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MULTIPLE CRITERIA ASSESSMENT OF MODERN TIMBER BUILDINGS

Case Study

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CONTENT

INTRODUCTION

The concept of sustainable development formulated in the 1990s is becoming more and more relevant these days. The aim is to use available resources in a way that meets the needs of today's generations without jeopardizing the ability of future generations to meet their own needs. Also, in order to achieve sustainable development, it is important to harmonize three main aspects: environmental, economic and social. Sustainable development is especially relevant in the construction and real estate sector.

When designing new buildings, more attention is paid to their impact on the environment, i.e., the entire life cycle is evaluated, from the initial idea to the use phase and the demolition of the building. It is evaluated where and how raw materials for building materials are obtained, how much energy the building consumes, whether its structures will be able to be used a second time after the building is demolished, etc.

Due to global climate change, in order to preserve nature and create a sustainable environment, construction from wood is being increasingly chosen. Wood is a renewable building material, in the production process of wooden structures and elements less greenhouse gases are emitted compared to reinforced concrete and steel, carbon dioxide (CO_2) is not emitted into the environment during the period of use of a wooden building. Also, wood has good thermal conductivity properties, which can be useful in order to save energy during the use phase of the building. With the development of wood processing and construction technologies, the construction of multi-story wooden buildings is becoming popular in the world. There is a need to examine the projects of already built buildings, to assess their coherence. In order to evaluate the sustainability of wooden high-rise buildings, it is necessary to choose appropriate evaluation indicators. Since the concept of coherence is complex, the evaluation system must consist of indicators of different significance and measurement units. In order to comprehensively assess the sustainability of buildings according to many criteria, multi-criteria assessment methods are chosen.

The aim of present case study is to assess the sustainability of modern high-rise timber buildings using multi-criteria assessment methods in different countries, i.e. Mjøstårnet in Norway, Brock Commons in Canada, Treet in Norway, Forte in Australia, Strandparken in Sweden and Stadthaus in UK.

The case study was prepared in frames of the EU funded project "Circular Economy in Wooden Construction" (Wood in Circle), which aims at delivering innovative student-centered transdisciplinary education in circular economy-based wooden construction to postgraduate students across the European countries (https://woodincircle.eu/).

1. MULTIPLE CRITERIA ASSESSMENT METHODOLOGY

In order to assess the sustainability of high-rise timber buildings, a multi-criteria assessment was chosen because it allows to take into account all aspects of sustainability: environmental, economic and social, to determine the significance of selected indicators, as well as to compare values with different units.

Figure 1 shows the developed methodology, which consists of six steps.

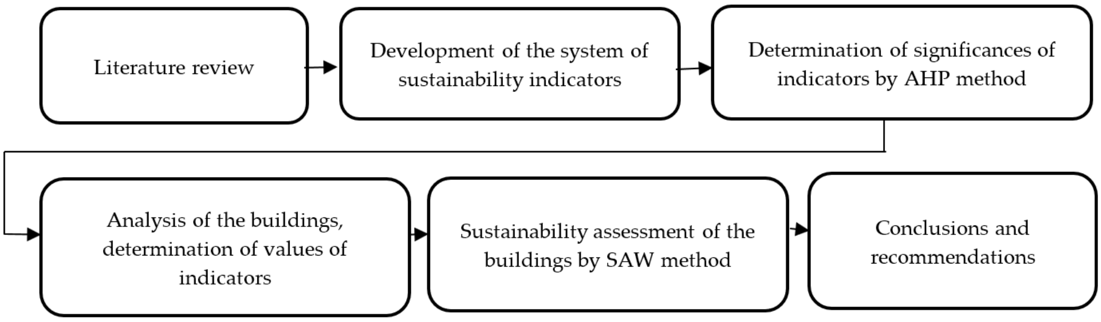

Figure 1. Research methodology

Step 1 – analysis of scientific literature. Based on the examined scientific literature, the main categories for sustainability assessment have been identified, i.e., environmental, economic/technological and social.

Step 2 – setting indicators for sustainability assessment of the buildings. Different indicators are distinguished in various literature sources. The most important indicators describing the three dimensions of sustainability were selected for the study and a hierarchical system was developed.

Step 3 – determining the significance of indicators. A questionnaire based on pair-wise comparisons was developed to determine the significance of selected indicators and sent to the experts by e-mail. The survey involved 4 experts working in national and international timber design and construction companies and 2 academics whose research area is related to sustainable construction. All experts had 10 to 20 years' experience in their field. Based on their knowledge and expertise, the experts assessed the sustainability indicators and distinguished the most important ones.

The Analytic Hierarchy Process (AHP) method by Saaty (1980) was chosen to determine the significances of the indicators. The AHP is a useful method for weighting sustainability indicators as it allows to create a hierarchical system of evaluation indicators, which is aligned with the structures of most sustainability frameworks; is simple and flexible; and provides a consistent verification.

According the AHP method, indicators are compared in pairs by each expert and assessed using a scale of 1–9 from equally important (value of 1) to extremely most important (value of 9).

Judgment matrices, filled by experts were used for the calculation of indicators' significances (Saaty, 1980):

$$q_i = \frac{\left(\prod_{j=1}^{m} c_{ij}\right)^{1/m}}{\sum_{k=1}^{m}\left(\prod_{j=1}^{m} c_{kj}\right)^{1/m}}, \tag{1}$$

and

$$\lambda_{max} = \sum_{i=1}^{m}\left\{\left(\sum_{j=1}^{m} c_{ij}\right) \times q_i\right\}, \tag{2}$$

where: k – number of experts; m – number of indicators; c_i – i^{th} determinant; q_i – significance (weight) of the i^{th} indicator; λ – eigenvalue.

The consistency ratio (CR) of each matrix was checked (Saaty, 1980):

$$CR = \frac{CI}{RI}, \tag{3}$$

where: RI – random consistency index and CI – consistency index.

Further significances provided by each expert were aggregated and assumed as distribution and the averages of these distributions were calculated in order to determine the final significances of indicators. An open source BPMSG AHP Online System (http://bpmsg.com/academic/ahp_calc.php) was used for calculations.

Stage 4 – analysis of the buildings and determination of values of indicators. Six high-rise timber buildings were selected for analysis. Values of indicators have been determined by using publicly available information.

Step 5 – multi-criteria sustainability assessment of the buildings. For this purpose, the Simple Additive Weighting (SAW) method, summarized by MacCrimmon (1968) was selected. It is one of the oldest, widely known, simple and practically used multi-criteria assessment method. It allows to integrate values of indicators and their significances into a single magnitude by calculating efficiency index R_j of each building alternative:

$$R_j = \sum_{j=1}^{n} q_i \bar{x}_{ij}, \tag{4}$$

where q_i is the weight of the i^{th} indicator; $\bar{x}_{ij}$ – normalized attribute value of the j^{th} alternative.

Step 6 – conclusions and recommendations. Based on the results of an expert survey and a multi-criteria evaluation, conclusions and recommendations have been provided.

2. CASE STUDY

2.1. Evaluation indicators and their significance

Following an analysis of the literature, BREEAM and LEED certification systems, the most frequently used sustainability evaluation indicators were selected, some indicators were added by authors. Table 1 provides a description of these indicators and their measurement.

Table 1. Description of evaluation indicators.

Indicator	**Description & measurement**
Environmental indicators	
Reduced CO_2 emissions (E1)	Reduced CO_2 emissions to the atmosphere when comparing a timber-framed building with a similar reinforced concrete building. The unit of measurement is tons. The bigger the difference, the less negative environmental impact the building has.
Reduced waste during construction (E2)	Prefabricated, modular construction technologies produce less waste than conventional construction methods. The less waste generated during construction, the less negative impact the building has on the natural environment. The unit of measurement is points (3 points – modular construction is applied, all elements are brought to the construction site ready for installation, many works are carried out in the factory (windows are installed, plumbing equipment, finishing is carried out, a minimum amount of waste is generated; 2 points – prefabricated construction is used, only a small amount of waste is generated; 1 point – prefabricated construction is applied, all elements are brought to the construction site ready for installation, but the amount of construction waste is higher because part of the building is made of reinforced concrete.
Possibility of reusing structures after building demolition (E3)	Possible reuse or recycling of building structures, which reduces negative impact on the environment during demolition of the building. In the case of prefabricated construction, the use of timber elements decreases the number of chemical connections. Mechanical joints are easier to disassemble; the structures remain intact and can be reused. Also, less dust is generated during the demolition of the building. The unit of measurement is points (3 points – the building's timber structures are prefabricated, modular and have almost no reinforced concrete; 2 points – the building's timber structure is prefabricated, modular, with reinforced concrete ground floor or rigid cores; 1 point – the building's timber structures are prefabricated, modular, with several floors and reinforced concrete rigid cores).
Preserving the natural environment around the building (E4)	Impact of the building on the local natural environment. The unit of measurement is points (3 points – the project preserves natural environment and creates pedestrian paths; 2 points – the project has no significant impact on the environment, new plants are planted on the site, footpaths are created; 1 point – after the project, most of the site is covered with pavements (tiles, cobblestones, asphalt), with few plants).
Energy consumption (E5)	Annual energy consumption per square meter of a building. The smaller the value, the more energy-efficient the building is and the less negative the impact on the natural environment. Unit of measurement – kWh/m^2 per year.
Renewable energy deployment (E6)	Deployment of renewable energy systems (solar, wind, geothermal). The unit of measurement is points (3 points – the building has several renewable energy systems (solar panels, wind turbine, geothermal heating) and electric

	car charging stations; 2 points – the building is equipped with at least one such system; 1 point – there are no such systems in the building, or there is no record of installed systems).
Use of local raw materials (E7)	Building materials which are manufactured within a defined radius or produced locally using raw materials obtained within a defined radius. Unit of measurement – points (5 points – using building materials from local sources less than 100 km away; 4 points – 101–500 km away, 3 points – 501–1000 km away; 2 points – 1001–1500 km away, 1 point – more than 1500 km away).
Heat transfer coefficient of the external envelope (E8)	The heat transfer coefficient, measured by *U*-value. Unit of measurement – W/m^2K.
Amount of wood used (E9)	Relative value indicating the proportion of used timber structures (m^3) per square meter of the building.
Using certified wood (E10)	The building materials are made from wood that is certified and sourced from replanted forests. The unit of measurement is points (3 points – the timber used for the building's construction is certified by the Forest Stewardship Council (FSC) or other authorized certification body, and some of the structures are made from recycled wood waste; 2 points – the wood used for the building's construction is certified; 1 point – the wood is not certified).
Sustainability certification (LEED, BREEAM, etc.) (E11)	The building is certified for sustainability (LEED, BREEAM or other) and meets international or global environmental standards. The unit of measurement is points (3 points – the building is LEED, BREEAM, Green Star or other certified; 2 points – the building has been designed to one of these standards but has not yet received it; 1 point – the building is not certified).
Technological and economic indicators	
Building height (ET1)	Architectural height of the building (meters).
Number of floors in the building (ET2)	The number of floors above ground in a building, sometimes buildings of the same height may have different numbers of floors. The more floors, the larger the area of the building that can be sold/leased. The unit of measurement is the number of floors.
Cost of implementing the project (ET3)	The ratio of the project's implementation cost to the project's gross floor area. The lower the cost, the more cost-effective the project is. Unit of measurement – EUR/m^2.
Installation time of the structures (ET4)	The time taken to install the load-bearing structures of one floor of the building. The shorter the installation time, the more cost-effective the construction of the building. Unit of measurement – floor/day.
Duration of the project (ET5)	The time taken to complete the project. The shorter the time, the more successful the project. The unit of measurement is months.
Social indicators	
Indoor acoustic comfort (S1)	Ensuring the acoustic comfort. The unit of measurement is points (3 points – the sound class of the premises meets the requirements of class B (< 55 dB), the materials used are sound absorbing, resulting in maximum acoustic comfort; 2 points – the sound class of the premises meets the requirements of class C (≥ 55 dB), the materials used are sound absorbing, which creates acoustic comfort; 1 point – data on the sound class of building envelope components are not available, but the solutions implemented in the project meet the requirements for sound class, the materials used suppress the generated sounds).
Building location, accessibility (S2)	Assessment of the location of the building, taking into account the accessibility of the site, the infrastructure, the distances to the main social

	facilities, and the transport links. The unit of measurement is points (3 points – within 5 km there is the school, kindergarten, shop, public transport stops, good access by car, the building is close to major cities; 2 points – the nearest school, kindergarten, shop, public transport stops can be reached within 10 km, with good access by car; 1 point – more than 10 km from the nearest school, kindergarten, shop, public transport stop).
Indoor microclimate, comfort (S3)	An indicator that measures a person's psychological state and productivity in a given environment. It has been scientifically proven that working, living in an environment with timber elements reduces stress, improves a person's psychological state, productivity and mood. The unit of measurement is points (5 points – exterior and interior timber structures of the building are exposed as interior details, additional timber elements predominate in the finishing; 4 points – the internal timber structures have been retained as interior fittings; 3 points – timber structures are hidden, but timber elements dominate the decoration of the common areas; 2 points – timber structures are hidden, timber elements predominate in the decoration of the apartment; 1 point – finishing is done without using timber details).
Aesthetic appearance of the building (S4)	An indicator assessing a building's aesthetics, architectural idea, and the overall architecture of the dominant buildings in the city. Measured by points (3 points – the building fits perfectly into the city's architecture; 2 points – the building stands out from the surrounding buildings, but does not have a negative impact; 1 point – the building does not correspond at all to the architecture or elements of the buildings prevailing in the area).
Project awards (S5)	An indicator that measures the awards a building has received. Measured by points (3 points – received awards for adapted technologies, new world-class achievements; 2 points – received awards for adapted technologies, new local achievements; 1 point – the building has not won any awards).
Fire resistance (S6)	An indicator assessing the ability of the building envelope to withstand minutes of fire, additional fire protection measures installed. Measured by points (5 points – the load-bearing structures can withstand 120 minutes of fire, a sprinkler system has been installed; 4 points – 90 min., a sprinkler system has been installed; 3 points – 60 min., a sprinkler system has been installed; 2 points – > 60 minutes, no additional fire-fighting measures; 1 point – the building does not meet fire safety requirements).
Spaces for communities (S7)	An indicator of the extent to which a building supports creation of communities, i.e. whether common spaces are created around or within a building. Measured by points (3 points – the building provides meeting spaces for communities beyond the building's occupants, such as a shared terrace, a sports club or a café, so that people can live and work in the same building, and the environment has been landscaped with new pedestrian walkways and parks; 2 points – creating common spaces for the building's residents only, landscaping the environment; 1 point – the building does not add any social value, there are no common spaces).

The significance of the indicators was assessed using an expert survey and the AHP method. The key environmental indicators identified are: renewable energy deployment – significance level 0.205, sustainability certification (LEED, BREEAM or other) – 0.166, and energy consumption – 0.130. In the economic/technological category, the most significant indicators are the cost of the project with a significance of 0.365, the duration of the project with a significance of 0.286, and the duration of the installation of the structure with a significance of 0.147. The most important social indicators, in accordance with the experts, are the fire resistance of the building – 0.291, the indoor microclimate, comfort – 0.196 and the location of the building, accessibility – 0.188. It is assumed, that all sustainability dimensions are of equal importance and therefore have equal significance, i.e. environmental, social and economic/technological indicators have a significance of 0.333.

The hierarchical system of sustainability indicators and their significances are provided in Figure 2.

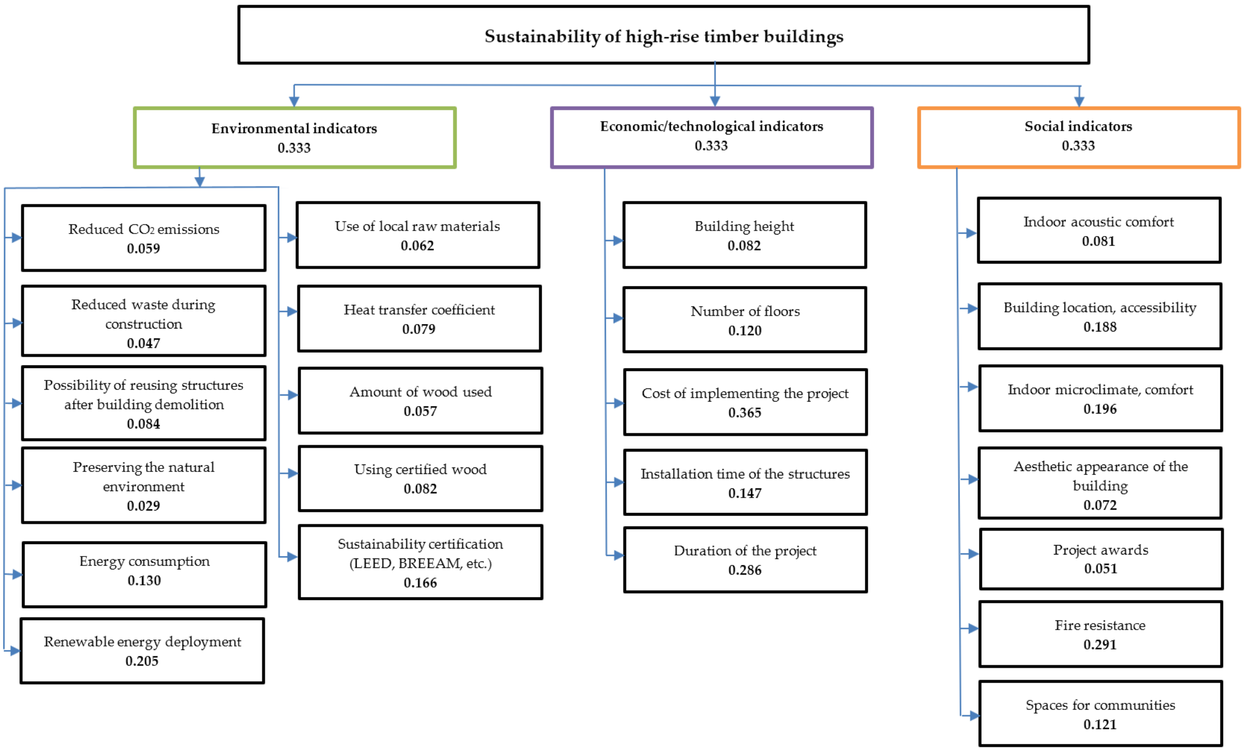

Figure 2. Hierarchical system of sustainability indicators

2.2. Description of the high-rise timber buildings to be assessed

In the light of the multi-criteria evaluation indicators chosen, a description of the buildings to be compared is given below. Six sites in different parts of the world were selected for the multi-criteria evaluation: Mjøstårnet (Norway), Brock Commons (Canada), Treet (Norway), Forte (Australia), Strandparken (Sweden) and Stadthaus (UK).

***Mjøstårnet or The Mjos Tower* (A1)** in 2020 was the tallest timber-framed building in the world at 18 storeys and 85.4 meters high (Figure 3). The building has a total area of 11,300 m^2, with each floor covering about 630 m^2, and a 4,900 m^2 public bath with swimming pools. The cost of the project was EUR 51.15 million, of which EUR 4.82 million was for the construction of the building. Construction of the building took 24 months, starting in April 2017 and finishing in March 2019. The installation of the timber structures took 10 months, i.e., on average one floor of the building was installed in 12 business days (Abrahamsen, 2015).

Mjøstårnet is located in the small town of Brumunddal in Norway, about 140 km from Oslo, next to the motorway, on the shores of Norway's largest lake, Mjøsa. The building is easily accessible by car and train [40]. Distance to the nearest school – 9.1 km, kindergarten – 14.5 km, train station – 0.9 km, bus station – 15.4 km, supermarket – 8.6 km. The building's setting is also significant in terms of its relationship with nature, as the area is well known for its forestry and timber industry.

The building's main structural elements were prefabricated, which resulted in minimal waste during the construction process, and all the products have been brought to the site from the factory. However, the building is not made entirely of timber. Other construction materials that generate waste, such as concrete foundations and finishing materials, were used in the construction.

Figure 3. Mjøstårnet (Burmunddale, Norway) (European Organisation of the Sawmill Industry, 2021)

The glued laminated timber structures were manufactured at the plant of the Moelven Industrier ASA group, located 15 km from the construction site, using local spruce forest raw material, which is within a radius of 50 km from the building being built [40]. Wood façade elements were supplied by Woodify AS, about 200 km from the construction site. From the building's overview terrace, it is seen where the wood was taken from and where it was processed. Approximately 11 to 13 thousand trees were used in the production of glued laminated timber structures, i.e., a total of 2 600 m^3 of timber structures (European Organisation of the Sawmill Industry, 2021). The timber was FSC certified and complies with the European Union Timber Regulation (EUTR).

The building complies with the requirements for a passive house and energy class A in accordance with the Norwegian standard NS 3701 (Ringsaker, 2021). Its external envelope components have a heat transfer coefficient U-value of 0.11 W/m^2K, the building consumes 102 kWh/m^2 per year (Ostgard, 2021). There are charging stations for electric vehicles nearby and the building uses wind energy as an alternative energy source (Ringsaker, 2021). CO_2 emissions are 1 577 t lower than for the same building of reinforced concrete construction (Madsen & Sydow, 2019). BREEAM-NOR certification is planned, but documentation is still being prepared (Ostgard, 2021).

The impact of the building on the area is positive, i.e., there is a parking lot, pedestrian paths, lighting of the territory, new trees planted, shrubs, herbaceous plants. Public gardens and outdoor spaces connected to pedestrian paths and bicycle paths are located near the lake. This multi-storey building is of special landscape significance because of its proximity to Norway's largest lake, and the building, which can be seen from afar, has quickly become an important symbol of the city. The Mjøstårnet tower looks like a tree, with pine cladding and support columns made of wooden beams, and fits perfectly into the landscape of the area, looking aesthetic.

The project has made a positive contribution to the social development of the region. The building is mixed-use, with offices, 33 apartments, 72 hotel rooms, a conference room and a roof terrace. The roof terrace is open to residents, hotel guests and staff, while other guests can access it with a ticket. The ground floor is open to the public and includes a lobby, reception and restaurant. There is also a public bath and two 25-metre swimming pools on the ground floor. This creates shared public spaces accessible to all, where communities can meet (Abrahamsen, 2015). The city of Bruumiundal was notorious for its crime in the 1990s, where one third of all racist attacks in Norway took place. It is expected, that a new high-rise timber building will attract more tourists and investors. It is also planned to construct three lower multi-storey buildings of a similar type next to each other in the future (Abrahamsen, 2015).

Mjøstårnet project received the award for Best Architectural Design 2018 at the New York Design Awards and the Norwegian Technical Award in the construction category.

Brock Commons **(A2)** is an 18-storey, 54-metre-high timber-framed building in Canada with a total floor area of 15.12 thousand m^2 (Figure 4). The cost of the project was EUR 36.34 million. The construction of the building took 20 months, starting in December 2015 and finishing in July 2017. The concrete foundations, 1st and 2nd floors and two free-standing concrete rigid cores (elevator shafts) were installed in 7 months. Installation of the timber structures took 70 days. Looking at the whole building structure, on average, one storey of the building was erected in 12 business days and the timber storey in 5 business days (The University of British Columbia, 2021).

Figure 4. Brock Commons (Vancuver, Canada) (Korody, 2021)

The main use of the building is as dormitory rooms for students on campus, so the location on the University of British Columbia site is appropriate, with excellent facilities for students (close to the university, library, sports fields).

The use of prefabricated elements in the building's construction has reduced the amount of waste on site by about two thirds, but as in the Mjøstårnet project, not only timber structures have been used, i.e., 1st and 2nd floors and the elevator shafts are made of reinforced concrete. The structures were manufactured 430 km away from the site. Local materials (38%) and recycled materials (19%) were used to make the structures. A total of 2,233 m^3 of timber structures were installed in the building (Naturallywood, 2017). The wood was sourced from sustainably managed forests, FSC certified.

The value of the heat transfer coefficient of the building's external envelope components is 0.063 W/m^{2}K, energy consumption 135 kWh/m^2 per year, 5% of consumed electricity comes from renewable sources. The building is equipped with an electric vehicle charging station (The University of British Columbia, 2021). The choice of timber for the main load- bearing structures avoided 2,432 tons of CO_2 emissions (Gintoff, 2016). The building is certified LEED Gold BD+C for new construction (The University of British Columbia, 2021).

The impact of the building on the area is positive, the environment around the building is arranged, i.e. pedestrian paths, lighting of the territory, the territory is planted. A forest near the university campus has created a lasting harmony with the tree (Canadian Wood Council, 2016). The building's architecture is in harmony with the nearby dormitories.

The project has made a positive contribution to the social development of the region. The building is equipped with more than 400 student rooms, study and common areas, and lounges. These places become academic and recreational hubs for the student community.

The information collected by the Building Management System (BMS) allows operators to assess the performance of the system and check air quality and temperature. In order to continuously improve living conditions for students, the University conducts an annual survey that assesses staff, dormitory accessibility, noise levels in the building, building design, lighting, indoor air quality, thermal comfort and acoustics (The University of British Columbia, 2021). Timber elements predominate in the decoration of the rooms and common areas, with exposed timber structures in some places.

The building has won many awards in various fields: Wood Design and Building 2017, Fast Company Innovation by Design 2017, Favourite Projects of the Year 2017 Construction Dive Five, National Council of Structural Engineers Associations Award for Excellence in Structural Engineering 2017, Canadian Wood Council Wood Products Awards 2018 (Architect's Award, Engineer's Award, Innovation Award).

***Treet* or *The Tree* (A3)** is a 14-storey and 52.8-metre-high timber building in Norway, the total area of the building is 5.83 thousand m^2 (Hamburg et al., 2018) (Figure 5). The cost of the project was EUR 22 million, it took 20 months to complete construction of the building. Construction started in April 2014 and finished in November 2015. The installation of the timber structures took 10.5 months, i.e., one floor of the building was erected in 15 business days on average (Abrahamsen & Malo, 2014).

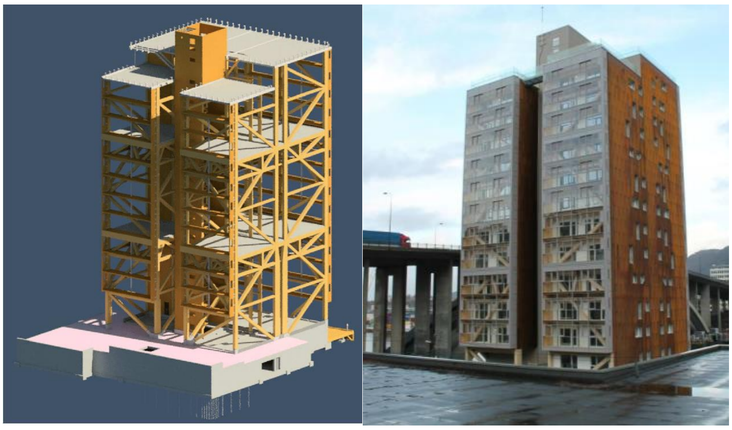

Figure 5. Treet (Bergen, Norway) (Avellan, 2018; Kjolberg, 2017)

The building is located in the central part of the city of Bergen. Bergen is the second largest city on the west coast of Norway. The building is located near a large bridge that crosses the Puddefjorden fjord (Abrahamsen & Malo, 2014). Distance to the nearest school – 7.1 km, kindergarten – 3.4 km, train station – 3.0 km, bus station – 3.8 km, supermarket – 1.1 km.

The main structural elements were prefabricated and modular. The building modules that make up the apartments were supplied by the Estonian company Kodumaja, which is located 1,560 km away from the construction site, resulting in high transport costs. Moelven Industrier ASA supplied glulam and cross-laminated timber structures (Hamburg et al., 2018). The factory is 450 km from the site and the raw materials for the structures came mainly from local Norwegian forests. In total, 935 m^3 of wood was used, which was FSC certified and complies with the EUTR regulation.

The building complies with the requirements for a passive house and energy class A in accordance with the Norwegian standard NS 3700/3701 (Abrahamsen & Malo, 2014). The U-value of the heat transfer coefficient of its external envelope is 0.12 W/m^2K, the building consumes 84 kWh/ m^2 per year. A shared electric car is available for the building's residents. Only 25 parking spaces were provided for 62 apartments, thus promoting the sharing economy. The building is equipped with a heat recovery ventilation system, which reduces electricity consumption. CO_2 emissions to the environment are 2,000 t lower than in the same building from reinforced concrete structures (Kleppe & Abrahamsen, 2016). There is no information on the use of renewable energy sources or the environmental and sustainability certificates obtained.

The building has a positive impact on the area, with landscaping, pedestrian walkways and lighting. The building fits perfectly into its surroundings. In recent decades, the technology developed to build timber bridges has been applied to the construction of the building, making it similar to the nearby bridge (Kleppe & Abrahamsen, 2016). The building fits well into the landscape of the area and its architecture is aesthetically pleasing. There is a terrace at the top of the building on the 13th and 14th floors and a gym on the 9th floor with views of the city and the fjords.

To create a comfortable environment, the interior of the apartments has been left with exposed timber structures. To reduce the building's fluctuations, giving more weight to the building, concrete slabs were cast to increase the comfort of the people living on the upper floors.

In 2015, Treet was the tallest timber building in the world. The project received the Construction of the Year Award 2015.

Forte **(A4)** is a nine-storey building with a height of 32.2 meters in Australia and a total area of 1.9 thousand m^2 (Lend Lease, 2013) (Figure 6). The cost of the project was EUR 9.87 million. Construction of the building took 11 months, starting in February 2012 and finishing in December 2012. The installation of the timber structures took 50 days, i.e., one floor of the building was assembled in 6 business days on average (Lend Lease, 2013).

The property is close to public transport, car and bike sharing facilities and shops, the nearest school is 5.1 km away, a kindergarten is 11.4 km away, a train station is 1.8 km away, a bus stop is 0.4 km away, and a supermarket is 0.2 km away.

The main structural elements were prefabricated, resulting in minimal waste during construction. The cross-laminated timber panels were manufactured by KLH Massivholz GmbH in Austria and then shipped to Australia on two ships in 25 containers (Lend Lease, 2013), incurring high transport costs as no local raw materials were used. In total, the building has approximately 883 m^3 of timber structures, and all the cross-laminated timber used in the building is certified to PEFC (Programme for the Endorsement of Forest Certification) standards.

Figure 6. Forte (Melbourne, Australia) (KLHUK, 2012)

There is no information on the heat transfer coefficient of the external envelope of the building and its energy consumption, so it is assumed that the building has similar dimensions to building A6 and therefore has a U-value of 0.13 W/m^{2}K and an annual consumption of 144 kWh/m^2. The building does not have any renewable energy systems installed. CO_2 emissions are 1.451 t less than for the same reinforced concrete building. The building has received a 5-star rating under Australia's GREEN STAR certification (Lend Lease, 2013).

The Forte has a positive impact on the area, with landscaping around the building, such as pedestrian paths, lighting and new landscaping. The architecture of the building fits in with the surrounding buildings and the landscape of the area and has an aesthetic appearance. There are four luxury townhouses in the neighborhood. The buildings reflect the contemporary urban lifestyle of Victoria Harbour (Lend Lease, 2013).

The project contributed to the social development of the region. It has 23 apartments and a commercial space on the ground floor, allowing residents to work, live and socialize in one building. There is a community garden nearby and vegetables are grown on the balconies. Each apartment is designed to maximize sunlight and natural ventilation. The interior has been left with open cross-laminated timber wall panel structures, and the finishing is dominated by timber elements.

In 2012, the Fort was the tallest residential timber building in the world and the first cross-laminated timber building in Australia (Lend Lease, 2013).

Strandparken **(A5)** is an 8-storey, 25-metre-high building in Sweden with a total area of 4,300 m^2 (Figure 7). The cost of the project was EUR 8.16 million. Construction of the building took 20 months, starting in 2013 and finishing in April 2014 (Larsson et al., 2017). The installation of the timber structures took 120 days, i.e., one floor of the building was installed in an average of 15 business days.

Figure 7. Strandparken (Sundbyberg, Sweden) (Swedish Wood, 2016)

Strandparken is located in the small Stockholm suburb of Sundbyberg. Distance to the nearest school – 7.1 km, kindergarten – 3.6 km, train station – 0.6 km, bus stop – 0.9 km, supermarket – 2.7 km. The building's setting is also significant in terms of its relationship with nature, with the Lake Balstaviken Bay nearby and the abundance of trees.

The amount of waste generated during the construction process was minimal, as all products and structures were brought to the site from the factory. 90% of the building's structures can be reused or recycled (Lundgren, 2014). Local spruce wood was used as structural material. The cross-laminated timber panels were supplied by Moelven Industrier ASA and Martinsons. The building is constructed from prefabricated cross-laminated timber wall and floor elements, which were manufactured approximately 700 km from the site. Total use of timber structures: about 1,290 m^3. All the wood used in the building was certified in accordance with the Programme for the Endorsement of Forest Certification (PEFC) and FSC standards and complies with the EUTR regulation.

The building complies with the requirements for a passive house in accordance with the FEBY12 standard. Its external envelope components have a heat transfer coefficient U-value of 0.16 W/m^2K, the building consumes 65 kWh/m^2 per year (Larsson et al., 2017). Renewable energy systems were not installed. CO_2 emissions are 1.451 t less than for the same reinforced concrete building (Lundgren, 2014). The building does not have any sustainability certificate.

The building has a positive impact on the area, with a car park, footpaths, lighting, new trees, shrubs and herbaceous plants. The architectural appearance of the building fits well with its surroundings. For the façade of this building, Canadian cedar planks were chosen, which change color to greyish over time.

Strandparken received the Swedish Wood Award 2016, which is awarded every 4 years to a timber building for its architecture and use of today's technology (Swedish Wood, 2016).

Stadthaus **(A6)** is a 9-storey and 26-metre-high multi-apartment building in the United Kingdom with a total area of 2.89 thousand m^2 (Figure 8) (Hamnburg et al., 2018). The cost of the project was EUR 4.46 million. The construction of the building took 24 months, starting in 2007 and finishing in 2009. The installation of the timber structures took 9 weeks, i.e., one floor of the building was installed in an average of 5 business days.

Figure 8. Stadthaus (London, UK) (Waugh Thistleton Architects, 2021; TRADA, 2021)

Stadthaus is in the London Borough of Hackney. Distance to the nearest school – 3.7 km, kindergarten – 14.3 km, train station – 4.0 km, bus station – 0.5 km, supermarket – 2.9 km.

The building's structures were assembled by a local company, KLH UK, but the factory from which the structures were supplied is located in Austria, some 1 400 km from the site. This has led to high transportation costs. The façade is designed of 5,000 cross-laminated timber panels (1,200×230 mm each), made of 70% waste wood. In total, about 900 m^3 of wooden structures were installed (TRADA, 2021). All cross-laminated timber is PEFC-certified and the raw materials used for the panels came from sustainably managed forests.

The value of the heat transfer coefficient of the external envelope components is 0.13 W/m^2K, the building consumes 144 kWh/m^2 per year. CO_2 emissions are 310 t lower than for the same building made of reinforced concrete (TRADA, 2021). All rooms have mechanical ventilation with a thermal break, which retains 70% of the heat that would normally be lost. Photovoltaic panels (PV panels) on the roof provide a small amount of renewable energy.

The architects designed the façade of the building in accordance with the changing light and shadows created by the surrounding buildings and trees (TRADA, 2021). The project includes landscaping and children's playgrounds in the inner courtyard. The building has 29 apartments, the local community has its own meeting place in the basement and the first three floors of the building are dedicated to social housing.

The building has two separate staircases and corridors, creating a more welcoming neighborhood for residents. Inside, the timber structures are hidden, but wooden floors dominate the finishes.

Awards received by Stadthaus: Timber in Construction Awards 2008, Timber Journal Awards 2008, British Construction Industry Awards 2009, Building for Life Gold Standard, CABE 2009.

2.3. Assessment of the buildings

The multi-criteria assessment was performed according to the SAW methodology (see Section 1). Table 2 shows the initial decision-making matrix in which the values of the indicators for each building are provided.

The initial decision matrix was normalized, according to the SAW methodology, the obtained values of the indicators were multiplied by their significances and the obtained vales have been summed to calculate efficiency index R_j. Finally, rankings of the buildings in each sustainability dimension were determined (see Table 3).

Table 2. Decision-making matrix

Dimension	**Indicator**	**Significance**	**Max/Min***	**Unit**	**Buildings**					
		data			A1	A2	A3	A4	A5	A6
Environmental	E1	0.059	Max	Tons	1577	2432	2000	1451	1470	310
	E2	0.047	Max	Points	1	1	3	2	2	2
	E3	0.084	Max	Points	2	1	2	3	3	3
	E4	0.029	Max	Points	2	1	2	2	1	2
	E5	0.130	Min	kWh/m^2 per	102	135	84	144	65	144
	E6	0.205	Max	year	3	2	2	1	1	2
	E7	0.062	Max	Points	3	2	2	1	1	1
	E8	0.079	Min	Points	0.11	0.06	0.12	0.13	0.16	0.13
	E9	0.057	Max	W/m^{2}K	0.23	0.15	0.16	0.46	0.30	0.31
	E10	0.082	Max	m^3/m^2	2	3	2	2	2	2
	E11	0.166	Max	Points	2	3	2	1	1	1
				Points						
Economic/ Technological	ET1	0.082	Max	Meters	85.4	54.0	52.8	32.2	25.0	26.0
	ET2	0.120	Max	Number	18	18	14	9	8	9
	ET3	0.365	Min	EUR/m^2	4527	2403	3774	5195	1898	1543
	ET4	0.147	Min	Days per floor	12	12	15	6	15	7
	ET5	0.286	Min	Months	24	20	20	11	20	24
Social	S1	0.081	Max	Points	2	2	2	1	3	2
	S2	0.188	Max	Points	2	3	3	3	3	1
	S3	0.196	Max	Points	5	4	5	5	5	2
	S4	0.072	Max	Points	3	3	3	3	3	3
	S5	0.051	Max	Points	3	2	3	3	2	2
	S6	0.291	Max	Points	5	5	4	4	3	3
	S7	0.121	Max	Points	3	3	2	3	1	2

Note: *Max – the higher value is preferred; Min – the lower value is preferred.

A multi-criteria assessment revealed that the most sustainable building in terms of environmental performance is Mjøstårnet (A1). The building was built from locally sourced wood, main structural elements were prefabricated, which resulted in minimal waste during the construction process. It has high energy performance, complies with the requirements for a passive house. In addition, the building is surrounded by electric vehicle charging stations, which use wind energy as an alternative energy source. The Stadthaus (A6) was ranked as best building in terms of economic-technological performance, as it had the lowest cost of implementation compared to other projects, however, it was built earlier than other buildings and its height is two times lower compared to Mjøstårnet (A1) and Brock Commons (A2). In terms of social performance, the Brock Commons student residence (A2) is the best performing building, with a 120-minute fire resistance rating for the main load-bearing structures and fire alarm and extinguishing systems throughout the building. The building also offers comfortable living conditions and is well located, with easy access to the university, the library and the sports fields.

Table 3. Normalized-weighted matrix and calculation results

Dimension	Indicator	Buildings					
		A1	A2	A3	A4	A5	A6
Environmental	E1	0.038	0.059	0.049	0.035	0.036	0.008
	E2	0.016	0.016	0.047	0.031	0.031	0.031
	E3	0.056	0.028	0.056	0.084	0.084	0.084
	E4	0.029	0.015	0.029	0.029	0.015	0.029
	E5	0.083	0.063	0.101	0.059	0.130	0.059
	E6	0.205	0.137	0.137	0.068	0.068	0.137
	E7	0.062	0.041	0.041	0.021	0.021	0.021
	E8	0.043	0.079	0.040	0.036	0.030	0.036
	E9	0.029	0.019	0.020	0.057	0.037	0.038
	E10	0.055	0.082	0.055	0.055	0.055	0.055
	E11	0.111	0.166	0.111	0.055	0.055	0.055
	Index	0.726	0.703	0.684	0.531	0.561	0.553
	Rank	1	2	3	6	4	5
Economic/ Technological	ET1	0.082	0.052	0.051	0.031	0.024	0.025
	ET2	0.120	0.120	0.093	0.060	0.053	0.060
	ET3	0.124	0.234	0.149	0.108	0.297	0.365
	ET4	0.074	0.074	0.059	0.147	0.059	0.126
	ET5	0.131	0.157	0.157	0.286	0.157	0.131
	Index	0.531	0.637	0.509	0.632	0.590	0.707
	Rank	5	2	6	3	4	1
Social	S1	0.054	0.054	0.054	0.027	0.081	0.054
	S2	0.125	0.188	0.188	0.188	0.188	0.063
	S3	0.196	0.157	0.196	0.196	0.196	0.078
	S4	0.072	0.072	0.072	0.072	0.072	0.072
	S5	0.051	0.034	0.051	0.051	0.034	0.034
	S6	0.291	0.291	0.233	0.233	0.175	0.175
	S7	0.121	0.121	0.081	0.121	0.040	0.081
	Index	0.910	0.917	0.874	0.888	0.786	0.556
	Rank	2	1	4	3	5	6

In the next step an overall assessment was performed. For this purpose, the aggregated values for each sustainability assessment category were used. Aggregated values were multiplied by the significances of dimensions (0.333 each) and the obtained vales have been summed to calculate an overall efficiency index.

A summary assessment of the sustainability of buildings is presented in Figure 9.

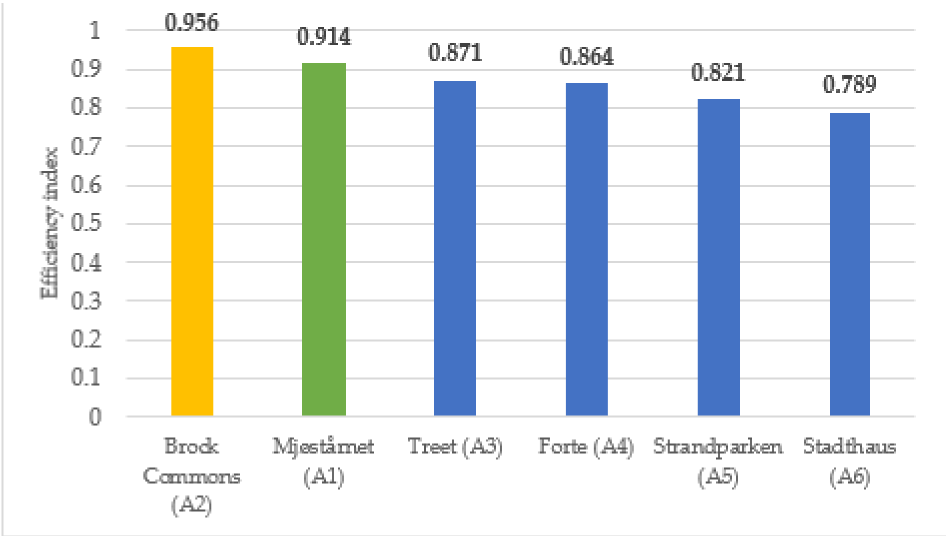

Figure 9. Overall assessment results

Calculations show that the most sustainable building in all sustainability assessment categories is Brock Commons (A2). This building was in second place in terms of environmental indicators, but the social indicators were better compared to other buildings. The Mjøstårnet building (A1) is in the second place, and its overall rating is not much different from that of the Brock Commons building (A2). The building has the highest environmental performance, but the Brock Commons (A2) building has better socio-economic performance.

CONCLUSION

Six wooden high-rise residential buildings were selected for multi-criteria sustainability analysis: "Mjostarmet" in Norway, "Brock Commons" in Canada, "Treet" in Norway, "Forte" in Australia, "Strandparken" in Sweden and "Stadthaus" in the United Kingdom. After carrying out a multi-criteria evaluation using the SAW method, it was determined that the most sustainable building in terms of environmental indicators is "Mjostarmet", because there are charging stations for electric vehicles near it, and the building uses wind energy as an alternative energy source. According to the economic-technological indicators, the best building is the "Stadthaus", because the project implementation cost was the lowest compared to other projects. The best building in the field of social indicators is "Brock Commons" student dormitory, because its main load-bearing structures have a 120-minute fire resistance, fire alarm and extinguishing systems are installed throughout the building. Also, the building has comfortable conditions for living, the location of the building is chosen properly, because students can easily reach the university, library or sports fields.

After the general evaluation of the buildings' sustainability, it was found that the most sustainable building is "Brock Commons". This building ranked second in terms of environmental protection and economic-technological indicators, but its social indicators were better than other projects.

Same multiple criteria assessment methodology can be used for sustainability evaluation of other buildings.

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