Use of cross laminated timber (CLT) in industrial buildings in Nordic climate – A case study

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Use of cross laminated timber (CLT) in industrial buildings in Nordic climate – A case study

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Abstract. In recent years there has been a greater interest in developing new more sustainable solutions in the construction of buildings and in particular of large commercial and industrial buildings. This study analyses the feasibility and degree of sustainability of using cross laminated timber (CLT) as building material in industrial buildings in Nordic climate. An industrial building located in Eastern Norway, MAXBO Bjertnestangen, has been used as case study for the analysis. Two scenarios have been studied: i) the first analyses the existing industrial building (Scenario 1) built in steel, and ii) the second implies that the building components are replaced with CLT-elements (Scenario 2). For the structural analysis a commercial finite element method (FEM) code has been used and the results confirm that the CLT building achieves approximately equal mechanical and structural properties. For studying building physics in the two buildings, a commercial numerical simulation tool that couples hygrothermal with energy performance and uses the finite volume method (FVM) has been employed. The results show that it is possible to achieve a total energy saving of 3.3%, for the industrial building consisting of CLT-elements compared to the existing building. Furthermore, the life cycle analysis (LCA) shows that the total emission of CO_2-eq is 16.7% lower in the CLT building, however the building's construction costs are higher 13% compared to the existing industrial building. Finally, an optimized solution has been proposed in which sandwich panels in the roof are combined with CLT in rest of the building. In this case, the difference associated with costs is narrowed to 3.3%, while the difference in the total emission of CO_2-eq stays still significant, i.e. 13.6%.

1. Introduction

Norway and other countries with large economies are facing major challenges in relation to greenhouse gas emissions which contributes to global warming of the earth, and consequently to increased risk for major environmental impacts. The concentration of CO_2-eq in the atmosphere has increased by about 40% since 1750, and measurements show that the air temperature in 2012 was higher by 0.85 °C compared to 1880 [1]. In order to tackle this trend, modern societies needs a 'green' shift, with key players to introduce new innovative sustainable solutions. This is resulting in new opportunities for the forest and tree industry [2]. Today, the forest is a valuable resource for Norway, including as a raw material for several different products [3]. The growth of wood is more than twice as large as the outlet, and based on this, it is possible to utilize the wood sustainably for energy and construction [2]. In particular, the construction and operation of buildings today account for about 40% of the total energy consumption in the world, and 39% of energy-related emissions of CO_2-eq [4]. This means that there are considerable opportunities for contributing to a more sustainable development in this particular sector. This has led building industry to the development of more environmentally friendly building systems and materials, e.g. cross laminated timber (CLT) elements [5].

Wood is considered a hygroscopic material, which means it can absorb moisture (water vapor) from the surroundings [6]. These qualities result in a moisture buffering, and studies shows that this contributes to a reduced ventilation requirement [7]. When the water vapor condenses in the hygroscopic structures of the material, a latent heat exchange will take place [8], [9], [10]. This can lead to lower temperature variations in the room, and thus also a reduction in the building's total energy consumption [11], [12].

Most of the wood used in Norway today is transported from abroad. In 2017 the transport of forest and timber products accounted for approximately 8% of the transport work performed. Direct and indirect greenhouse gas emissions from the construction sector make up about 14% of the total Norwegian greenhouse gas emissions. Researchers argue that the largest proportion of this is related to the production and transportation of the material in question, and that only 4% are directly related to the operation of the building through its life cycle [3].

There are several types of industrial buildings in Norway today, such as large centres and warehouses. Based on the large category that exists for this type of building, it has to be specified and classified further. The classification is done according to NS 3457-3: 2013 «Classification of construction works. Part 3 Building types», by main function, building group and building type. According to the standard, the building are classified as "3 Office and business buildings" on a single-digit level. This is because it covers the largest proportion (86%) of the building's main function. At the double-digit level, the building is classified as "32 Business building", because this category covers the largest share (74%) within "3 Office and business buildings". The building is classified at three-digit level as "321 Shopping mall / warehouse", because it covers the largest share (39%) within building group 32 [13].

Research shows that the use of wood products in buildings generally results in higher investment cost than steel and concrete. This is partly due to the lack of expertise and experience of larger building consisting of specifically CLT-elements [14]. This study will address the use of CLT elements in today's industrial buildings, and at the same time evaluate the material's total environmental and economic impact. Specifically, the analysis has been carried out as a case-study of the MAXBO Bjertnestangen industrial building, and relevant simulations have been carried out, i.e. structural, hygrothermal and energy analyses.

2. Methodology

2.1. Case-study MAXBO Bjertnestangen

This study analyses the feasibility and degree of sustainability of using cross laminated timber (CLT) as building material in industrial buildings in Nordic climate. Today's industrial buildings usually consist of structural systems where steel and concrete elements are combined, in addition to the use of sandwich elements in facades. An industrial building located in Eastern Norway, MAXBO Bjertnestangen, has been used as case study for the analysis. The structural system consists of steel, while concrete is used in floors and foundations, and the facades is consisting of sandwich panels (steel-polyurethane-steel), aluminium and glass [15].

The building has a total floor area of 2693.9 m^2 and an overall total height of 10 m. Since the specific building combines merchandising, warehousing and offices, thermally the building is a combination of heated and unheated zones. Table 1 is describing the floor area and thermal zones. Figure 1 shows a 3D model of the industrial building's geometric structure, and Figure 2 illustrates the thermal zones of the industrial building.

Table 1: *Overview of current building parts and thermal zones for MAXBO Bjertnestangen.*

Building unit	**Area [m^2]**	**Thermal zone**
Construction materials	1042.9	1
Store	954.4	2
Technical room	50.2	3
Office space and goods delivery	646.4	4

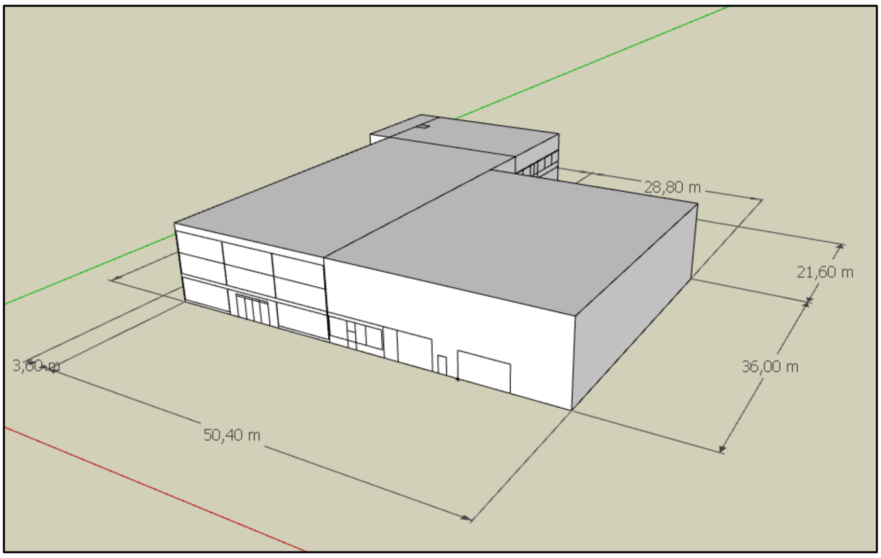


Figure 1*: 3D model of the industrial building's geometric structure.*

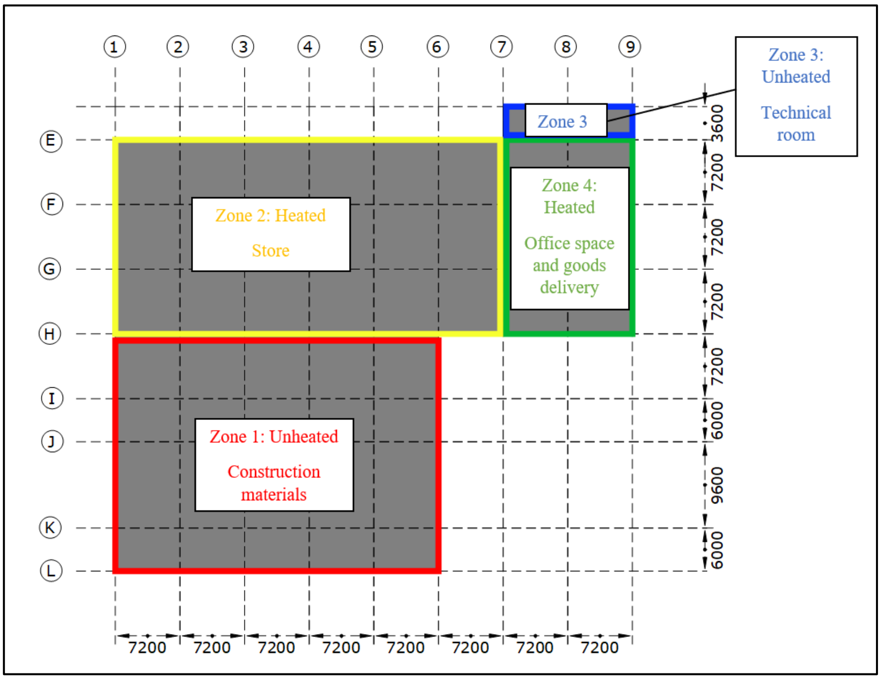


Figure 2*: Thermal zones of the industrial building.*

2.2. Scenarios studied – Building materials

The starting point for all the analyses is i) the existing industrial building in steel (Scenario 1) and ii) the replacement of all current building components with glued laminated timber and CLT-elements (Scenario 2). Building's geometry and functionality have been preserved in both Scenarios.

The structural system of the industrial building in Scenario 1 consists of HUP columns, IPE beams and steel girders, in quality s355 and roof built in steel. The remaining building elements are sandwich elements in facades (steel-polyurethane-steel) and composite elements of gypsum board-insulation-gypsum board in partition walls. In addition, the floor between the office space and the goods delivery area is separated by a concrete hollow core floor slab.

The building in scenario 2 consists of structural CLT-elements in outer walls, interior walls and roof, while the rest of the building consists of glued laminated timber columns and beams, in quality Gl30c. Concrete hollow core floor slab is here replaced with CLT-elements, supported by a CLT-wall and a glued laminated timber beam. The foundations and ground are the same for both scenarios and are built in concrete.

2.3. Defining the functional unit for the life cycle assessment (LCA)

In order to assess whether CLT elements can be categorized as a more environmental friendly construction solution than steel and concrete, life cycle assessment (LCA) have been carried out. The analysis has been implemented for both Scenarios. In addition, an assessment of the building's costs related to the building construction has been carried out. The results from an LCA can only be compared when two (or more) systems are equivalent [16]. Based on this, functional units have been defined and employed in connection to the analysis of the construction's structural and thermal performance. Figure 3 illustrates functional units, connected to structural and thermal performance for the LCA-analysis performed.

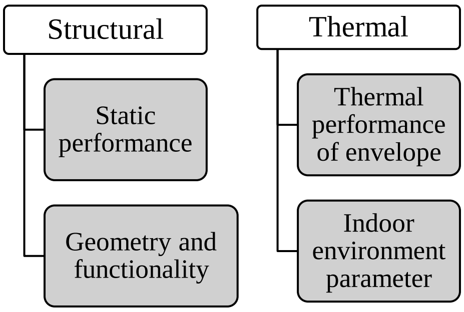


***Figure 3** - Illustration of functional units*

2.3.1. Structural performance. For the FEM-structural analysis a commercial finite element methods (FEM) code has been used and the results confirms that the CLT building achieves approximately equal mechanical and static structural properties. The FEM analysis is calculated according to 1st order's linear theory. In addition, selected hand calculations have been used to verify the model. All calculations and analyses are done according to the Eurocodes [17]. This also applies to loads and load combinations, such as wind, snow, dead and live loads. Dynamic loads, such as fire and seismic loads have not been included in the simulation.

Coupled hygrothermal and energy performance. The dynamic, hygrothermal energy simulation has been carried out in accordance with NS3031: 2014 «Calculation of buildings 'energy performance - Method and data» [18], and NS-EN 15251: 2007 + NA: 2014 «Indoor climate parameters for the dimensioning and assessment of buildings' energy performance including indoor air quality, thermal environment, lighting and acoustics» [19]. For specifications in relation to thermal performance, the simulation is based on the U-values stated in the technical description for the building [15]. It is used a U-value of 0.15 W/m^{2}K for the exterior-walls, and 0.8 W/m^{2}K is used for the windows. Further, it is used a U-value of 0.12 W/m^{2}K for the roof, and 0.14 W/m^{2}K for the floor.

Furthermore, corresponding input data for the two simulations has been used. Zone 2 and zone 4 are categorized as heated zones. Zone 1 and zone 3 are categorized as unheated zones. For the heated zones, an indoor temperature of between 19 ℃ and 21 ℃ is defined for the building's heating system. The cooling system is operated at a temperature of 26 ° C. All zones should have a relative humidity between 25% and 60%. Mechanical ventilation has been used in all zones. When the building is in operation, zone 1 is ventilated at an airflow of 8294.4 m^3/h and zone 2 at an airflow of 12130.56 m^3/h. Zone 3 is ventilated at an airflow of 414.72 m^3/h and zone 4 at an airflow of 2177.28 m^3/h. Outside operation, zone 1 is ventilated at an airflow of 2073.6 m^3/h, and zone 2 at an airflow of 1866.24 m^3/h. Zone 3 is ventilated at an airflow of 103.68 m^3/h and zone 4 at an airflow of 622.08 m^3/h. The simulation has been carried out during the period 01.01.2019 - 01.01.2020, and it is used climate data for Gardermoen, Norway.

2.4. Input - LCA

The LCA has been carried out in accordance with NS 3720: 2018 «Method for greenhouse gas calculations for buildings», to assess the total environmental impact of the industrial building [14]. The focus during simulation is phase A1-A3, A4, B4-B5, B6, B7 and C1-C4, of the building's life cycle. Results applied to the hygrothermal energy simulation have been used in relation to the industrial building's heating, cooling and mechanical ventilation demand. The calculation of annual energy requirements associated with lighting, equipment and hot water, is completed in accordance with NS3031: 2014. It is assumed that the building's annual energy consumption is covered by 60% electricity and 40% district heating.

In order to assess how transport of materials affects the building's total environmental impact, 2 simulations have been carried out for the building consisting of CLT-elements. Table 2 summarizes the various distances connected to the different simulations that has been carried out, connected to the life cycle analysis.

Table 2: *Transport distances for the different scenarios, connected to the life cycle analysis.*

Scenario	Transport general materials	Transport steel/CLT-elements
Scenario 1 – Existing industrial building	100 km	100 km
Scenario 2 – Building with CLT-elements	100 km	100 km
Scenario 2 – Building with CLT-elements	200 km	1800 km

2.5. Cost assessment

The analysis of the industrial building's costs associated with the construction of the building (phase A0-A5), has been carried out in accordance with NS 3454: 2013 “Life cycle costs for construction works. Principles and classification» [21]. The cost analysis has been carried out based on the life cycle analysis, and because of this, corresponding data has been used for this analysis.

3. Results

3.1. Structural performance

The existing industrial building (Scenario 1) is already designed and constructed and is therefore used as a basis for comparison for the building in CLT-elements (scenario 2). The FEM analysis and the hand calculations showed that the building had enough capacity according to the standard. Based on this and

CLT-elements strength and stiffness properties, it can be concluded that the CLT-construction is sufficiently secure against breakdown, while satisfying certain functional requirements related to its use and purpose. The building's static properties and capacity can also be defined as equivalent in the two cases, because displacements and capacity utilization are similar in the two cases. Selected results of Scenario 2, according to Eurocode, are illustrated in Table 3. The table is presented to show that the relevant design results are in accordance with the standards. Some of the results show that the capacity of some building components is within the standards. This is because the capacities and displacements should be as similar as possible in both Scenarios.

Table 3: *Selected results of Scenario 2 according to Eurocode.*

Component	**Dimension/span [mm]**	**Stress [N/mm^2]**	**Percentage of capacity**
Glulam beam	250x1575/21600	16,1 (bending)	87,5 %
Glulam beam	250x1575/21600	1,5 (shear)	51,9 %
Glulam column	215x675/8500	2,4 (comp.)	33 %
Component	**Dimension/span [mm]**	**Displacements [mm] (capacity buckling)**	**Demand (L/300) [mm]**
Glulam beam	250x1575/21600	48	72
CLT separating floor	240/7200	23,6	24
CLT roof	240/7200	18,5	24
CLT wall	120/9000	14,7 (76%)	30

3.2. *Coupled hygrothermal energy simulation*

The results from the coupled hygrothermal energy simulation are illustrated in Table 4. Results associated with heating, cooling and latent heat are collected directly from the simulation. Results associated with lighting, equipment and hot water are obtained from NS3031: 2014, and are therefore similar for the two scenarios. As the table shows, although the thermal performance of envelope is the same, there is still a difference in the energy performance. This is mainly because the exposed wood absorbs moisture (water vapor) from the environment, which further results in a moisture buffering. This contributes to a reduced ventilation requirement for the building consisting of CLT-elements.

Table 4: *Energy supply and distribution of electricity and district heating, for the two scenarios.*

Energy requirement/distribution	**Scenario 1 – Existing industrial building**	**Scenario 2 – Building with CLT-elements**
Energy requirement heating/cooling/latent heat [kWh/year]	**153753,1**	**148606,1**
Energy requirement lightning, equipment, and hot water [kWh/year]	**86496,12**	**86496,12**
Total [kWh/year]	**240249,22**	**235102,22**
Electricity	**144149,532**	**141061,332**
District heating	**96099,688**	**94040,888**

An assessment has also been made of the needs associated with humidification and dehumidification for the existing industrial building and the building consisting of CLT-elements. Figure 4 illustrates kg water used for humidification connected to the two scenarios. Figure 5 illustrates the total need for dehumidification, in kg water, connected to the two scenarios. In addition, the difference between the simulations is also illustrated.

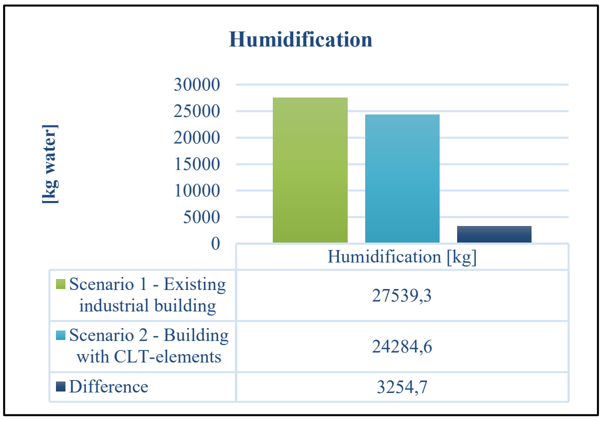


Figure 4: *Kg of water used for humidification for the existing industrial building and the building with CLT-elements.*

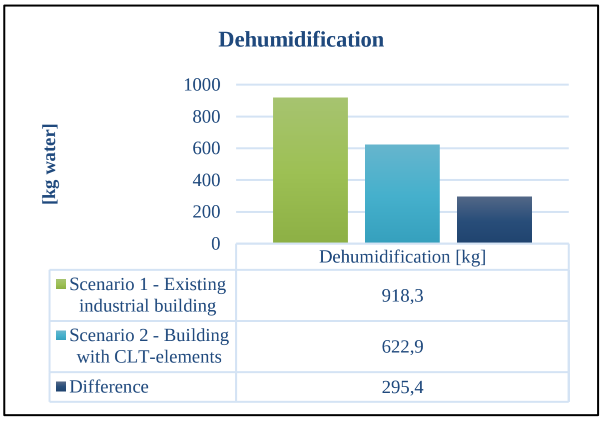


Figure 5: *Dehumidification, in kg water, connected to the existing industrial building and for the building with CLT-elements*

In order to assess the total energy savings that occur on the basis of the reduced need associated with humidification and dehumidification, the latent heat by absorption is calculated. The latent heat released and absorbed by condensation of the water vapor in the hygroscopic structures of the wood is calculated as follows:

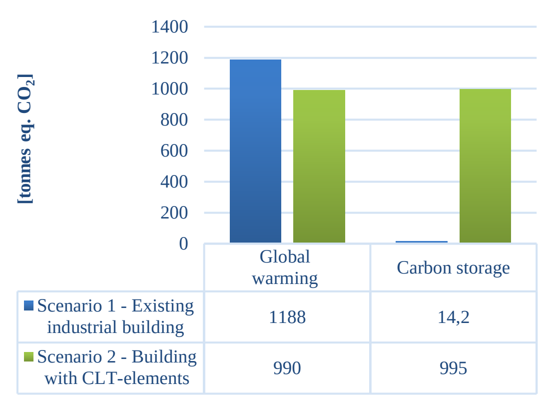
$$H = 3550{,}1 kg\ water \cdot 2501 kJ/kg = 8878800{,}1 kJ = 2466{,}3 kWh$$

The results show that due to latent heat released in the wood's hygroscopic structures, it is possible to achieve a total energy saving of 2466.3 kWh. Furthermore, there is a total energy saving for the building with CLT-elements of 5147 kWh, if one expects the energy requirement associated with heating and cooling. This implies a percentage energy saving of about 3.3%.

In order to investigate which results occur if higher air volumes are used, an extra simulation of the building consisting of CLT-elements (scenario 2) has been performed. All the results above is based on minimum ventilation demand. If the building consisting of CLT-elements are dimensioned using higher ventilation rates, which is typical, the results shows that the advantage of the moisture buffer capacity disappears.

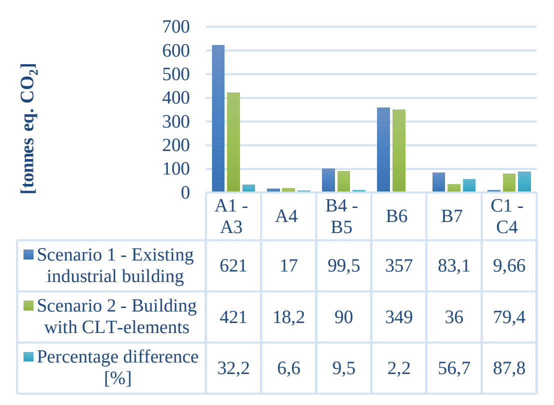
3.3. LCA-analysis

3.3.1. Global warming and storage of biogenic carbon. Figure 6 illustrates results associated with global warming and storage of biogenic carbon, for the life cycle analysis performed. The results apply to phase A1-A3, A4, B4-B5, B6, B7 and C1-C4. The emission of eq. CO_2 is about 16.7% higher for det existing industrial building, and the storage of biogenic carbon is 98,8% higher for the building with CLT-elements. Figure 7 illustrates the total emission of eq. CO_2 for the relevant phases of the building's life cycle. The results show that the total emissions are reduced by about 32.2% for phase A1-A3 (product stage), if CLT-elements are used as replacement for steel and concrete.



	Global warming	Carbon storage
■ Scenario 1 - Existing industrial building	1188	14,2
■ Scenario 2 - Building with CLT-elements	990	995

***Figure 6**: Results of global warming and biogenic carbon storage.*



	A1 - A3	A4	B4 - B5	B6	B7	C1 - C4
■ Scenario 1 - Existing industrial building	621	17	99,5	357	83,1	9,66
■ Scenario 2 - Building with CLT-elements	421	18,2	90	349	36	79,4
■ Percentage difference [%]	32,2	6,6	9,5	2,2	56,7	87,8

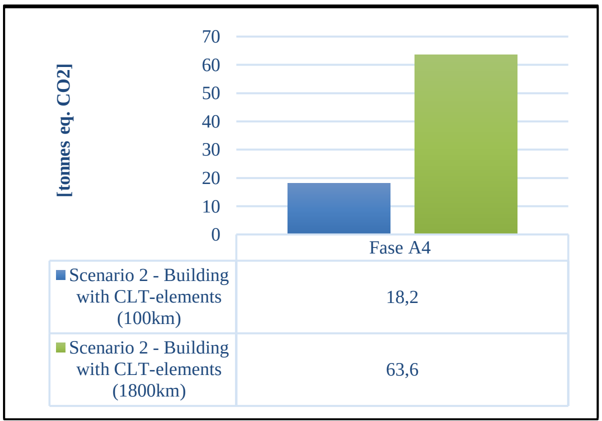
***Figure 7**: Total emission of eq. CO_2 for the relevant phases of the building's life cycle.*

3.3.2. Environmental impact during transport. Figure 8 illustrates the total emission of eq. CO_2 associated with phase A4, when it is assumed that CLT-elements is produced at a distance of 1800km and that common components are produced at a distance of 200km. There is a difference of 45.4 tones eq. CO between the two scenarios. This implies a percentage difference of 71.5% for phase A4, but only an increase of 4.6% for the total emission of eq. $CO_{2.}$ Earlier, as shown in Figure 7, the percentage difference for phase A4 was 6.6%.

Figure 9 illustrates emissions of eq. CO_2 associated with current phases of the building's total life cycle, in percentage. As the figure illustrates, it is still phase A1-A3 (the product stage), and phase B6 (energy use in operation), which is resulting in the highest emission of eq. CO_2.

3.4. Cost assessment

Figure 10 illustrates the total costs associated with phase A0 - A5, for the industrial building and the building consisting of CLT-elements. The existing industrial building has a total cost of 24.3 million NOK, and the building consisting of CLT-elements has a total cost of 27.9 million NOK. This implies that the building consisting of CLT-elements is about 13% more expensive than the building consisting of steel and concrete.



	Fase A4
■ Scenario 2 - Building with CLT-elements (100km)	18,2
■ Scenario 2 - Building with CLT-elements (1800km)	63,6

***Figure 8**: Emissions of eq. CO_2 associated with transport of materials for the building with CLT-elements.*

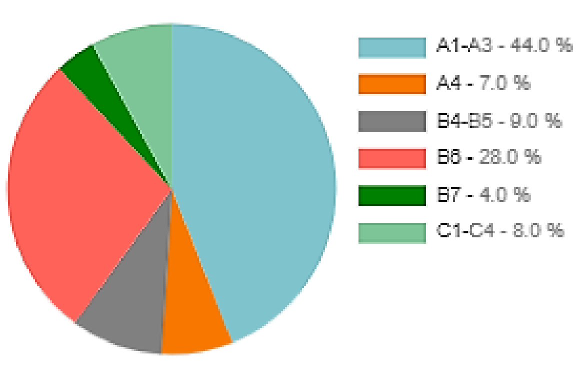


***Figure 9**: Emission of eq. CO_2, in percentage, for CLT-elements produced at a distance of 1800km.*

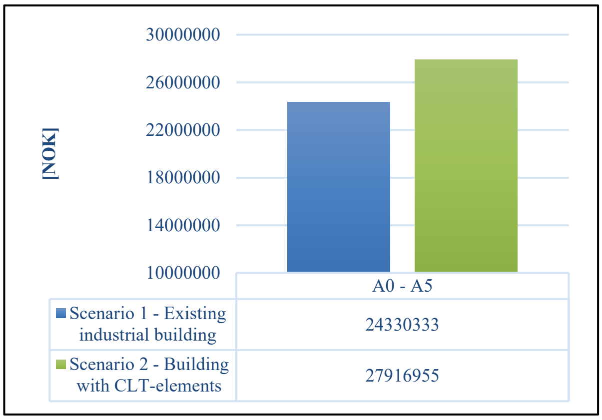


Figure 10*: Total costs associated with phase A0 - A5, for the industrial building and the building consisting of CLT-elements.*

4. Conclusion

In our study all load-bearing elements from the existing industrial building have been replaced with CLT-elements and laminated wood elements. The results show that all construction parts are satisfactory according to the current standard. The two buildings can be characterized as equivalent systems, on the basic of the static properties of the various construction parts.

Results related to the hygrothermal energy simulation, shows that it is possible to achieve a total energy saving of 3.3%, for the industrial building consisting of CLT-elements. The energy saving generally occurs on the basis of the latent heat released and absorbed during condensation of water vapor in the wood's hygroscopic structures. Furthermore, the results shows that if the building is dimensioned at higher ventilation rates, the advantages of solid timber’s hygroscopic properties vanish.

Based on this, assessments have been made of two equivalent systems for the life cycle analysis and the analysis of the building's life cycle costs, associated with the construction of the building. Results associated with the life cycle analysis shows that the emission of CO_2-eq. is 16.7% higher for the existing industrial building. Furthermore, there is a percentage increase of 71.5% for phase A4, but only an increase of 4.6% for the total emission of eq. CO_2, when CLT-elements are produced at a distance of 1800km. The analysis of the lifecycle costs, associated with the construction of the building, shows that the building consisting of CLT-elements is about 13% more expensive than the existing industrial building.

The costs associated with the structural system of the existing industrial building make up 28% of the total costs, and for the building with CLT-elements the support system constitutes 33% of the total costs. From previous projects, it has been reported that the main problem associated with the costs of buildings with CLT-elements, is the roof. Based on this, an optimized solution has been proposed, in which steel roofs are used, instead of roof consisting CLT-elements. Results are reported in table 6. The analysis shows that if steel roofs are used, instead of roofs consisting CLT-elements, the difference associated with costs between the industrial building and the building with CLT-elements, is now only 3.3%. Further, there is still a difference of 13.6% in favor of the building with CLT-elements, associated with the total emission of eq. CO_2.

Table 5: *Summary of current analyzes, in addition to specifications of differences associated with the various analyzes*

Scenarios	**Total energy consumption [kWh]**	**Emissions of eq. CO_2 [ton]**	**Cost materials [Norwegian kr]**
Scenario 1 – Existing building	153753,1	1188	24 330 333
Scenario 2 – Building with CLT-elements	148606,1	990	27 916 955
Difference (%)	-5147 (3.3%)	-198 (16.7%)	3 586 622 (12.8%)
Building with CLT-elements (with steel roof)	-	1027	25 150 914
Difference (%)	-	-161 (13.6%)	820 581 (3.3%)

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