Aalborg Universitet

Analysis of Hybrid Timber Construction by Multiple Criteria Decision-Making Method

Dolgunovas, Markas; Norvaišienė, Rosita

Published in:
NSB 2023 - Book of Technical Papers: 13th Nordic Symposium on Building Physics

DOI (link to publication from Publisher):
10.54337/aau541025944

Creative Commons License
Unspecified

Publication date:
2023

Document Version
Publisher's PDF, also known as Version of record

Link to publication from Aalborg University

Citation for published version (APA):
Dolgunovas, M., & Norvaišienė, R. (2023). Analysis of Hybrid Timber Construction by Multiple Criteria Decision-Making Method. In H. Johra (Ed.), *NSB 2023 - Book of Technical Papers: 13th Nordic Symposium on Building Physics* (Vol. 13). Article 128 Department of the Built Environment, Aalborg University. https://doi.org/10.54337/aau541025944

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal -

Take down policy
If you believe that this document breaches copyright please contact us at vbn@aub.aau.dk providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from vbn.aau.dk on: May 02, 2024

Analysis of Hybrid Timber Construction by Multiple Criteria Decision-Making Method

Markas Dolgunovas, Rosita Norvaišienė

Kaunas University of Applied Engineering Sciences,Tvirtovės av. 35, 50155 Kaunas, Lithuania

rosita.norvaisiene@edu.ktk.lt

Abstract. When selecting materials for a building, designers should not only think about structural requirements but also to the sustainability of the selected materials. The article presents a study of a single building using methods that comprehensively evaluate alternative design solutions. The approach is based on the complex system of criteria allowing a comprehensive evaluation of alternative solutions at an early design stage, combining life cycle assessment (LCA) and multi-criteria decision analysis (MCDA).

This study evaluates the environmental impact of five alternative types of building components (reinforced concrete, hybrid wood elements), while determining the most rational alternative solutions according to the specified criterion (price, CO_2 emissions, human time consumption, envelope thicknesses).

The results show that, when the columns, ceilings and beams are made of reinforced concrete and the external envelope comprises SIP panels, the version of building structures ranks in the second place in terms of theoretical significance (81 points) and in the first place in terms of subjective significance (79 points).

Keywords: Multiple Criteria Decision-Making Method, Life Cycle Analysis, Hybrid Timber, One Click

1. Introduction

Modern buildings and structures consist of mainly masonry, steel, and concrete. Reinforced concrete possesses especially good overall stability - it combines high compressive strength of concrete with high tensile strength of steel. Reinforced concrete is extremely durable, even under dynamic weather conditions. However, it also has its drawbacks such as huge amounts of manufacturing energy, process and subsequently recycle reinforced concrete, which causes large amounts of CO_2 emissions [1-2]. The construction industry is liable for huge amounts of energy-related CO_2 emissions (39%) [3]. Noha Ahmed [4] found that reinforced concrete has a significant negative impact on ecosystems, as it accounts for 78% of all carbon dioxide emissions.

Hafner's [5] life cycle assessment (LCA) calculation indicated that building's operational phase accounts between 45% and 80% of total CO_2 emissions, while the materials used in construction account for 20-55% of total CO_2 emissions. Sizirici et al. [6] found that the application of alternative additives/materials in construction (planning, design and construction) or methods/systems can reduce the CO_2 due to material use up to 90%.

The European Union supports the construction sector's emissions reduction initiative to increase the target from 29% to 40% reduction by 2030. The amount of GHG emissions from buildings can be influenced by the selection of building materials. Because the use of timber structures can help in reducing the concentration of greenhouse gases, such as CO_2, Europe is increasingly moving towards timber-based constructions [8-11]. In recent years, wood has been considered as an alternative source of building materials because of its sustainability and design efficiency, but the cost-competitiveness of timber buildings is still under investigation because of reduced information.

Engineering timber products for construction (EWD - Engineered Wood Products) are used for load-bearing elements, or for interior or exterior fittings, usually in the form of panels or lumber. These products are formed from small cross-sections of securely interconnected blanks, allowing for the balance between building products, forest resources and the required working capacity and dimensions, while improving their mechanical properties in a targeted way [12].

Multiple studies [13-14] demonstrated that, when compared to concrete or steel, using wood or its engineered product derivatives such as Glued-Laminated Timber (GLT), Cross Laminated Timber (CLT), Laminated Veneer Lumber (LVL) and so on, presents a favorable environmental balance.

The combined energy and ecological efficiency of modern buildings increasingly depend not only on the technology of their construction and the quality of manufacturing, but also on the selection of building materials. The latter can be assessed by LCA and supplemented by multi-criteria analysis. This study proposes a common algorithm - the selection of a rational solution, combining LCA and multi-criteria analysis methods for selecting the structural elements of the building to achieve energy efficiency and reduce CO_2 emissions. The proposed algorithm can be used on a large-scale with the support of building information modeling (BIM) and can be applied to different types of buildings in different locations. The environmental impact of five alternative types of building components (reinforced concrete, hybrid wood elements), is evaluated, and the most rational alternative solutions according to the specified criterion (price, CO_2 emissions, human time consumption, envelope thicknesses) are determined.

2. Methods

Methods used for the building analysis combines LCA and Multiple Criteria Decision-Making Method (MCDM).

One Click LCA software can calculate and compare the embodied carbon footprint impact of a building project and the performance of the used materials. The tool considers the 10 most important building materials (concrete, steel, cement, bricks, glass, gypsum, insulation, wood) and provides access to global, up-to-date databases, including Environmental Product Declarations (EPDs), which describe the environmental impact of different products. One Click LCA provides extensive integration capabilities for software and file formats such as Autodesk Revit, Simple BIM and Naviate Simple BIM 5.0, Excel and DesignBuilder 5.1 or later.

Multiple Criteria Decision Making (MCDM) methods stand out from other optimization methods. These tasks set a solution objective: selecting the best alternative from a range of options proposed or ranking alternatives in relation to the assessment objective. Multi-criteria methods are based on a decision matrix, which includes statistics on the criteria characterizing the evaluation objective, or the values of expert judgements on these criteria.

Determining the significance of evaluation criteria using the theoretical entropy method. The objective weight entropy method is among the most used, although multivariate regression models and other ideas may also be used. The increase in entropy weight is related to the degree of dominance of one criterion value among all alternatives.

Determination of the significance of the assessment criteria using an expert ranking method. Ranking is a procedure in which the most important criterion is given the highest rank equal to a unit, the second in importance is given the rank two, etc., the last in terms of importance is given the rank m, where m - is the number of criteria compared. Equivalent criteria shall be given the same value, the arithmetic mean of the ordinal ranks.

3. Analysis of building design options

A conventional 2-storey building of 26x21m was selected for the study. The building has 30 reinforced 400 x 400 mm concrete columns, 8 m height, floor area - 518.16 m^2 , roof covering is made of multilayer Sandwich panels, 200 mm thick reinforced concrete slabs as ceilings (building A, Table 1). Building was analyzed according to 5 criteria - wall and roof thickness, construction cost, CO_2 emissions and labor costs - and compared with buildings modeled using hybrid timber construction. The criteria were chosen based on realistic criteria that could be held important when constructing a building, meaning most often are accented by clients.

Table 1. Design options for buildings

Building constructions	Building A (Original)	Building B	Building C	Building D	Building E
Columns	Reinforced concrete	Reinforced concrete	Reinforced concrete	Glulam	Glulam
Overlays	Reinforced concrete	Reinforced concrete	Reinforced concrete	CLT	OSB
Beams	Reinforced concrete	Reinforced concrete	Reinforced concrete	Glulam	Glulam
Walls	sandwich	CLT	SIPs	CLT	Timber frame
Roof	sandwich	sandwich	SIPs	CLT	OSB

The 4 hybrid timber building variants are shown in Table 1 (Buildings B, C, D and F).

Selecting the system of evaluation criteria and calculating their values (based on which criterion is selected).

Wall thickness (K1) at U = 0.17 W/(m²K), mm. The wall thickness criterion shows the thickness of an outer wall when U is at a value of 0.17 W/(m²K).

Roof thickness (K2) at U = 0.15 W/(m²K), mm. The roof thickness criterion indicates the thickness of a roof when U is at U value of 0.15 W/(m²K).

Price (K3), thousand Eur. The price criterion shows the approximate price that will have to be paid for the materials to build this building using the appropriate option of structures. The price will be determined by assessing the prices of the main structural elements of the building (walls, roof, ceilings, columns).

CO_2 emissions (K4), tCO_2e. The CO_2 emissions criterion shows how many tons of CO_2e are released into the atmosphere during the production of building materials. CO_2 emissions are calculated using the „One click LCA“ software.

Human time consumption per hour (K5). The human time consumption criterion shows how many labor hours the construction process will take, considering the installation of columns, ceilings, walls, and roof. This measurement was taken out of the official construction normative. It is calculated based on the average time it takes one person to complete a certain construction task.

The main factor when comparing different external wall structures is the heat transfer coefficient, which is defined as U=0.17 (W/m^2K) - currently the wall is subject to the requirement for energy performance class A++ for public buildings in Lithuania. The external walls, roof, overlay structures of the building are designed from different structural materials - CLT, multilayer panels "Sandwich", SIP panels with layers of thermal insulation.

Building construction option A. The building is designed with a reinforced concrete frame. The ceilings are made of reinforced concrete slabs 200 mm thick. Walls and roof are constructed of 135 mm and 120 mm thick Sandwich panels. Estimated building cost is 115818 EUR. Based on the „One click LCA“ the building produces 106 tCO_2e. Estimated human hour consumption is 1256 hours.

Building construction option B. The building is designed with a reinforced concrete frame. The ceilings are made of reinforced concrete slabs 200 mm thick. The walls are made from CLT panels (Figure 1). Roof is constructed out of sandwich panels. Estimated building cost is 119932 EUR. Based on the „One click LCA“ the building produces 112 t CO_2e. Estimated human hour consumption is 1191 hours.

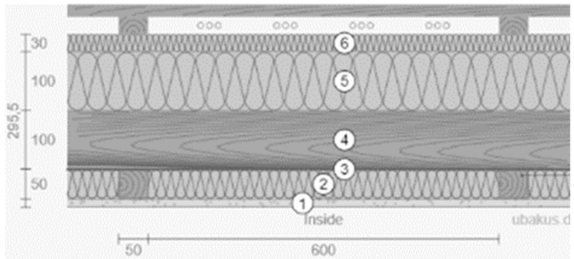

Fig.1. CLT panel wall construction (1 - plasterboard 15 mm; 2 - mineral wool 50 mm; 3 - vapor barrier 0.5 mm; 4 - cross laminated timber 100 mm; 5 - mineral wool 100 mm; 6 - hard mineral wool 30 mm)

Building construction option C. The building is designed from a reinforced concrete frame. The ceilings are made of reinforced concrete slabs 200 mm thick. The walls and roof are 205 mm and 224 mm thick and are made of SIP panels. Estimated building cost is 119932 EUR. Based on the „One click LCA“ the building produces 112 t CO_2e. Estimated human hour consumption is 1197 hours.

Building construction option D. The building is designed from glued timber (Glulam) columns. The walls, roof and ceilings are made of CLT. Estimated building cost is 119932 EUR. Based on the „One click LCA“ the building produces 121 t CO_2e. Estimated human hour consumption is 3251 hours.

Building construction option E. The building is designed from glued timber (Glulam) columns. Ceilings from OSB panels. The walls and roof - timber frame panel construction (Figures 2 and 3) are 255.5 mm and 273 mm thick. The ceilings are made of OSB panels. Estimated building cost is 90465 EUR. Based on the „One click LCA“ the building produces 101 t CO_2e. Estimated human hour consumption is 2525 hours.

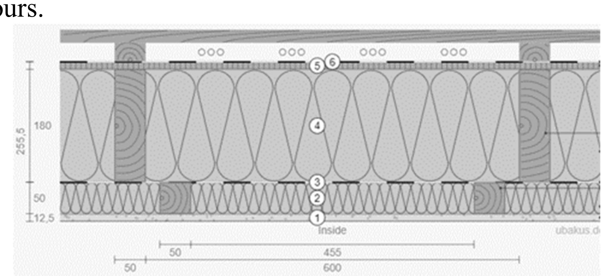

Fig.2. Timber frame panel construction - wall (1 - plasterboard 12.5mm; 2 – mineral wool 50 mm; 3 - vapor barrier 0.5mm; 4 - mineral wool 180 mm; 5 - OSB 12mm; 6 - windproof film)

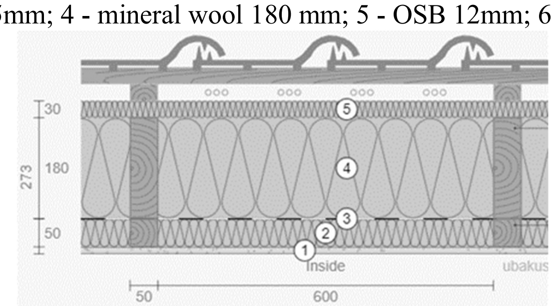

Fig.3. Timber frame panel construction - roof (1 - plasterboard 12.5 mm; 2 – mineral wool 50 mm; 3 - vapor barrier 0.5 mm; 4 - mineral wool 180 mm; 5 - hard mineral wool 30 mm)

When making engineering decisions, it is important to consider the main aspects affecting the function of the buildings and to evaluate all available options and their ability to fulfill their purpose. For this assessment, a single-criteria cost-effectiveness assessment will not reveal and evaluate the most important parameters of materials and engineering systems. Therefore, a multi-criteria approach is chosen, which allows the evaluation of the engineering solutions according to the chosen system of evaluation criteria and their significance. An expert judgement method is used to determine the subjective significance of the criteria.

The numerical values of the evaluation criteria are shown in Table 2.

Table 2. Numerical values of the evaluation criteria

Criteria / Options	Wall thickness (K1) at U = 0.17 W/(m²K), mm	Roof thickness (K2) at U = 0.15 W/(m²K), mm	Price (K3), Thousand Eur	CO_2 emissions (K4), tCO2e	Human time consumption per hour (K5)
A	135	120	116	106	1256
B	296	120	120	112	1191
C	205	224	156	41	1197
D	296	308	127	121	3251
E	256	273	91	101	2525

3.1. Determining the theoretical significance of criteria using the theoretical entropy method

The entropy method is a method for determining the theoretical significance of criteria, based on mathematical calculations using numerical values to determine the significance of the criteria.

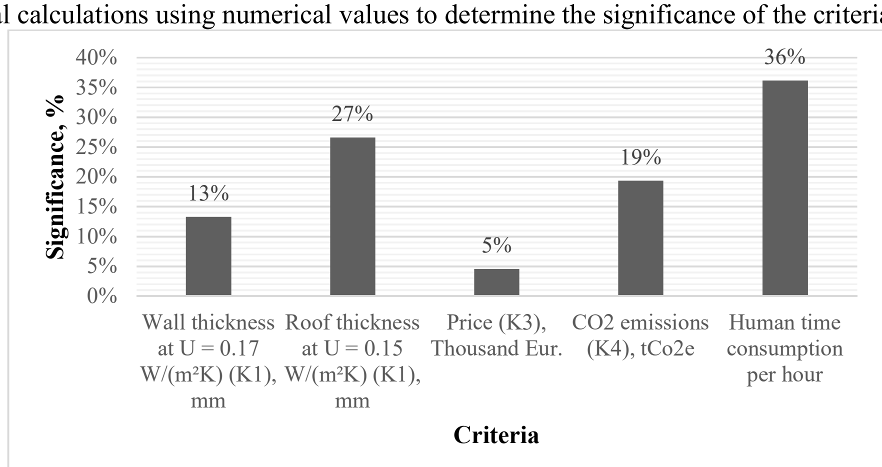

Fig. 8. Theoretical significance of the criteria using the theoretical entropy method

The calculations showed that the human time criterion (K5) has the highest theoretical significance with a theoretical significance of 36.16%, followed by roof thickness with U = 0.15 W/(m²K) criterion (K2) with a theoretical significance of 26.63%, the third place was taken by the criterion of CO_2 emissions (K4) with a theoretical significance of 19.37%, the fourth place was taken by the criterion of the thickness of the wall at U = 0.17 W/(m²K) (K1) with a theoretical significance of 13.30%. According to the theoretical significance calculations, Price (K3) is the least significant, with a significance of only 4.55%.

3.2. Determining the significance of evaluation criteria using the expert pair-wise comparison method

The expert pair-wise comparison method allows the significance of the criteria to be determined, considering the subjective views of the stakeholder groups. The criteria are ranked in order of priority: K3 > K4 > K5 > K1 = K2. The criteria are compared in pairs according to the priority ranking, with the more important criterion receiving 2 points and the less important criterion receiving 0 points. If the criteria are approximately equal, they shall be awarded one point each. The results of the calculation are shown in and Figure 4.

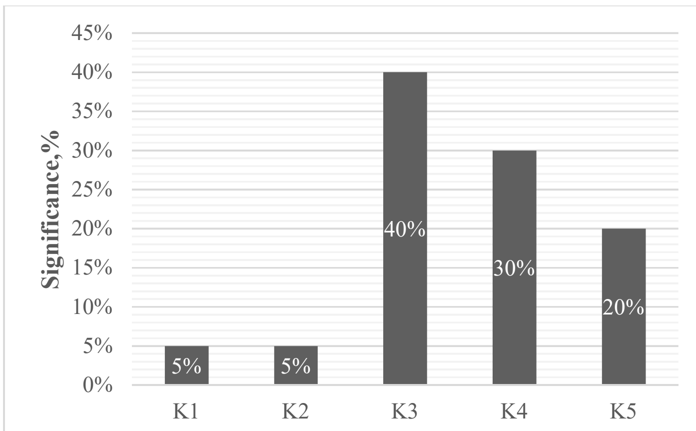

Fig. 4. Subjective significance of the criteria using the expert pair-wise comparison method

The calculations indicated that price (K3) has the highest subjective significance, with 40% of the significance. CO_2 emissions (K4) was the second most significant indicator with 30% of the subjective importance. Human time consumption (K5) is a fairly important indicator, with 20% significance. Wall thickness at 0.17 W/(m²K) and roof thickness at 0.15 W/(m²K) each scored 5% significance, showing that these indicators are almost irrelevant for the subjective choice of building design when compared to the other criteria.

3.3. Determining a rational solution using a multi-criteria utility value approach

This method identifies a rational engineering solution in the following sequence:

1. Based on the calculation data in Table 1, the initial data matrix P is constructed, the optimality of the criteria is determined, and the best value is found.
2. The matrix is normalized to a dimensionless matrix. The criteria to be maximized are normalized and the criteria to be minimized are normalized.
3. A rating scale is selected [0;100], the utility score for each criterion is calculated to determine the rational solution, i.e., the solution with the most useful criteria. Based on the results of the calculation, a priority queue of building design options is created.
4. The criteria values are scored, considering the theoretical and subjective significance of the criteria.

The priority lines and results of the building design options are shown graphically (Figure 4).

The most important criterion in the theoretical significance approach was the "human time cost criterion (K5)" and the order of priorities was as follows: K5>K2>K4>K1>K3.

In the subjective pair-wise comparison method, the most important criterion was "cost per m^2 (K3)" and the order of preference was: K3 > K4 > K5 > K1 = K2.

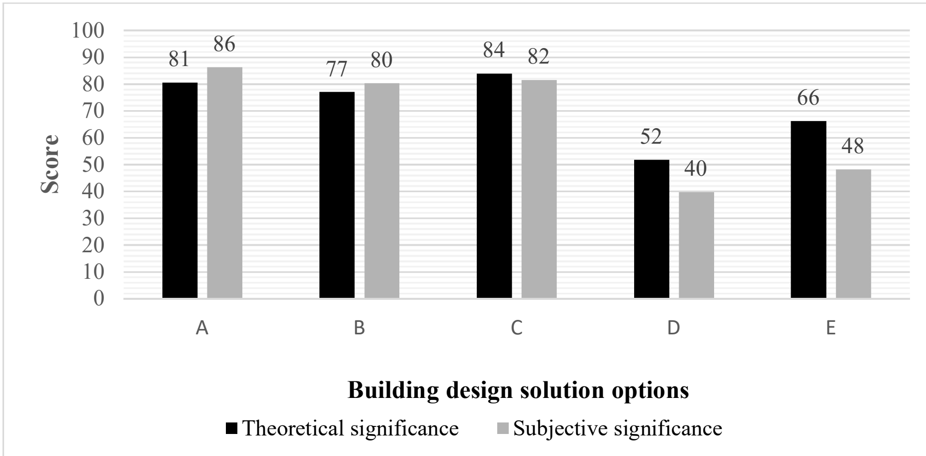

Fig.4. Usefulness of building design solutions when the theoretical and subjective significance of the criteria is assessed

The theoretical and subjective significance assessment produced the following results: Option A of the building design is ranked second in terms theoretical of significance (81 points) and first in terms of subjective significance (86 points) (Fig.4).

In terms of subjective (80 points) and theoretical (77 points) significance, building design option B is third. Building design option C is ranked first in theoretical significance (84 points) and second in subjective significance (82 points). Building design option E is ranked fourth in terms of theoretical (66 points) and subjective (48 points) significance. Building design option D is the least optimal in terms of theoretical (52 points) and subjective (40 points) significance.

4. Conclusion

The article represents the approach based on the complex system of criteria that allows comprehensive evaluation of the alternative solutions on an early design stage combining the life cycle assessment (LCA) and the multi-criteria decision analysis (MCDA).

When making engineering decisions, it is important to consider the main aspects that affect the function of the building and to make a targeted assessment of all available options and their ability to fulfill their purpose. The multi-criteria approach, which allows the evaluation of engineering solutions according to a selected system of evaluation criteria and their significance, has been chosen, and it has been found that the criterion of human time consumption (K5) has the highest theoretical significance with a theoretical significance of 36%. According to the theoretical significance calculations, price (K3) is the least significant with a significance of only 6%.

The theoretical and subjective significance assessment produced the following results: option A is ranked second in terms of theoretical significance (81 points) and first in terms of subjective significance (86 points). Building design option D is the least optimal in terms of theoretical (52 points) and subjective (40 points) significance.

The third option (building C) was the most environmentally friendly according to the data obtained by the „One click LCA" software: the building was constructed out of a reinforced concrete frame, ceilings from 200 mm thick perforated reinforced concrete panels; walls and roof designed of SIP panels.

The results obtained in this study can be applied to the design of various buildings by altering the criteria to be in line with the priority of design decisions. Criteria can be selected based on what goals need to be met while designing the building. This allows for a levelheaded, concise approach in evaluation and selection of building parameters that is not possible otherwise. The methodology used can be further improved if needed, by introducing more complex calculative multi-criteria decision-making comparisons.

Acknowledgments
This material is based upon the activities supported by the framework Erasmus+ Call 2020 EC Project Number 2020-1-FR01-KA203-080308 “Sustainable, High-Performance Hybrid Timber Building Construction“.

References

[1] Andrew, R. M.: Global CO_2 emissions from cement production, Earth Syst. Sci. Data, 10, 195–217, https://doi.org/10.5194/essd-10-195-2018, 2018.
[2] EU responses to climate change Source: https://www.europarl.europa.eu/news/en/headlines/society/20180703STO07129/eu-responses-to-climate-change [viewed 2022-06-09].
[3] World green building council. https://www.worldgbc.org/ [viewed 2022-06-12].
[4] Noha Ahmed, Mohamed Abdel-Hamid, Mahmoud M.Abd El-Razik, Karim M.El-Dash. Impact of sustainable design in the construction sector on climate change. Ain Shams Engineering Journal Volume 12, Issue 2, June 2021, Pages 1375-1383 https://www.sciencedirect.com/science/article/pii/S2090447920302446
[5] Hafner, A. Contribution of timber buildings on sustainability issues. In Proceedings of the World Sustainable Building 2014, Barcelona, Spain, 28–30 October 2014.
[6] Sizirici, B.; Fseha, Y.; Cho, C.-S.; Yildiz, I.; Byon, Y.-J. A Review of Carbon Footprint Reduction in Construction Industry, from Design to Operation. Materials **2021**, 14, 6094.
[7] EU responses to climate change. Source: https://www.europarl.europa.eu/news/en/headlines/society/20180703STO07129/eu-responses-to-climate-change [viewed 2022-06-12].
[8] Ritter, M.; Skog, K.; Bergman, R. Science Supporting the Economic and Environmental Benefits of Using Wood and Wood Products in Green Building Construction; General Technical Report FPL-GTR-206; U.S. Department of Agriculture, Forest Service, Forest Products Laboratory: Madison, WI, USA, 2011; pp. 1–9.
[9] Lolli, N.; Fufa, M.S.; Wiik, M.K. An assessment of greenhouse gas emissions from CLT and glulam in two residential nearly zero energy buildings. Wood Mater. Sci. Eng. **2019**, 14, 342–354. [CrossRef]
[10] Lukic, I.; Premrov, M.; Leskovar, Ž.V.; Passer, A. Assessment of the environmental impact of timber and its potential to mitigate embodied GHG emissions. IOP Conf. Ser. Earth Environ. Sci. **2020**, 588, 1.01–1.05. [CrossRef]
[11] Shafayet, A.; Arocho, I. Analysis of cost comparison and effects of change orders during construction: Study of a mass timber and a concrete building project. Journal of Building Engineering. Volume 33, January 2021, 101856 https://www.sciencedirect.com/science/article/pii/S2352710220334896?via%3Dihub
[12] Timber products for construction. Source: https://www.ekspertai.lt/medines_konstrukcijos/straipsniai/statybines_medienos_produktai [viewed 2022-07-20].
[13] Wooden structures - the future of high-rise buildings. Source: https://issuu.com/statybairarchitektura/docs/sa_2021_n1/s/11750521 [viewed 2022-07-21].
[14] Building the future with cross-laminated timber (CLT). https://www.storaenso.com/en/products/wood-products/massive-wood-construction/clt