 m³ of CLT panels, it stored 3.22×10^5 kg of CO₂e. This carbon remains fixed for as long as the panels are used in buildings. This represents 32% of the total GHG emissions until the building construction. Therefore, if the impacts of the temporary fixation of biogenic carbon are included in the assessment, the overall GHG emissions will be lower. The GHG emissions per area amounted to 7.11×10^2 kg-CO₂e/m²; however, if the biogenic carbon storage impact is included, it would be reduced to 4.85×10^2 kg-CO₂e/m². Nevertheless, if the CLT panels were decomposed at the end-of-life stage of a building, the stored biogenic carbon will be released into the atmosphere. Hence, it is recommended to utilize the CLT building for a long time and/or to reuse the CLT panels used in the construction.

4.5. Comparison with Other Studies

Another study investigates the GHG emissions from the construction of a mid-rise CLT office building in the US [4]. According to the study, the total GHG emissions amounted to 0.126 t-CO₂e/m², including the impact of biogenic carbon storage. In a similar manner, the impacts evaluated for low-rise CLT buildings in Slovenia [5], including the impact of carbon storage, totalled 0.027–0.163 t-CO₂e/m².

Both are significantly smaller than the result of this study, 4.85×10^2 kg-CO₂e/m². However, the building investigated in this study was a two-story building for research experiments, with the floor plan entirely different from that of high- and mid-rise office buildings, hence the different results achieved in these studies were inevitable. In addition, Japan has stricter seismic standards than other countries and it also has stricter structural requirements, hence the environmental impacts per unit area are considered to have increased. IDEA, The Japanese LCA database, presents the value of wooden buildings for offices as a general building value in Japan, which is 0.422 t-CO₂e/m², without including carbon storage. As a result, the value of this building was higher than that of a general wooden office building in Japan.

5. Conclusions

In Japan, to utilize the abundant forest resources in the country, the government has promoted the use of wood for buildings, and the number of buildings using CLT has increased. However, the environmental impact of CLT building construction in Japan has not been studied. This study assessed the environmental impacts of cradle-to-installation of CLT building constructed in 2017–2018. The input of materials and energy required for the construction of a two-story research and experiment building in Kumamoto, Kyushu, Japan was investigated. It was clarified that the concrete used for constructing the foundations accounted for 23%, while the cement-based soil stabilizer used for ground reinforcement accounted for 19% of the total GHG emissions. This will be increased to 53% on adding the impact of the deformed bars used for the foundations. The construction site was previously utilized as a seedbed field, which necessitated the need for ground reinforcement. Furthermore, the large foundations were arranged to raise the low height of the wooden structure from the ground level. Therefore, the development and application of methods with lower environmental impacts for ground reinforcement and building foundations are recommended. In addition, it is clarified that the use of biomass-derived electricity in CLT manufacturing could reduce the environmental impacts of the CLT panel manufacturing, thus reducing the environmental impact of the entire building.

The biogenic carbon fixed in the building accounted for 32% of the total GHG emissions of the building construction. The biogenic carbon will be released to the atmosphere at the end-of-life stage of the building; thus, long-term use of the building and/or reusing the CLT panels in other buildings is recommended.

Author Contributions: All authors contributed to the research presented in this paper. Conceptualization, N.H.; Data curation, K.N.; Formal analysis, K.N.; Funding acquisition, M.K. and N.H.; Investigation, K.N. and M.K.; Methodology, K.N.; Project administration, M.K.; Supervision, N.H.; Writing—original draft, K.N.; Writing—review and editing, M.K. and N.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by grants from the Project of the NARO Bio-oriented Technology Research Advancement Institution (the special scheme project on vitalizing management entities of agriculture, forestry and fisheries).

Acknowledgments: The authors thank to Nacása & Partners Inc. for providing Figure 1a, and to Yukiharu Takematsu + E.P.A Co., Ltd. for preparing Figures 2 and 3.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Ministry of Land, Infrastructure, Transport and Tourism, Japan. Current Survey on Construction Statistics. Japan, 2019. Available online: <http://www.mlit.go.jp/toukeijouhou/chojou/stat-e.htm> (accessed on 11 March 2020).
2. Forestry Agency of Japan. New Wooden Public Building in Japan: Ten Case Studies. Tokyo, Japan, 2017. Available online: <https://www.rinya.maff.go.jp/j/riyou/koukyou/attach/pdf/index-69.pdf> (accessed on 11 March 2020).
3. Sahoo, K.; Bergman, R.; Alanya-Rosenbaum, S.; Gu, H.; Liang, S. Life cycle assessment of forest-based products: A review. *Sustainability* **2019**, *11*, 4722. [CrossRef]

4. Nakano, K.; Ando, K.; Takigawa, M.; Hattori, N. Life cycle assessment of wood-based boards produced in Japan and impact of formaldehyde emissions during the use stage. *Int. J. Life Cycle Assess.* **2018**, *23*, 957–969. [[CrossRef](#)]
5. Chen, C.X.; Pierobon, F.; Ganguly, I. Life Cycle Assessment (LCA) of Cross-Laminated Timber (CLT) produced in Western Washington: The role of logistics and wood species mix. *Sustainability* **2019**, *11*, 1278. [[CrossRef](#)]
6. Ferro, F.S.; Silva, D.A.L.; Rocco Lahr, F.A.; Argenton, M.; González-García, S. Environmental aspects of oriented strand boards production. A Brazilian case study. *J. Clean. Prod.* **2018**, *183*, 710–719. [[CrossRef](#)]
7. Jia, L.; Chu, J.; Ma, L.; Qi, X.; Kumar, A. Life cycle assessment of plywood manufacturing process in China. *Int. J. Environ. Res. Public Health* **2019**, *16*, 2037. [[CrossRef](#)] [[PubMed](#)]
8. Liu, Y.; Guo, H.; Sun, C.; Chang, W.S. Assessing cross laminated timber (CLT) as an alternative material for mid-rise residential buildings in cold regions in China—A life-cycle assessment approach. *Sustainability* **2016**, *8*, 1047. [[CrossRef](#)]
9. Guo, H.; Liu, Y.; Meng, Y.; Huang, H.; Sun, C.; Shao, Y. A Comparison of the energy saving and carbon reduction performance between reinforced concrete and cross-laminated timber structures in residential buildings in the severe cold region of China. *Sustainability* **2017**, *9*, 1426. [[CrossRef](#)]
10. Robertson, A.B.; Lam, F.C.F.; Cole, R.J. A Comparative Cradle-to-Gate Life Cycle Assessment of Mid-Rise Office Building Construction Alternatives: Laminated Timber or Reinforced Concrete. *Buildings* **2012**, *2*, 245–270. [[CrossRef](#)]
11. Leskovar, V.Ž.; Žigart, M.; Premrov, M.; Lukman, R.K. Comparative assessment of shape related cross-laminated timber building typologies focusing on environmental performance. *J. Clean. Prod.* **2019**, *216*, 482–494. [[CrossRef](#)]
12. Dodoo, A.; Gustavsson, L.; Sathre, R. Lifecycle primary energy analysis of low-energy timber building systems for multi-storey residential buildings. *Energy Build.* **2014**, *81*, 84–97. [[CrossRef](#)]
13. Takano, A.; Pal, S.K.; Kuittinen, M.; Alanne, K. Life cycle energy balance of residential buildings: A case study on hypothetical building models in Finland. *Energy Build.* **2015**, *105*, 154–164. [[CrossRef](#)]
14. Hafner, A.; Schäfer, S. Comparative LCA study of different timber and mineral buildings and calculation method for substitution factors on building level. *J. Clean. Prod.* **2017**, *167*, 630–642. [[CrossRef](#)]
15. Anand, C.K.; Amor, B. Recent developments, future challenges and new research directions in LCA of buildings: A critical review. *Renew. Sustain. Energy Rev.* **2017**, *67*, 408–416. [[CrossRef](#)]
16. Tait, M.W.; Cheung, W.M. A comparative cradle-to-gate life cycle assessment of three concrete mix designs. *Int. J. Life Cycle Assess.* **2016**, *21*, 847–860. [[CrossRef](#)]
17. El Bachawati, M.; Manneh, R.; Belarbi, R.; Dandres, T.; Nassab, C.; El Zakhem, H. Cradle-to-gate Life Cycle Assessment of traditional gravel ballasted, white reflective, and vegetative roofs: A Lebanese case study. *J. Clean. Prod.* **2017**, *137*, 833–842. [[CrossRef](#)]
18. Hasegawa, T. *Introduction to the Building Standard Law—Building Regulation in Japan*; Building Center of Japan: Tokyo, Japan, 2013.
19. ISO. ISO 21930—Sustainability in Buildings and Civil Engineering Works—Core Rules for Environmental Product Declarations of Construction Products and Services. Available online: <https://www.iso.org/standard/61694.html> (accessed on 11 March 2020).
20. Myhre, G.; Shindell, D.; Bréon, F.-M.; Collins, W.; Fuglestedt, J.; Huang, J.; Koch, D.; Lamarque, J.-F.; Lee, D.; Mendoza, B.; et al. Anthropogenic and Natural Radiative Forcing. In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Eds.; Cambridge University Press: Cambridge, UK, 2013; pp. 731–738.
21. WMO Scientific Assessment of Ozone Depletion, WMO Global Ozone Research and Monitoring Project: Report No.44. Available online: https://library.wmo.int/?lvl=notice_display&id=15453#.XmhgrEq9PIU (accessed on 11 March 2020).
22. Itsubo, N. Inaba A LIME2 summary In JLCA Newsletter No.12, Life Cycle Assessment forum of Japan. Available online: https://lca-forum.org/english/pdf/No12_Summary.pdf (accessed on 12 March 2020).
23. *LCA Database IDEA Version 2. National Institute of Advanced Industrial Science and Technology*; Sustainable Management Promotion Organization: Tsukuba, Japan; Tokyo, Japan, 2016.
24. Nakano, K.; Shibahara, N.; Nakai, T.; Shintani, K.; Komata, H.; Iwaoka, M.; Hattori, N. Greenhouse gas emissions from round wood production in Japan. *J. Clean. Prod.* **2018**, *170*, 1654–1664. [[CrossRef](#)]

25. Nakano, K.; Koike, W.; Yamagishi, K.; Hattori, N. Life cycle assessment of cross laminated timber production in Japan. Unpublished work, 2020.
26. MLIT. *Ministry of Land Infrastructure Transport and Tourism Japan Housing Quality Assurance Act*; MLIT: Tokyo, Japan, 1999.
27. Ministry of Economy, Trade and Industry. *Japan's Energy 2018*; METI: Tokyo, Japan, 2019.



© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).