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Comparative analysis of life cycle GHG emissions of off-site Prefabricated modular volumetric construction and Panelized construction system for High rise wooden residential buildings in Norway.

The potential of prefabricated wood Constructions as an efficient and sustainable building practice and their life cycle implications.

Student thesis in Sustainable architecture
Supervisor: Patricia Schneider-Martin
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Abstract:

In this report, we will evaluate the development of tall wood and exploring the potential of prefabrication in the construction process of high wooden residential buildings and their Life cycle performance as low carbon construction systems. We will also compare the GHG emissions from two different systems: prefabricated volumetric Modules and Prefabricated building kits (Panelized system). With an initial assumption that Adopting prefabrication may contribute with significant environmental benefits and GHG emission reductions. The greenhouse gas emissions were calculated based on the Life Cycle Assessment (LCA) methodology.

This study sets a calculation boundary and six emission sources for the prefabricated construction process: Production of building materials, transportation of building materials to construction site, transportation of construction waste and soil, Site construction operations, operative energy use and waste and including end of life stage.

The results shows that Modular construction's total global warming impact is 30% less than a panelized system, and by considering each life cycle stages: the production stage modular system had significant impact with 31% higher carbon emissions than a panelized system (excluding the concrete use), However the Panelized system has a higher mitigation impact on carbon emissions with a 40% reduction in GHG in the transport process.

Modular systems are highly time efficient for the installation stage as they don't require intensive on-site machinery. Furthermore, the emissions from several prefabricated construction technologies were investigated using reference buildings and a variety of scenarios and assumptions. the results suggest that panelized systems outperform volumetric prefabricated modules in terms of end-of-life advantages and CO2 payback.

Finally, the outcome of this study is influenced by the holistic construction strategy and methodology, such as structures, foundations, and infrastructures. Despite the fact that the popularity of tall timber buildings is on the rise in the construction sector, concrete remains ubiquitous and necessary for structural purposes which means a definitive conclusion would be hard to be drawn from this investigation report on itself as a consequence to the restricted samples and assumptions it is based on. But Modular system seems to be a more efficient construction method compared to panelized system for Timber residential buildings.

List of abbreviations

CEN The European Committee for Standardization

LCA Life cycle assessment

LCI Life cycle inventory

LCIA Life cycle impact assessment

CHTBU Council on Tall Buildings and Urban Habitat

GWP Global Warming Potential

GHG Greenhouse gases

EWP Engineered Wood products

MMC Modern Methods for construction

CLT Cross Laminated Timber

GLT Glued Laminated Timber

LVL Laminated Veneer Lumber

PPVC Prefabricated Prefinished Volumetric constructions

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1. Introduction:

We must cut building-related carbon emissions by 60 to 70 percent by 2030 to attain net zero by 2050, which is a tough task. We've concentrated on lowering operational carbon to fulfill these goals, but this isn't enough. The importance of embodied carbon in the production of materials, as well as the construction, renovation, and demolition of structures, is growing.

Housing is one of the most immediate basic human needs. the residential building demands is increasing due to the fast urbanization of the cities and clusters, and which represent 75 % of the building sector in Europe. and is estimated to be responsible of 17 % of the global energy/related co2 emissions in the world. While in the past few decades an increased interest was observed in minimizing the negative environmental impact of buildings, the rise of popularity in wooden building and their higher potential to mitigate the emissions has been in the forefront.

This thesis report on a holistic investigation into the GHG emissions associated with the construction process of High-rise residential wooden buildings and evaluate their economic performance during specific life cycle phases. We explore two Alternatives scenarios where we will compare and analyses two different prefabricated wood construction methods, a modular system, and prefabricated elements (kits)system. This assumes that a modular system might be more efficient than the assembly of multiple construction components for a high-rise wood building. These two scenarios were chosen for lack of a comparable study case of conventional on-site construction of high-rise wooden buildings.

According to Gangolells et al. (2009), transportation, construction machinery, waste production, and water consumption all have substantial environmental implications, meaning that any improvements in these aspects could be key targets for decreasing a building's overall life cycle impact. (Takano. Pittau, 2014).

The goal is to assess the GHG emissions from production, transport, construction and installation, emissions from energy use and possibly the implications in life cycle costs [1]and the end-of-life phase.

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[1] ISO 15686-5:2017- life cycle cost assessment

2. Background:

2.1. Wooden high-rise buildings

As more buildings are build higher to maximize their rentability and respond to the increase in Housing needs in central areas occurring due to the population fluctuation shift, it becomes essential to reduce the building environmental footprint and gas emissions. Over the past decade, the concept of green buildings[2] has become more mainstream and the public is becoming aware of the environmental benefits of this alternative to conventional construction.

Few building materials possess the environmental benefits of wood. It is not only our most widely used building material but also one with characteristics that make it suitable for a wide range of applications. It requires minimal amount of energy-based processing but also store the atmosphere Co2.

Until recently, wood frames were only used for 1-2 stories high while concrete predominated in the construction of multi-story buildings because of a century of fire safety restrictions prohibiting wood as a frame material as a result of a number of devastating fires in cities at the end of the 19th century.

The great extension of wood market promoted the potential for the use of wood in all types of buildings and were no longer limited to single-family housing and smaller temporary workspaces but are now being constructed for innovative buildings Using new technologies and construction methods and relying on sustainable forestry management to supply raw Timber Products.

2.2. Research questions:

Through this report we would like to determine:

A. which construction system has the most efficient environmental performance when it comes to the construction of high-rise wood buildings, in this instance I wanted to look

[2] Green building is defined as the practice of increasing the efficiency with which buildings use resources while reducing building impacts on human health and the environment—through better siting, design, material selection, construction, operation, maintenance, and removal—over the complete building life cycle.

into off-site prefabricated construction systems and analyze the different levels and methods available to develop a fundamental understanding of the advantages and disadvantages of prefabrication with its various levels?

B. How Low carbon construction systems using prefabricated engineered solid wood panels for urban infill significantly can reduce greenhouse gas emissions? And Which level of completion of prefabricated elements has the most promising potential to reduces the co2 emissions?

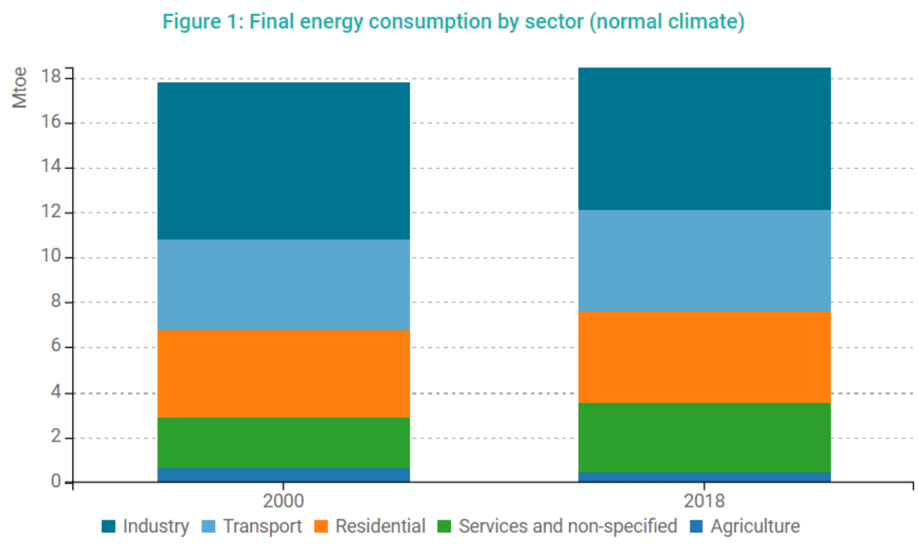


Figure 1 Energy consumption by sector in Norway (Odyssee,2021)

According to the Norwegian statistics bureau, the energy consumption in residential sector, was 4.1 Mtoe in 2018, compared to 3.9 Mtoe in 2000 (Odyssee, 2021) which is in a steady but constant growth. the need to improve the buildings performance is a goal set by the government by 2030. with performant energy measures and an early design process that offers opportunities for large impacts on performance to the lowest cost and disruption. Thus, it is important to integrate energy performant systems and sustainable materials to help create an airtight, insulated building and reducing the energy consumption.

2.3. Research agenda:

The goals in this research are to assess the GHG emissions due to the construction of high - rise wood buildings and demonstrate why high levels of prefabrication is an efficient and sustainable building practice.

1. Determine through GHG emissions calculation and comparison which Prefabrication system is more likely to offer significant opportunities for greenhouse gas emissions reduction and waste avoidance for high rise buildings.
2. Demonstrate if Higher levels of prefabrication (Prefabricated volumetric modules) represent a facilitating indicator for low energy consumption during project construction and on which building stage is it more likely to influence the building environmental performance.
3. Assess Potential environmental impacts through GHG assessment of which the prefabrication systems cause least GWP over the life cycle of the building and meet the goals and target for sustainable development by 2030.

Figure 2Sustainable Goals 2030. source:(UN Agenda for sustainable development)

Examination of case studies

Two built projects using glulam as a load bearing structure but assembled using two different prefabrication methods are employed for preliminary comparison of the differences in GHG emissions.

3. STATE OF THE ART:

3.1. Tall building development:

Although tall structures have existed since the beginning of civilizations in structures, tall building examples in architecture did not emerge until the second half of the nineteenth century during the industrialization period. The industrialization process and the use of new construction materials such as iron, steel, and glass are major factors in the creation of tall structures.

According to the CTBUH[3] database, most of the existing highest structures are composite, these material attributes have been divided into primary vertical and lateral structural parts by CTBUH. The structures of tall buildings are now divided into three categories: single material system, composite system, and mixed material system.

Wood:

Wood is also in theory the ultimate sustainable construction material Because of its adaptability, diversity, and aesthetic features. Timber, possibly the first building material, continues to have a prominent position in the construction industry. Brick, steel, glass, plasterboard, concrete, and especially aluminum all needs more energy to manufacture than wood, adding significantly to CO_2 emissions (Lyons, 2010).

With sustainable management of forestry resources, the wood production could effectively expend its scope worldwide. with wood products available locally and regionally across the world with different local tree species, diverse parts of the world which have a lack of timber building culture will have the opportunity to change following emerging building technologies, Materials development, and climate new goals guidelines.

In fact, sustainable management of forestry can improve wood production, knowing that wood CO_2 absorption rate varies from species to species and is connected to the tree rate of growth. Since young trees grows rapidly but as they mature, their rate of growth slows which also means

[3] Council for tall buildings and urban habitat

that their CO_2 absorption rate slows too until it will stop at some point in their life cycle. once the adult trees start their decaying process, they will release back the Co2 stored back into the atmosphere and becomes a source of CO_2 emission without the implementation of regeneration harvesting strategy.

the benefits of carbon sequestration when wood is converted into construction materials is a durable and sustainable plan of action for climate change mitigation. the carbon in wood products will be trapped as new growing trees will store more atmospheric carbon and thus achieving a circularity in the production cycle.

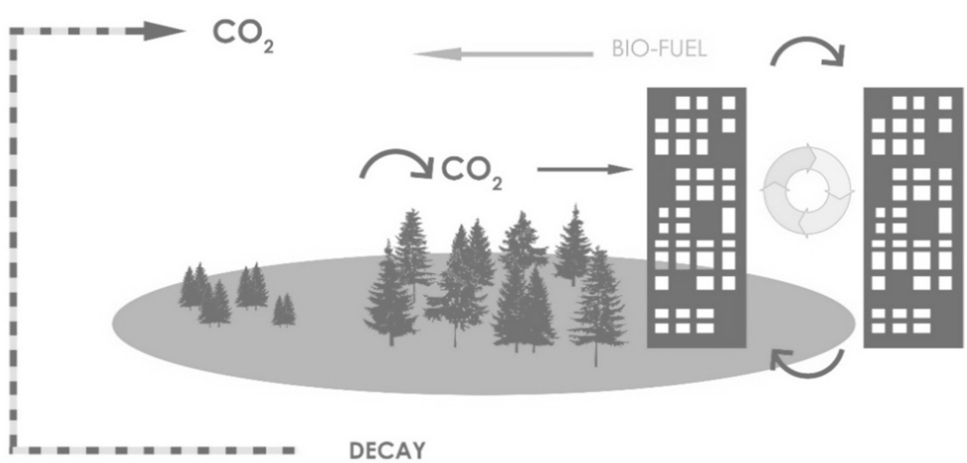


Figure 3circular life cycle of carbon emissions

Building Typology:

3.2. Residential wood buildings:

In Norway, Appartement blocks[4] are becoming more popular, and people are more inclined to buy an appartement with an affordable price than a single-family house. This also means that the housing development in centralized areas will grow.

As the world's population grows, it is expected that we will need to build 3 billion affordable housing units over the next 20 years. The great majority of these will be required in developing-world cities, which are seeing the fastest population expansion.

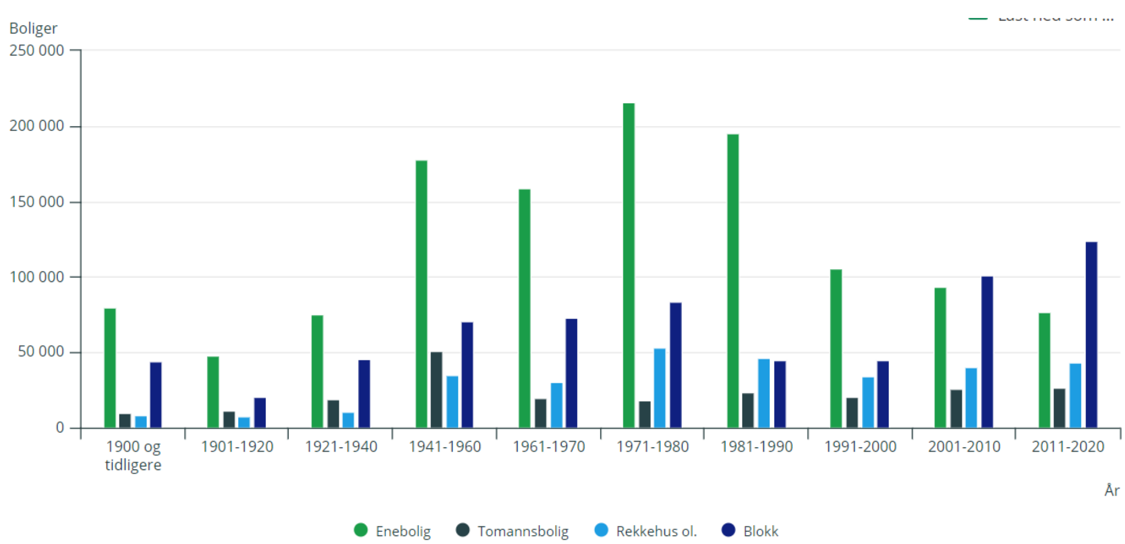


Figure 4Building statistics in Norway, housing type popularity

Climate change and housings need are intertwined matters. Indeed, according to sustainability researchers, social equity is a strong driver to implement global justice, and it is much of an environmental but also a social challenge. almost 1/3 of the carbon emissions are associated with building's construction and use life. The IPCC[5] has evaluated the GHG emissions to increase by

[4] Fakta om bolig (ssb.no)
[5] IPCC: intergovernmental panel on climate change

2% annually. concrete as a widely used construction material is responsible for up to 8% of global emissions followed by steel production with 4 %.

To respond to the housing shortage, the construction industry will increase its activity radically. Which will eventually catastrophically speed up the climate change.

In recent years. wood structure evaluations have demonstrated reductions in embodied energy and GHG emissions when compared to concrete or steel .one benefit main benefit of Timber production is that manufacturing waste could contribute to generate electricity through Biofuel which is a neutral carbon energy source. In addition, the transport of wood products: CLT, Glulam manufactured internationally has lower emissions than locally produced concrete.

3.3. Principles of tall residential wood buildings:

Wood as an organic material with a defined internal structure, this allows through different combination and compose stable structure with strength and ability to support loads.

Technology today supports a new type of wood engineered products or the so-called EWPs. these are composite material resulting from glued wood veneers together that is stronger and hardened. this process allows for manufacturer to avoid waste and ameliorate the rate of wood used.

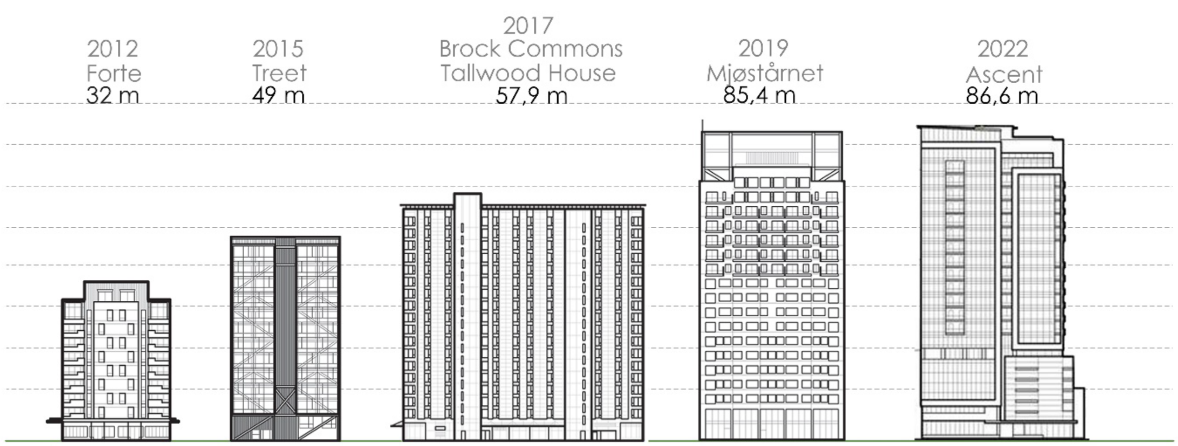


Figure 5 History of Timber residential prefabrication

3.4. Materials:

Wood offer flexibility as well as proprieties when it comes to fire. With mass timber, so many possibilities have been unlocked when it comes to high rise construction. new technologies and research monitoring have come to engineer EWPs a wood product with glued strands produced from smaller trees, the direction of which is very specified for the structural purpose. this offers a width reaching up to 3 which is limited by the factory machinery and an infinite length but only dictated by transportation to site (Michael Green and Jim Taggart, 2020).

One of those examples are:

a. Glued-laminated timber:

Glulam is manufactured by gluing together individual pieces of dimension lumber under controlled conditions to form larger linear elements. In Tall Wood buildings glulam is used for columns, beams, headers and sometimes Trusses (Birkhäuser, 2017)

b. Cross laminated timber

CLT Is comprised of multiple layers of boards stacked together, with alternating layers at right angles to one another. Layers are bonded to form a composite panel, most often using glue. The glue may be applied either on the faces of each board or on both the faces and edges. Boards may also be finger-jointed and glued in the longitudinal direction (Tall Wood Buildings: Design, Construction and Performance. Birkhäuser,2017).

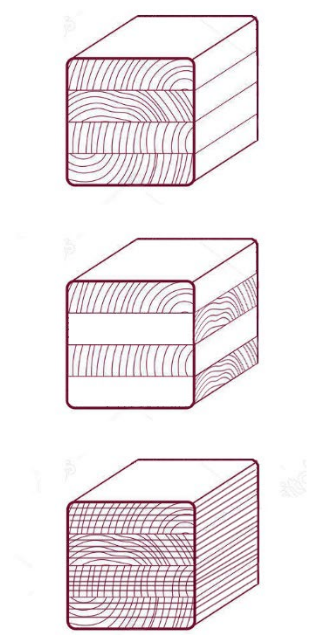


Figure 6 Schemas of different structural Timber materials

c. Laminated veneers lumber:

Laminated veneer lumber [ill. p. 28 top] is produced by bonding thin wood veneers together in a large billet so that the grain of all veneers is parallel to the long di-rection. Because LVL is made with scarfed or lapped jointed veneers, LVL is available in lengths far beyond conventional lumber lengths. As a structural panel product, it is uniform in appearance and highly predictable in performance.

4. Modern Methods of Construction

The building industry has been actively urged in recent decades to boost its use of Modern Methods of Construction (MMC) to address supply shortages and poor housing quality. Despite their numerous benefits, the building sector has been stagnant to embrace them. (Pan, et al., 2008)

MMC includes offsite construction, which is the fabrication and pre-assembly of components in a factory prior to installation in their final destination.

With the world's population expansion, off- site construction is becoming more crucial than ever for cities that are failing to provide adequate housing to their residents. Off-site housing appears to represent the start of a new era in the fight to alleviate the worldwide housing crisis. (Chazal, 2019).

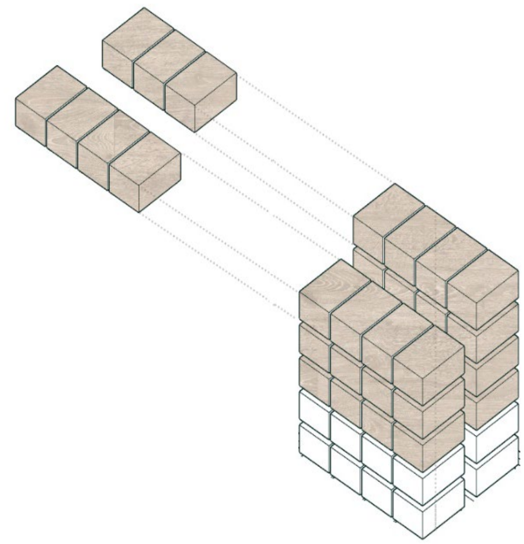
4.1. Off-site and on-site construction

It is considerably easier to produce high-quality workmanship and give the needed assurances of performance when the majority of the building work takes place in the controlled environment of a factory or manufacturing facility. In general, a factory provides a safer working environment by eliminating the effects of the weather, the risk of workplace injuries from tripping or falling, and the necessity for work to be done over-head or in cramped places by bringing operations to bench level. Furthermore, industrial output predictability can help with more precise cost and time estimates. Other advantages of prefabrication can also minimize the sounds and sonorous disruptions in local neighborhoods surrounding the construction site particularly in urbanized areas. It also addresses the issue of material inventory and storage by providing on-time deliveries with instant installation process.

When working with wood, the benefits of off-site construction become even more apparent. The lightness of wood allows for the prefabrication of volumetric components in addition to structural pieces like beams and columns and architectural elements like walls, floors, and roofs, which are commonly prefabricated. Fully enclosed modular modules, complete with all finishes and fittings, can be produced, cutting the time necessary for on-site building to a bare minimum.

4.2. Types of Industrialized Building System: Current Prefabrication applications:

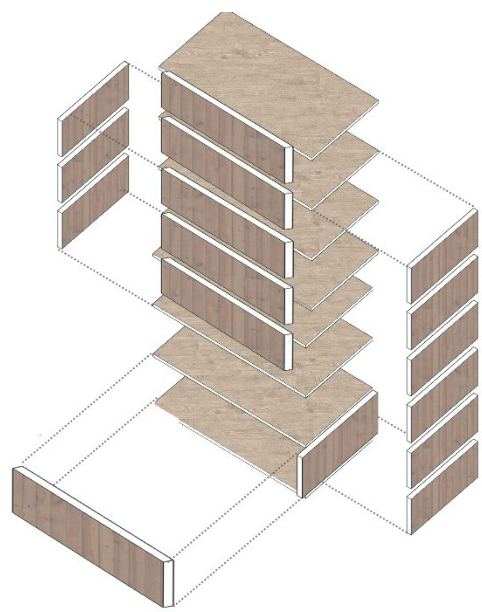
4.2.1. 3D Volumetric Prefabrication



Known as PPVC or prefabricated prefinished volumetric construction. they are a unitized system with 3 dimensional structural units which are built almost entirely in factories with a 95 % prefabrication completeness. Their primary benefits are economy of scale by manufacturing multiple similar units as well as fast installation process.

The modules have different categories such as: Uninsulated modules, Insulated modules without finished fittings, Insulated modules with finished lining on one side and Modules fully finished on all sides with integrated services (Built Offsite, 2016). Generally, prefabricated prefinished modules are able to support their own weight without an additional load bearing structure, but in other cases, modules are designed to support 4 levels of modules stacked on top of each other without the need for a Structure such as Treet example.

4.2.2. Panelized systems 2D:



Prefab panelized systems are a two-dimensional flattened panels that are made in a factory and then transported and installed on-site to create a three-dimensional structure. Concrete slab panels, timber panels, hybrid-timber, recycled timber, and structural insulated panels are some of the materials that may be used. Open-panel or closed-panel 2D prefab panel houses are available. To resume it, open panels are uninsulated and need additional construction work on site, whereas closed systems have insulated and completed panel walls. Enhanced panels are those that have things like windows, fittings, or piping added to them in the manufacture. The Australian residential building Forte (2012) has a structure that rely completely on the CLT panels that can support their own weight.

4.2.3. Hybrid systems:

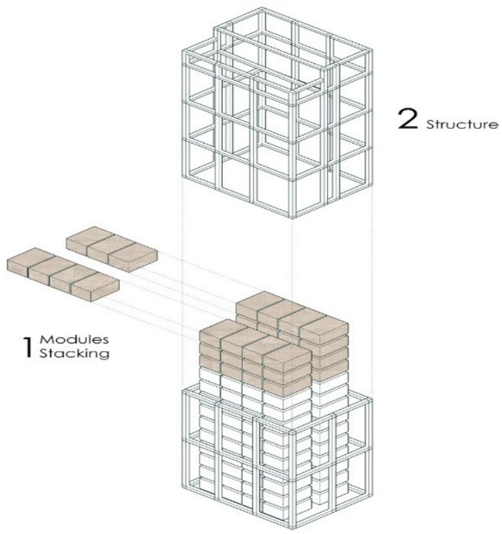


Figure 7 : Volumetric Hybrid systems

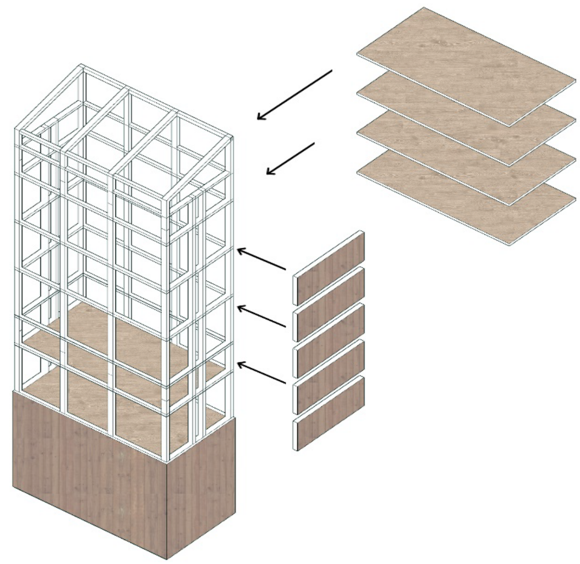


Figure 6: Panelised Hybrid systems

For high rise buildings that are higher than 5-6floors. the modules need to be stabilized by a frame system as a load bearing structure combined with either modules or Panels, the structure can consist of different materials depending on the preliminary design phase: it could be a reinforced Concrete core, Glulam Trusses, or steel, which then represent a hybrid system.

Truss structures: Structures of beams and columns that are attached together generally using Glued Laminated timber and steel connectors. Cross structures are often used in roof structures and bridges but can also be combined with beams and pillars for additional bracing in tall buildings (Julie Lyslo Skullestad ,2016).

Figure 9 Forte, Australia. Source: Cameron Jewell , 2013.

Figure 8 Structure of Treet with Trusses columns (Kato,2014)

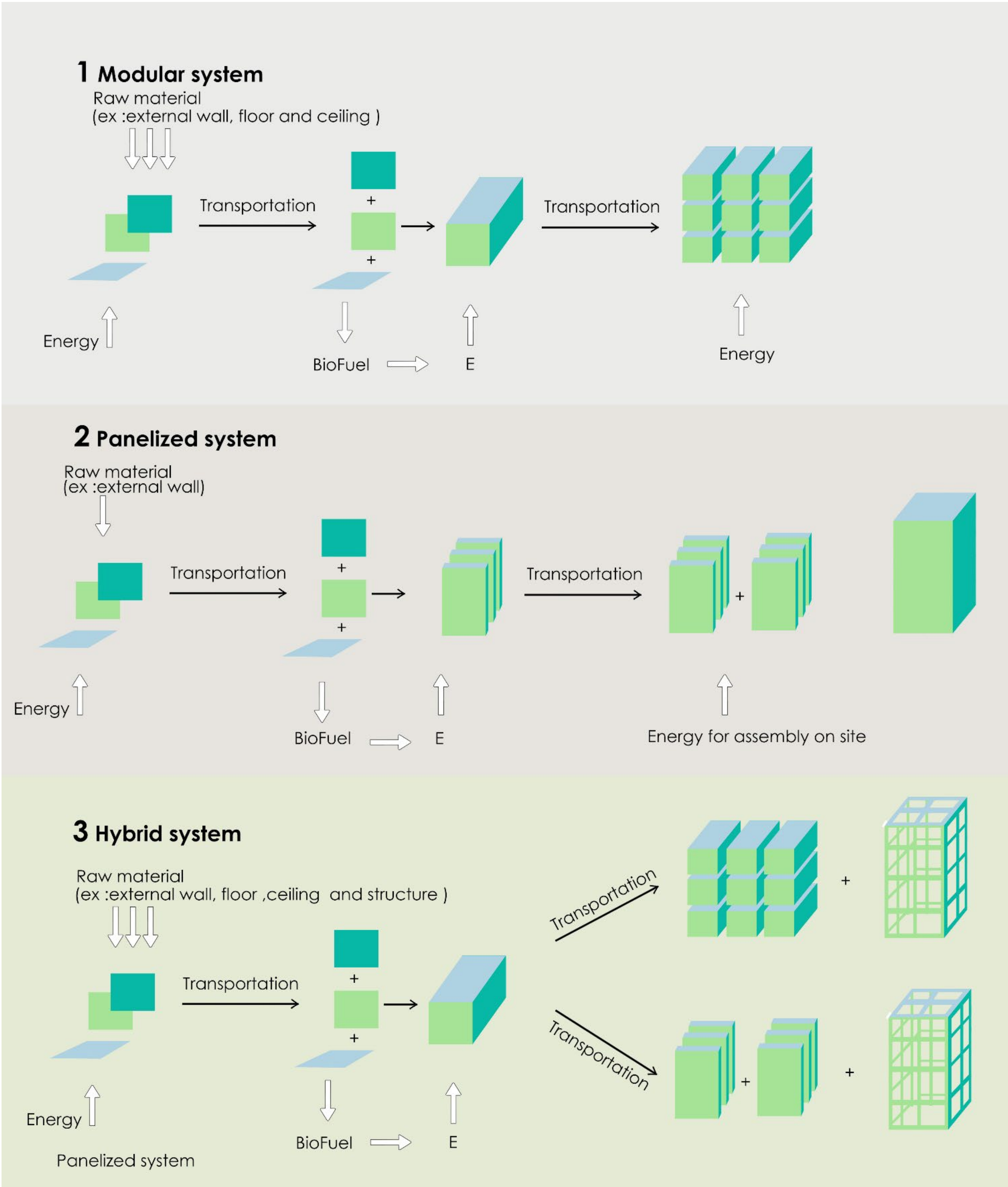


Figure 10 :prefabrication application different production and installation process

4.3. Environmental Aspects of Prefabrication:

International initiatives related to promoting new building techniques in the construction industry by quantify the environnemental aspects and setting indicators to new practices and their performances . Prefabrication is identified as one of them and was subjected to a requirements assessment and its potentiel to meet certains targeted improvements . the supplied table bellow explain the environnemental performance of prefabrication process in the building industry againt MFI Measures (Movement for innovation[6]) . These measures will be the topic of developement of the two case studies in this project while evaluation the environnemental impact of their prefabrication applications. (Paul waskett , 2001)

Table 1 Qualitative Performance of Prefabrication against the M4I Environmental (*Paul Waskett,2001).*

Sustainability Indicator	Effect of Using Prefabrication
Operational Energy	**Positive** – Improvements in build quality should ensure consistent standards of insulation and service installation.
Embodied Energy	**Positive** – Reduced waste and increased recycling in off-site manufacture should reduce the embodied energy associate with the manufacture of a given part.
Transport Energy	**Negative** – Movement of prefabricated components will necessitate the transport of some additional volumes of air (particularly for volumetric solutions)
Waste	**Positive** – Manufacture of components in a factory environment should reduce much of the waste currently associated with site activity.
Water	**Positive** – Manufacture of components that require water in their manufacture in a factory environment should allow more control, and potential for water recycling than would be found on site.
Species per hectare	**Positive** – Reduction of pollution on site by undertaking manufacture in a controlled environment should limit the impact on existing species on site.

[6] Construction procedures and practices to promote investments in new constructions.

4.4. Potential For a circular design:

In anticipation for a future in which resource shortages will make the recycling and reuse of buildings and building materials inevitable. MMCs and new prefabrication methods using a flexible, sustainable materials such as wood offer a great opportunity to contribute to the development of a circular economy.

Besides the obvious benefit of using Timber as a carbon input material, prefabricating wood material would not only reduce considerably the time and energy for production and installation but the perspective to adopt a strategy by adding assembly and disassembly design as a whole new dimension. This would allow the recovery and reuse of building materials and create endless cycle loops Add information regarding benefits disadvantages of modular versus panelized system Disadvantage replacement: if a module had any defect during the construction lifetime it would require more maintenance and worst case replace the whole module. while panelized system offers a flexibility to change one panel at a time.

Disassembly and reuse

The challenge of material supplies and population increase leads to questions about how structures should be created in a society where concrete is still deeply embedded. the architectural design process to create prefabricated and modular timber housing units to be mounted and demounted, demonstrate that the concept of circularity in construction can be achieved. This method with joined or reversible metal joints to enable easy disassembly and the reuse of elements can create economically efficient, aesthetic, and circular buildings.

Prioritizing prefabrication and modularity in the architectural design process has many benefits, including highly effective footprint reduction, large-scale infrastructure for flexible use, and independent housing units with communal activities, as well as ensuring the building conditions for future disassembly and recycling. (Marielle silva,2020).

REFERENCE BUILDINGS:

5. The Tree, ''TREET''

In Norway, "Treet" is a 14-story timber residential structure. construction Groundwork began in April 2014, and the project was completed in 2015. The structure is one of the world's highest timber structures. The structure is made up of load-bearing glulam trusses and two intermediately reinforced layers. Prefabricated building modules are piled on top of the reinforced floors and the concrete basement. The elevator shaft, interior walls, and balconies are all made of CLT. CLT, on the other hand, is not part of the primary load-bearing system. The structural wood is protected from rain and sun by glass and metal sheeting.

Figure 11 Treet 3d view (Abrahamsen &Kato, 2014)

5.1. Location:

The fourteen-story residential skyscraper is situated In Bergen, Norway, in 2011, the design the construction began in 2013 and the structure was completed in fall 2015 after the foundation was constructed in April 2014. The building has 62 flats with a net area of 5830 m2. The parking garage, technical rooms, and storage rooms are all located in the basement, which has a net area of 920 m2.

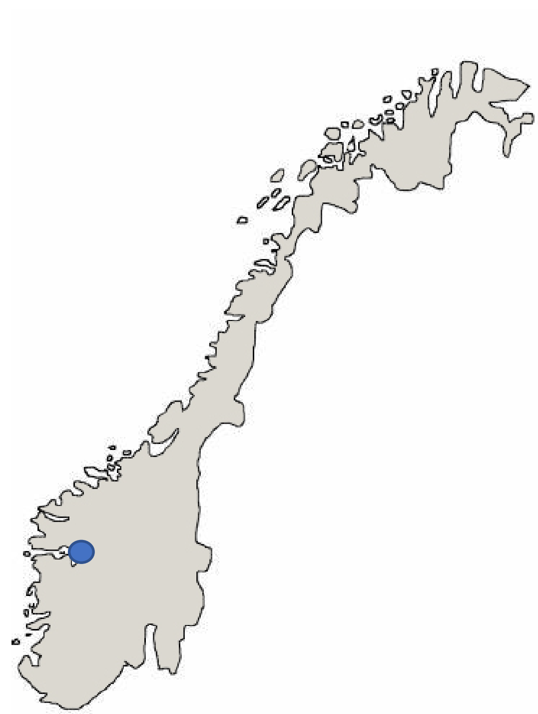


Figure 12 Bergen, Norway

Residents have access to a gym on the 9th level as well as a Terrasse on the Roof. BOB (Bergen og Omegn Boligbyggelag), a Norwegian housing association and a prominent residential developer in Bergen, owns the building. Norway's largest glulam producer, Moelven Limtre, delivers and installs glulam and CLT. Moelven Limtre receives the CLT from a subcontractor. The prefabricated construction elements that make up the flats are delivered by the Estonian business Kodu Maja. Artec, a Bergen-based firm is the project's architect. The technical design and design management are the responsibility of SWECO Norway. All of the participants were involved in the project's creation.

5.2. Concept:

the idea of the structural design concept may be explained by an analogy to a cabinet rack filled with drawers (Abrahamsen and Malo 2014). Here, the cabinet rack is formed by large glulam trusses, and the drawers consist of prefabricated residential modules. The glulam truss work has close resemblance to the design concepts used in modern timber bridge structures. The building's required rigidity is provided by the glulam trusses that run along the façade. The load bearing framework supports the CLT parts lightly, but the CLT structure contributes very little to the overall rigidity of the building. As a result, the CLT walls are nearly independent of the main load bearing system and do not exhibit large strains when subjected to horizontal loading. The major volume of the structure is made up of prefabricated construction components. (Abrahamsen and Malo 2014).

5.3. Construction sequence:

Before building a reinforcing structure to accommodate four more levels of stacked modules, the modules are stacked up to four stories. All of this is built on top of a concrete foundation. Level 5 is regarded as a powerful level with a reinforced structure.

The unique modules on level 5 are attached to the glulam framework rather than resting on the building modules below. A prefabricated concrete slab sits atop the "power storey," which, like levels 1–4, acts as the foundation for the next four floors of stacked modules (6–9). Floors 6–9 have no connections to the main weight-bearing structure other than the concrete slab that acts as their base.

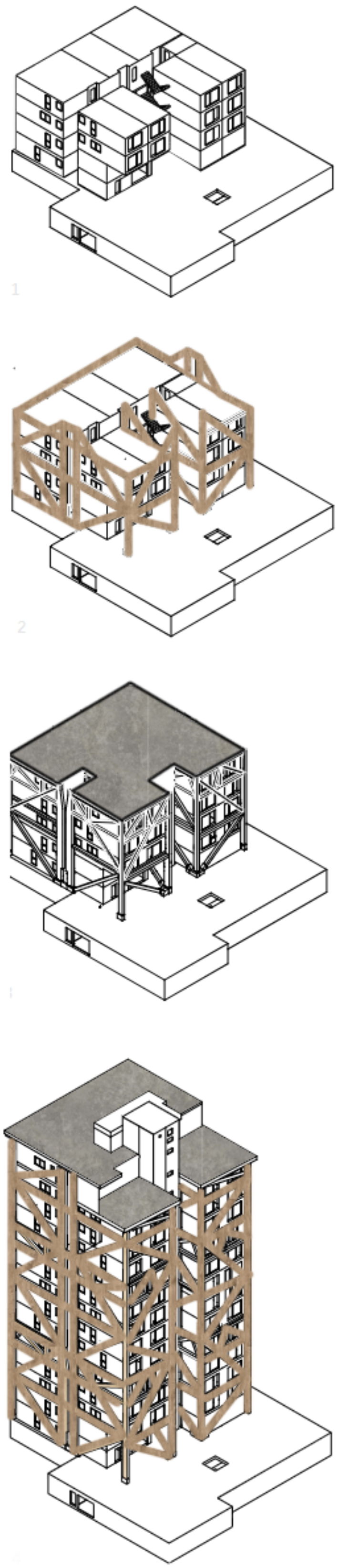
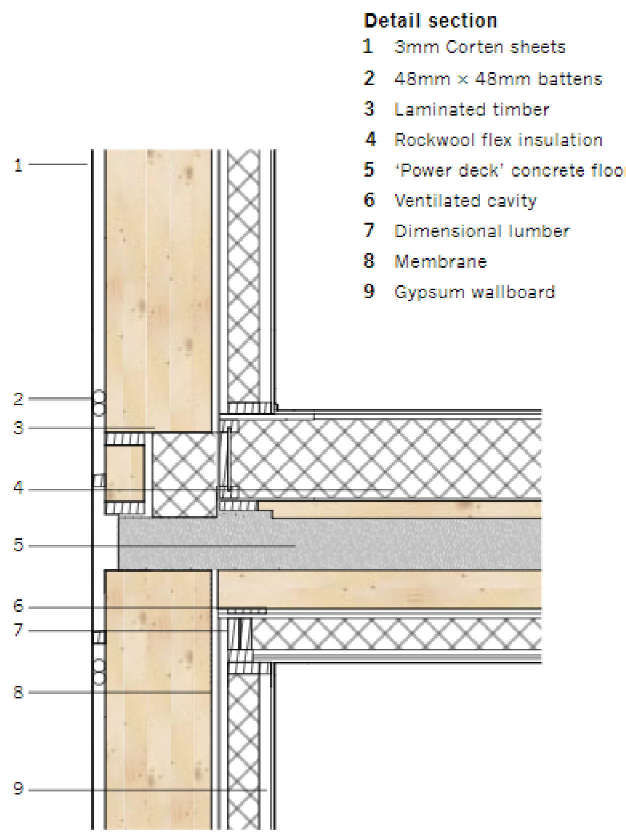


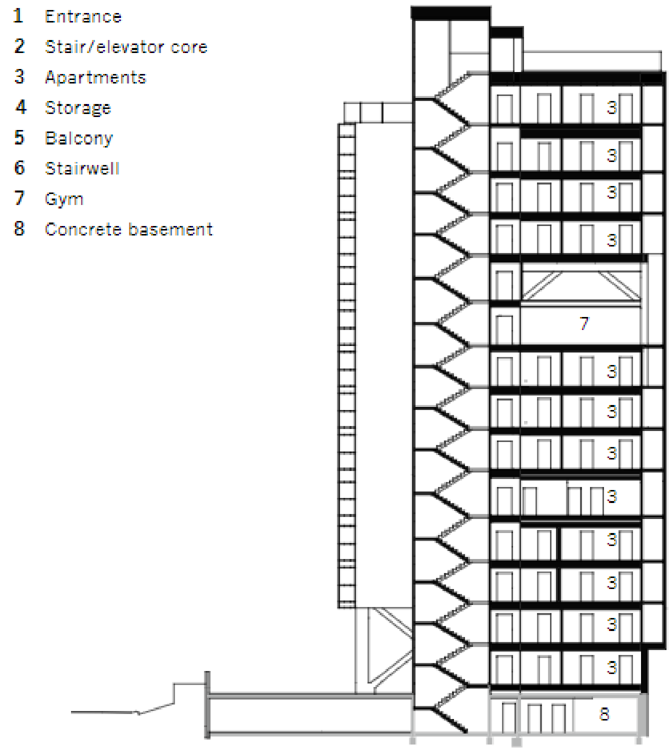
Figure 13 Structure installation steps (Michael Green, Jim Taggart, 2017)

The roof is also a prefabricated and element-based concrete slab. The concrete slabs are incorporated to connect the trusses, but an additional main function is to increase the mass of the building and hence to improve the dynamic behavior (Bjertnæs and Malo (2014).



5.4. Structural detailing:

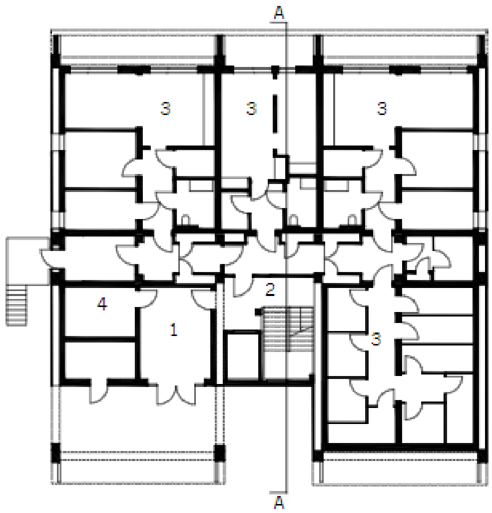
the base of the building is a rectangle with length of baselines equal to 23x21 m. The height of the building is about 45 m. The maximum vertical distance between the lowest and highest points of the timber components is about 49 m. All glulam elements are connected by use of slotted-in steel plates and dowels. This is a high-capacity connection commonly used in bridges and large buildings in Norway. (Michael Green, Jim Taggart, 2017).



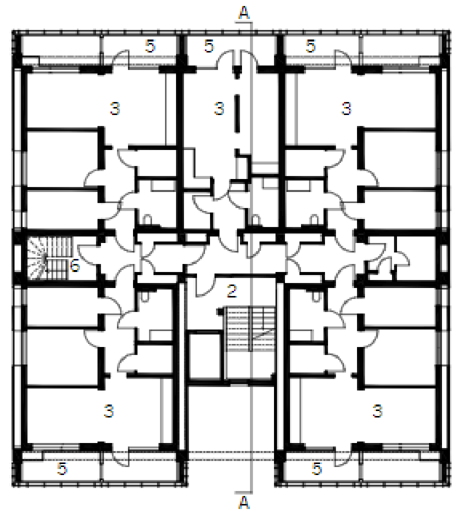
Section AA

The bedrock is about 5 m below the basement floor. Over 100 vertical and slanted steel core piles are driven into the bedrock to serve as the building's foundation. Some of the piles will have to withstand tension strains as well. When the building is subjected to wind loading, tensile forces can be applied to some of the diagonals and columns. These forces are conveyed to the ground by using slotted-in steel plates and dowels to connect the glulam columns to the concrete foundation.

A strong design is applied to the structure. The building will not collapse if a member fail. The removal of a truss member causes other members to take on more force, which was proven in the accidental limit state. Between building modules and glulam trusses, there is a potential clearance of 34 mm. This is sufficient to ensure the required building tolerances and to prevent possible horizontal module and truss movement.



Ground floor plan



Typical floor plan

5.5. Materials:

All main load-bearing structures in ‘‘Treet’’ are wooden; glulam is used for the trusses, and cross-laminated timber (CLT) is used for the elevator shafts, staircases, and internal walls. Timber framework is used in the building modules. In the structural model, the properties stated for glulam strength classes GL30c and GL30 h according to EN 14080:2013 (CEN 14080 2013) are used.

The majority of the glulam is made out of untreated Norway spruce. Glulam that can be exposed to weathering is made of copper treated lamellas from Nordic pine. Structural timber in the building modules and CLT is produced from Norway spruce. The steel plates in the connections have steel grade S355 and are hot dip galvanized.

The steel dowels are of type A4-80 (acid-proof stainless grade). The use of galvanized steel ensures that rust water will not discolor the timber during the assembly. The stainless dowels are smooth and strong, and easy to install. (Abrahamsen &Malo, 2014).

5.6. The Modules:

In Treet, typical residential units are made up of two volumetric modules: one ‘’wet’’ unit includes the kitchen and bathroom and the other ‘’dry’’ comprising the living room and bedrooms. The modules were built in Estonia and arrived completely equipped with windows, doors, cupboards, plumbing fittings, carpets, plasterboard, and other finishing materials. The water-front position in Bergen facilitated the transportation of modules from ship to site, with cranes lifting modules into place.

Assembly:

Treet is primarily put together on site by installing prefabricated elements. To ensure a smooth construction process, optimized logistics and installation procedures were applied. During the construction of the building, Kodumaja, the module manufacturer, and Moelven Limtre, the glulam producer used a tower crane and a climbing scaffolding system.

During the construction phase, temporary roofs are utilized to protect apartments, joints, and timber from dampness. A step-by-step model assures that the structure can be constructed according to the blueprints. The foundation and concrete parking garage are the first steps in the construction process. The stacking of four layers of prefabricated home modules is the next step. Because of transportation constraints, the glulam frames are prefabricated in as many massive pieces as possible.

Dowels and preinstalled slotted-in steel plates join the glulam frames in-between the modules. The lifting and installation of the modules into the strengthened storey on level 5 is the next step, followed by the completion of a concrete deck on top of that 5 th level. The reinforced level 5's concrete slab serves as the basis for an additional four levels of stacked modules. The metal cladding affixed to the glulam frames is regarded as the building's external weather skin, which also includes balcony glazing.

3D Model:

The project was modelled based on technical and 2d drawings of plans and sections, the objective is to obtain the material inventory for both case studies and base our comparative evaluation by using Revit materials Takeoffs list.

Material takes off schedules list the sub-components or materials of any Revit family. Material takes off schedules have all the functionality and characteristics of other schedule views, but they allow you to show more detail about the assembly of a component.

When Revit computes the volume of materials for individual layers within a wall, some approximations are made to maintain performance. Minor discrepancies might appear between the volumes visible in the model and those shown in the material take off schedule. These discrepancies tend to occur when you add a sweep or a reveal to a wall, or under certain join conditions. The Modules used in Treet have a 95 % off site prefabrication and assembly process, we have 2 types of modules:

1.One single module for 2 roms apartments

2.Two assembled modules for 3 Roms apartments.

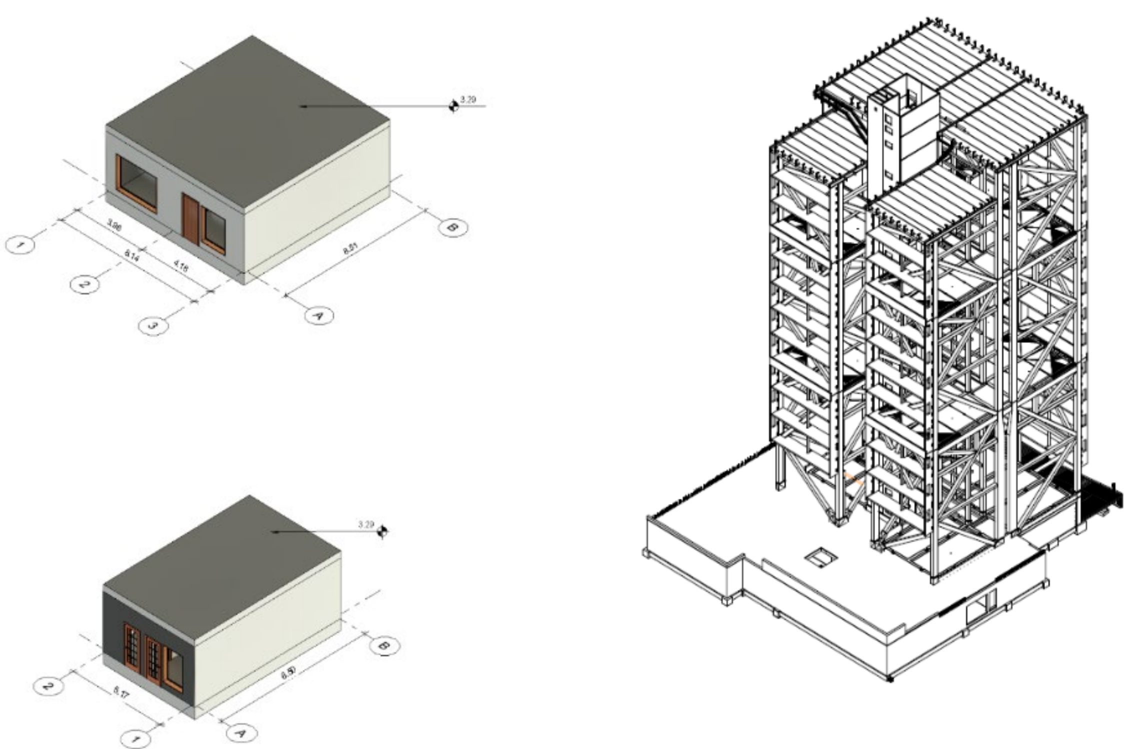
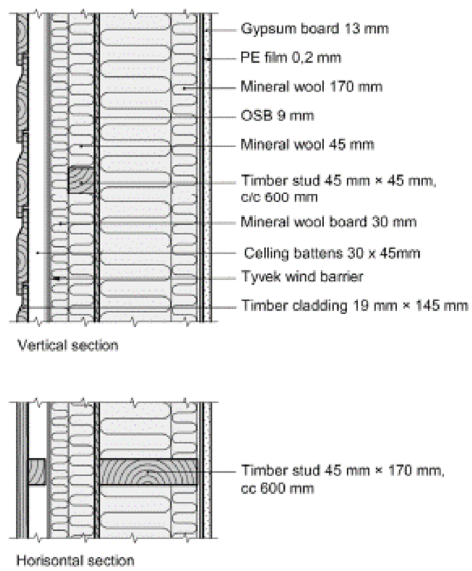


Figure 14 Modules 3d Visualisation

Basic Module Design details:



Standard wall

Figure 17 Standards wall

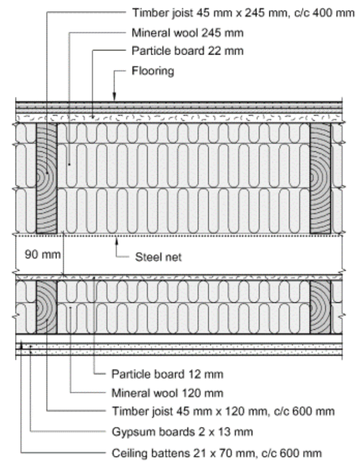


Fig. A5
Principle design of separating floor construction between modules. Solid wood joists.
The lowest part is the roof/ceiling structure of the bottom module, and the top part is the floor structure of the top module.

Figure 15Principal design of separating floor construction between modules

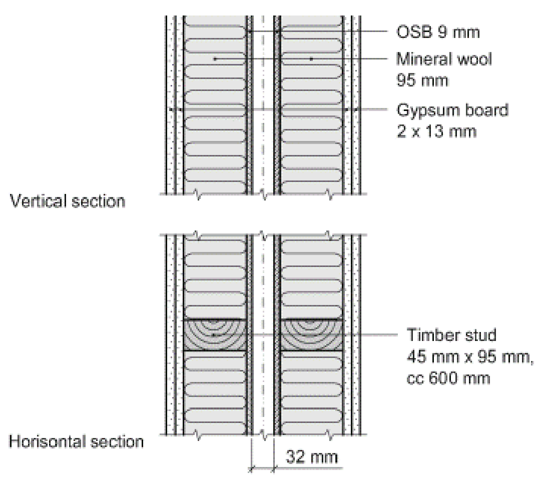


Fig. A3
Principle design of standard separating wall between modules and between housing units.

Figure 16Principal design of standard separating wall between modules and between housing units.

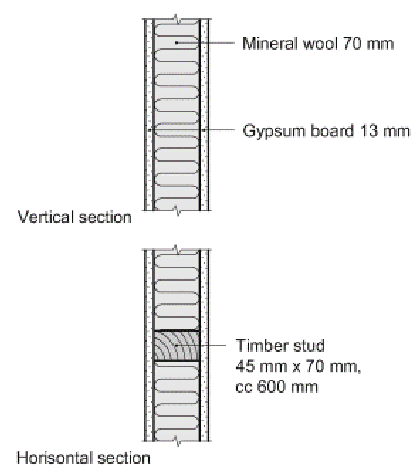


Fig. A2
Principle design of standard internal walls.
Stud dimension is 45 mm x 95 mm in loadbearing walls.
Shaft walls EI 30 have single layers of gypsum board on each side as shown, shaft walls EI 60 have double layers on each side or an additional 15 mm gypsum board type F on the shaft side.

Figure 18 Interior wall

5.7. Thermal Performance and Energy Efficiency:

Their Thermal resistance was assumed according to NS3700 standard for passive housing and compared to the values provided by the manufacturer's technical assessment document. U Value = 0.16 m2. K/W for Treet (walls)

U value = 0.18 m2. K/W Mjøstårnet: assumed Thermal requirement according toTEK17.

Thermal resistance

Table A4-1
Design thermal resistance of Kodumaja building modules calculated according to EN ISO 6946

Structure	Thermal insulation thickness mm	Total thermal resistance $(m^2K)/W$	Thermal transmittance (U) $W/(m^2K)$
External walls - Standard - Alternative	 245 200	 6.4 5.3	 0.156 0.188
Suspended ground floors - With I-beam joists	313	8.3	0.121
Roofs - With I-beam joists	300	7.8	0.127

Figure 19European Technical Assessment No. ETA-08/0178 issued on 07/09/2015

Tabell B.1 – Typiske *U*-verdier for passivhus og lavenergibygninger

Egenskap	Passivhus $W/(m^2 \cdot K)$	Lavenergibygning $W/(m^2 \cdot K)$
U-verdi yttervegg [a]	0,10 – 0,12	0,15 – 0,16
U-verdi tak [a]	0,08 – 0,09	0,10 – 0,12
U-verdi gulv [a, b]	0,08	0,10 – 0,12

a *U*-verdi regnes som gjennomsnittsverdi for de ulike bygningsdelene.
b *U*-verdi for gulv er en ekvivalent varmegjennomgangskoeffisient som inkluderer varmemotstanden i grunnen og redusert varmetransport gjennom gulv mot uoppvarmede rom/soner.

Figure 20Minimum requirements for building parts, components, and leakage figures

6. MJØSTÅRNET: Mjösa Tower - 85,6 m

6.1. Introduction:

Mjøstårnet is a mixed use building 18-story wooden building. foundation construction began in April 2017. The installation of timber structures began in September 2017, and the structure was completed in March 2019. There will be offices, a hotel, apartments, a restaurant, and a rooftop on a net area of 11300 m2. A big indoor swimming arena will be built next to the tower. The ambition for the project is for it to be a symbol of the green shift, demonstrating that big buildings can be constructed utilizing local resources, local producers, and sustainable timber materials.

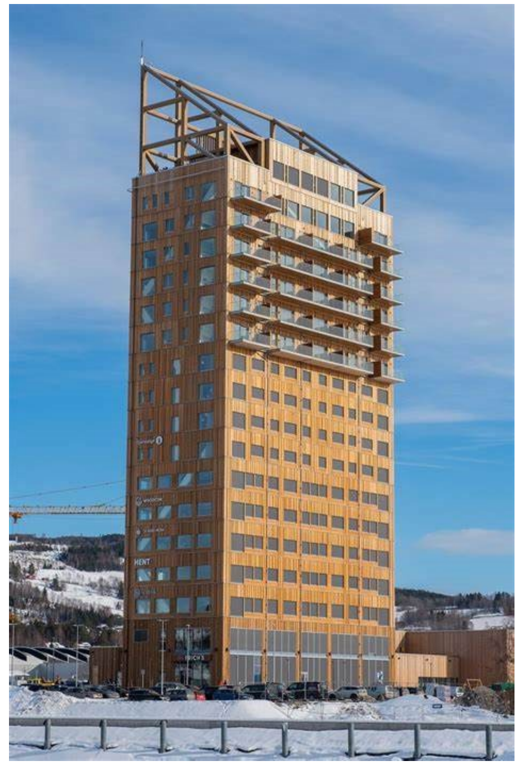


Figure 21Mjøstårnet view (Rune Abrahamsen, 2019)

6.2. Location

The building site is in the small town of Brumunddal, about 140 km north of Oslo. It is about the construction site is located in Brumunddal, a tiny village around 140 kilometers north of Oslo. The structure faces Lake Mjösa, Norway's largest lake.

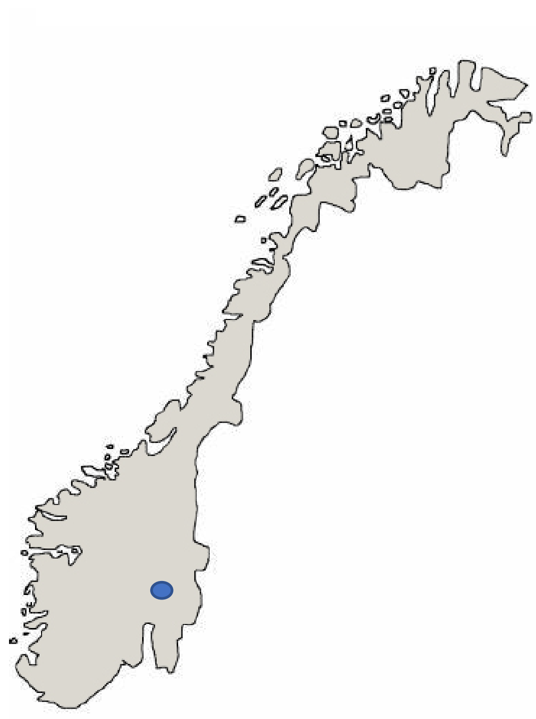


Figure 22 Mjøstårnet Location

6.3. Structural System:

The main load bearing consists of large-scale glulam trusses along the façades as well as internal columns and beams. The trusses handle the global forces in horizontal and vertical direction and give the building its necessary stiffness. CLT walls are used for secondary load bearing of three elevators and two staircases. The CLT does not contribute to the building's horizontal stability. Mjøstårnet has many similarities with the 14-storey timber building Treet in Bergen, which was completed in December 2015. The two most significant differences are that Mjøstårnet will be about 30 m taller, and that the building modules used in Treet are exchanged with prefabricated floor and wall elements. Building modules restrict the flexibility of the areas, and this was not compatible with the mixed functions required for Mjøstårnet. The large, prefabricated façade elements are attached to the outside of the timber structures and make up the envelope of the building. These sandwich type elements come with insulation and external panels already fixed. Wall elements do not contribute to the global stiffness of the building.

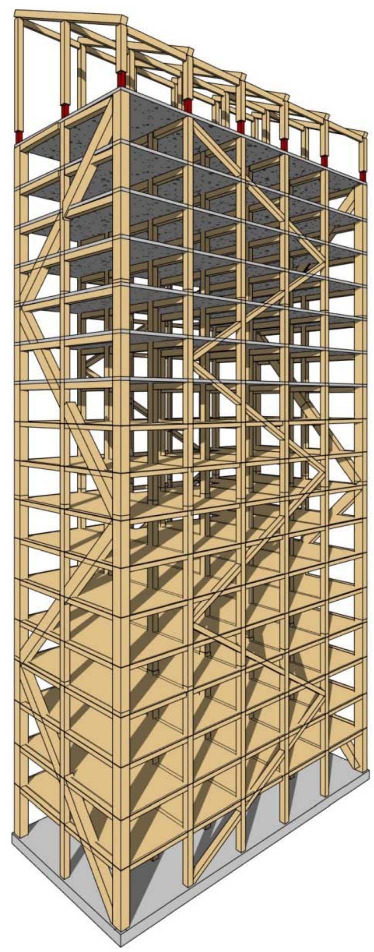


Figure 23 Structural system of Mjøstårnet

In total there are about 2600 m3 of timber structures in Mjøstårnet. The building has a footprint of about 17 x 37 m2. The huge concrete slab on the ground floor is supported by piles that are driven to the bedrock below. These piles can handle compression and tension forces. Floors 12 to 18 are 300 mm concrete floors. The concrete floors are a composite of a prefabricated bottom part which acts as formwork for a cast in place upper part. Replacing wood with concrete in the upper floors means that the building will be heavier towards the top.

This building is slender in its transversal direction, so the extra mass is necessary to comply with comfort criteria for apartments. The concrete decks also make it somewhat easier to get a high standard acoustic performance in the apartments. Steel core Pile: can go down to 60 m type that was chosen are embedded in the rock layer with a concrete fixature on the ground floor.

Figure 24 Typical Apartments Floor Plan

6.4. Materials

The glulam in the building has been produced by Moelven Limtre. The CLT is produced by Stora Enso. Untreated Norway spruce is the main species used for structural timber parts. For the structural design, glulam strength classes GL30c and GL30h according to EN 14080:2013[7]. The wooden floor elements are a combination of glulam from Moelven and LVL from Metsä Wood. The elements are insulated with Rockwool and are fitted with a diffusion open sheathing on top. Most elements have a 50 mm concrete screed on top. Powder coated S355

[7] European Standard sets the performance requirements of the following glued laminated products: CEN requirement Timber structures - Glued laminated timber and glued solid timber.

steel is used in connections combined with acid-proof steel dowels. The wooden cladding is supplied by Woodify and has fire retardant properties.

6.5. Fire Design:

Mass wood elements do not easily ignite, and when they do, it is at a gradual and predictable rate, according to full-scale testing undertaken in numerous nations. (Jim Taggart and Michael Green, 2017).

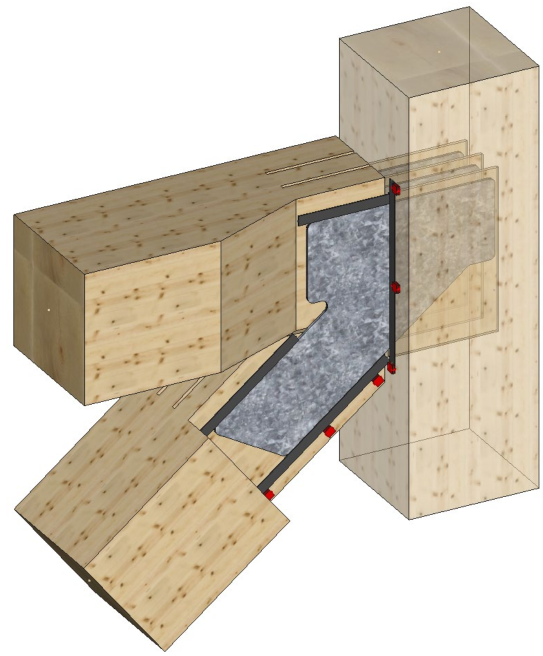


Figure 25 Steel plates incorporated into Glulam Structure (Rune Abrahamsen,2017)

Both projects have the ability to withstand 90 to 120 minutes of fire. After a couple hours the temperature was decreased, and the fire eventually stopped all together. Which prove that Laminated glued timber will self-extinguish and preserve their strength capacity combined with a fire-retardant painting and covering plasterboards. another measure incorporated is fire sprinklers and a firestop to prevent fire spreading to other rooms.

Metal sheets and dowels in the joints are deeply implanted in the wood. Intumescent fire strips will be installed in gaps and crevices between beams, columns, and plates. When the temperature exceeds 150 degrees, this material expands by around 20 times. This link is seen in Figure 5 after the fire. When it comes to robustness, the structure is built to withstand the loss of one timber floor's horizontal rigidity. It can also withstand the impact of a timber floor crashing to the ground below. (Rune Abrahamsen, 2017)

TRÄ8 Floor Elements:

Moelven's Trä8 floor cassettes are used in Mjøstårnet. Max span in Mjøstårnet is 7,5 m. These elements use less wood materials compared to CLT decks. They are light and quick to assemble. Moelven has done many tests of different build-ups in Sweden and Norway. The floors become very stiff and perform well. They can handle both acoustic requirements and fire requirements. The carbon footprint is particularly low, estimated at about 65 kg CO_2/m^2. (Rune Abrahamsen, 2017)

Assembly:

The assembly of Mjøstårnet is mostly about installing prefabricated elements on site. Optimizing the logistics and installation is important to get a smooth assembly. In addition, considerable measures have been taken to ensure safe working conditions on site. The main contractor HENT has a large tower crane that Moelven Limtre and other subcontractors can use to install elements. The timber structure is exposed to weather during construction. Based on our extensive experience this works fine as long as the structures will have the possibility to air out after the floors and the building shell have been installed. All glulam surfaces have been painted with one layer of varnish.

Visible surfaces will be painted with a top layer at a later stage. End grain of columns at the ground floor has been sealed with epoxy. Exposed end grain of column tops and exposed sides of LVL are also protected. A moisture control plan has been developed to ensure correct handling of wood on site. This plan includes measuring and monitoring moisture content of specified parts of the structure. (Rune Abrahamsen, 2017).

3D Modelling:

The project was modelled based on technical and 2d drawings of plans and sections provided by Voll architects and available on their website. the objective is to obtain the material inventory for both case studies and base our comparative evaluation by using Revit materials Takeoffs list.

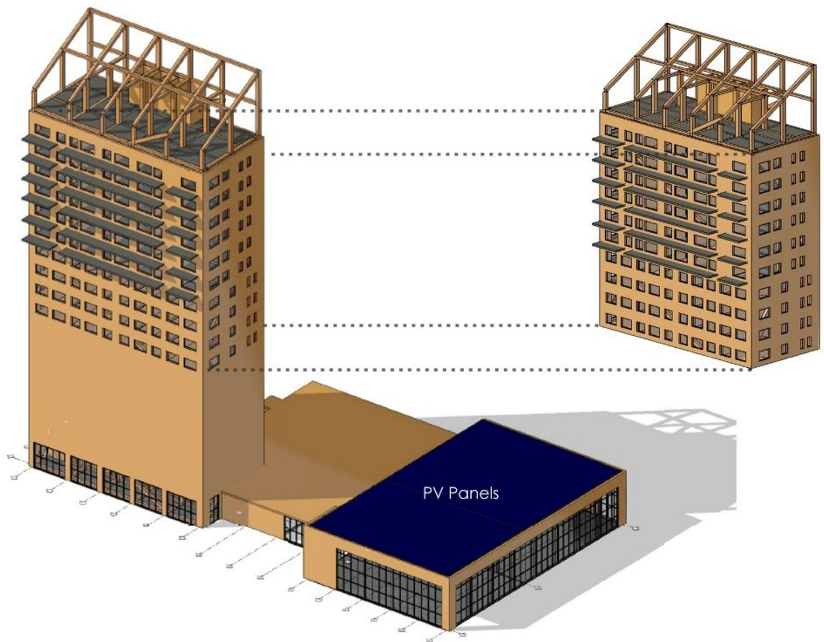


Figure 26 Revit 3D modeling depicting the Scope of comparison for Mjøstårnet, Brumunddal.

Since Mjøstårnet is a multi-zone building. the comparison scope was limited to include the residential zones as well as the hotel zone on the top levels to be able to obtain comparable results. the total Gross Area floor of Mjøstårnet Tower is 113000 m3 but is this study we take into consideration the residential living area which is 5200 m2.

The foundation and infrastructure of the building is also considered as well, including the technical equipment such as district heating, Photovoltaic solar panels energy production and electricity consumption.

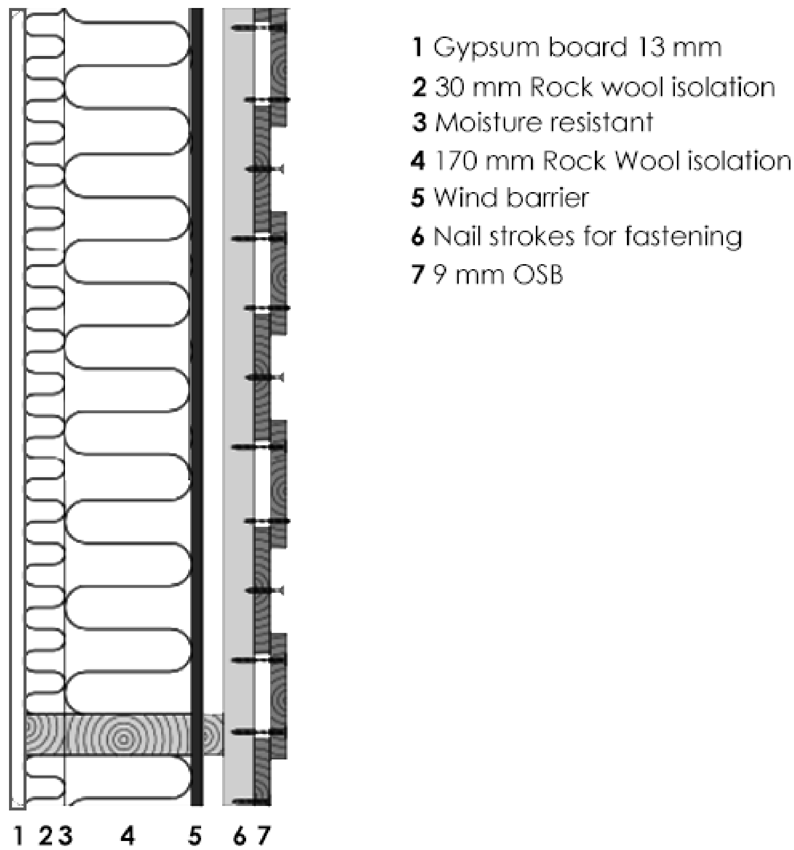


Figure 27 Example of a detail section of a Prefabricated sandwich timber panel.

The material inventory For Mjøstårnet walls, slabs and roofing elements compositions was mostly assumed based on information provided by Moelven's that roughly matched the description provided by the contractor's construction report for lack of components specification and documentations for technical assessment.

However, after extensive research to find which type of prefabricated sandwich panels using timber was employed in the building. we found a products catalogue on the manufacturer website describing multiple type of sandwich panels with assembly instructions for exterior facades.

Schema depicting the main structural difference between the two projects:

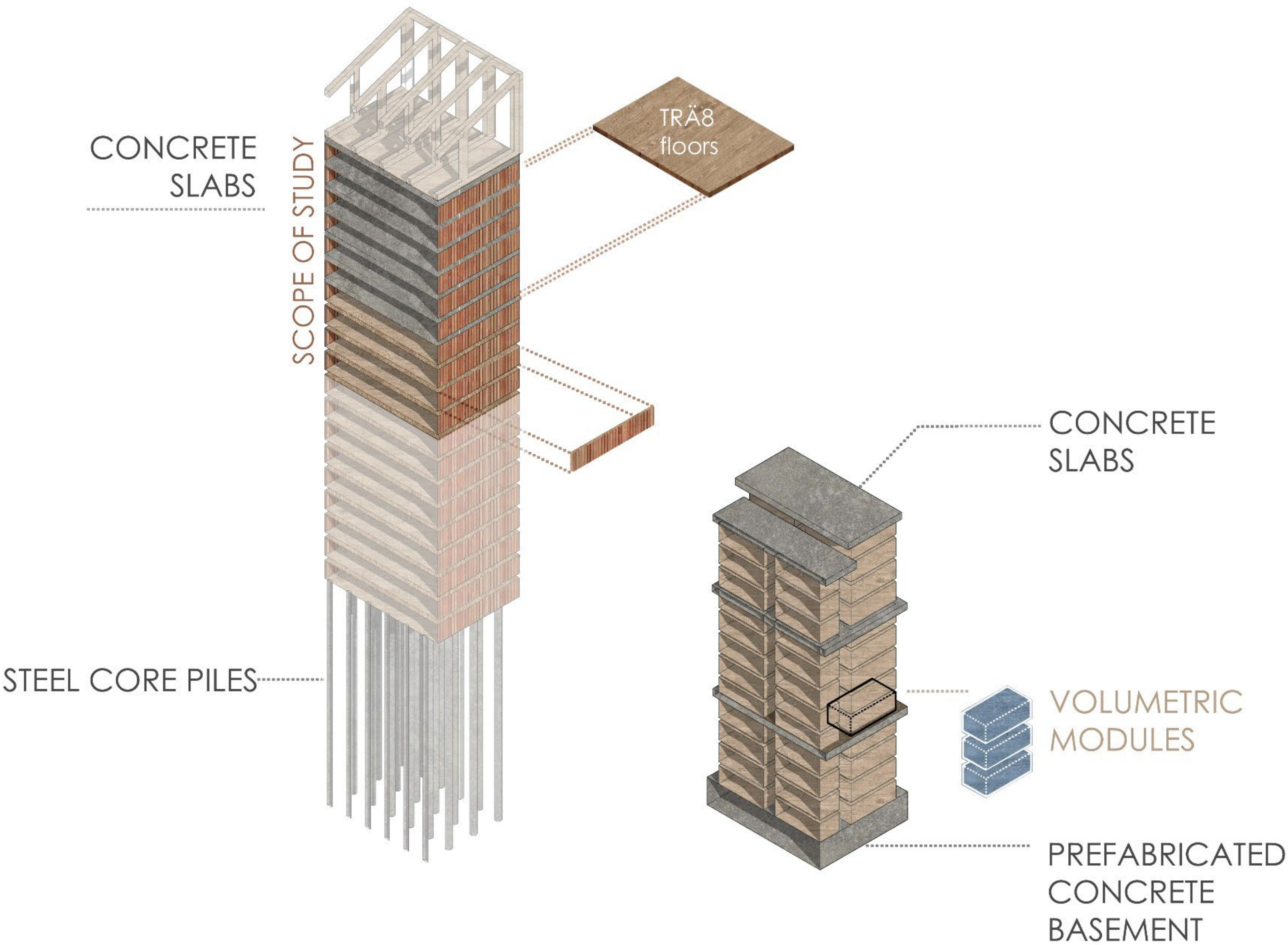


Figure 28 Structural difference between the reference projects

7. TOOLS AND METHODOLOGY:

7.1. Life Cycle Assessment[8]:

To determine the Carbon impact of a new building, The European Committee for Standardization (CEN) released EN 15978 as a standard for measuring the environmental sustainability of buildings and determine their Environmental Performance, Social Performance and Economic Performance.

This basis paved the way for a Norwegian equivalent standard to come to life like NS 3720 (Metode for klimagassberegninger for bygninger) as a tool for calculating greenhouse gas emissions. And a new methodology for CO2 emissions calculations for buildings and a tool to conduct a life cycle assessment (LCA) that has been divided into different phases and several cycle modules. the embodied carbon emissions are connected to the production phase (A1-A3), Transport (A4), installation and construction (A5) and the end-of-life stage (C1-C4), including the carbon emissions associated to the use phase (B1-B7), An illustration of the carbon emissions throughout a building's life cycle is provided in table 1.

BUILDING LIFE CYCLE INFORMATION				supplementary information beyond the building life cycle
(A1-A3) Product stage A1 Raw materials A2 Transport A3 Manufacturing	(A4-A5) Construction stage A4 Transport A5 Construction installation Process	(B1-B7) Use stage B1 Use B2 Maintenance B3 Repair B4 Replacement B5 Refurbishment B6 Operational energy use B7 Operational Water use	(C1-C4) C1 De-construction Demolition C2 Transport C3 Waste processing C4 Disposal	D Benefits and Loads Beyond the system boundary Reuse Recovery Recycling

Table 2Boundaries of the environmental impact assessment

[8] The European Committee for Standardization (CEN) EN 15978 for sustainability measuring of buildings.

There are four phases in an LCA study:

the goal and scope definition phase:

The scope, including the system boundary and level of detail of an LCA depends on the subject and the intended use of the study. The depth and the breadth of an LCA evaluation can differ considerably depending on the goal of a particular LCA.

a) the inventory analysis phase:

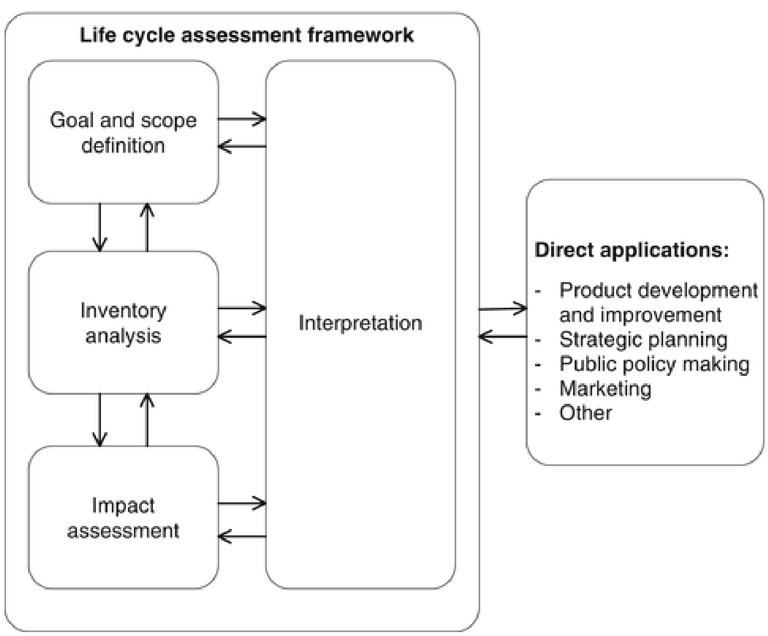
The life cycle inventory analysis phase (LCI phase) is the second phase of LCA. It is an inventory of input/output data with regard to the system being studied. It involves collection of the data necessary to meet the goals of the defined study.

b) the impact assessment phase:

The life cycle impact assessment phase (LCIA) is the third phase of the LCA. The purpose of LCIA is to provide additional information to help assess a product system's LCI results so as to better understand their environmental significance.

c) the interpretation phase:

Life cycle interpretation is the final phase of the LCA procedure, in which the results of an LCI or an LCIA, or both, are summarized and discussed as a basis for conclusions, recommendations and decision-making in accordance with the goal and scope definition.



One Click LCA:

The Global Carbon tool has been made to perform Global Carbon assessments and utilizes the largest database as an LCA tools. It does not have a mandatory material scope. The assessment includes:

1.The life-cycle stages scope: A1-A3, A4, A5, B1, B3, B4-B5, B6, B7, C1, C2, C3, C4, D

2.The results indicators scope: Global Warming Potential (GWP kg CO2e), Biogenic Carbon Storage (kg CO2e bio) and Social Cost of Carbon (in desired currency format).

3.Available material selection / EPDS.

Benchmarking approaches for buildings:

Benchmarks, in general, are comparison points that allow the performance of a process, product, or building to be evaluated. As part of evaluating sustainability performance, this idea may be applied to carbon emissions from buildings, especially embodied carbon.

Sustainability in buildings Indicators and benchmarks is a standard developed by the International Organization for Standardization (ISO) (ISO 21678:2020). Benchmarking is defined in this standard as the process of gathering, analyzing, and comparing performance data from comparable buildings or other types of construction projects.

The tools we use to conduct this Evaluation are:

Life cycle assessment according to EN 15978 provided by One click LCA : the Life-Cycle Assessment Parameters setup was set to default in One Click LCA tool but the main life cycle approach is -1/+1 which accounts for stored and emitted Carbon during production, construction and end of life, the LCA main indicator will be GWP or the total global warming potential and the environmental impact will be mainly relating to Co2 emissions as well as biogenic carbon storage (how much our buildings store carbon) . The Building Circularity will also be included by tracking, quantifying, and optimizing the circularity of materials sourced and used during the building life cycle, as well as the circularity at the end of life.

7.2. The Environmental Impact Categories according to EN 15804:

Table 3 Environnemental Impacts

Climate change – total, fossil, biogenic and land use	kg CO_2-eq	Indicator of potential global warming due to emissions of greenhouse gases to air.
Ozone depletion	kg CFC-11-eq	Indicator of emissions to air that cause the destruction of the stratospheric ozone layer
Acidification	kg mol H+	Indicator of the potential acidification of soils and water due to the release of gases such as nitrogen oxides and sulphur oxides
Eutrophication – freshwater	kg PO_4-eq	indicator of the enrichment of the freshwater ecosystem with nutritional elements, due to the emission of nitrogen or phosphor containing compounds
Eutrophication – marine	Kg N-eq	Indicator of the enrichment of the marine ecosystem with nutritional elements, due to the emission of nitrogen containing compounds.
Eutrophication – terrestrial	mol N-eq	Indicator of the enrichment of the terrestrial ecosystem with nutritional elements, due to the emission of nitrogen containing compounds.
Depletion of abiotic resources – fossil fuels	MJ, net calorific value	Indicator of the depletion of natural fossil fuel resources.
Photochemical ozone formation	kg NMVOC-eq	Indicator of emissions of gases that affect the creation of photochemical ozone in the lower atmosphere (smog) catalysed by sunlight
Water use	m3 world eq. deprived	Indicator of the relative amount of water used, based on regionalized water scarcity factors.

8. SCOPE:

8.1. Life Cycle product inventory

This study's Life cycle material inventory takes into consideration the building parts such as materials for the envelope, structure, foundations, and vertical and horizontal structure excluding MEP (Mechanical, electrical, and plumbing systems).

The data collection of such a complex system such as a building require an extensive data classification which is still not totally transparent for both chosen case study projects.

The procedure used for the material inventory of the buildings consist of an estimation of material quantities and their composition. the building data information was extracted from Revit using the material Takeoff plugin (BIM Tool) or Building information modeling

Table 4 basic information of reference buildings

Project	Location	Structure	Frame	Heated Gross Area	Living Area	Floors	Yearly Operative energy use
Mjøstårnet	Brumunddal	Glulam Trusses	CLT non load bearing structure +prefabricated Timber panels.	11300 m2	6400 m2 (including apartments And Hotel Rooms)	18 (this study considers only the last 10 floors)	98,0 Kwh/m^2
Treet	Bergen	Glulam Trusses	CLT non load bearing structure +prefabricated volumetric Modules	5830 m2	5830 m2	14	78,4 Kwh/m^2

8.2. Production Stage: (A1-A3)

Data collection of Building materials:

In distinction, the data regarding materials for Treet and Mjøstårnet was collected from different sources. but in this study, we relied mostly on plans and technical drawings in order to model both projects using Revit Material take off Plugin for material quantities. (Appendix D, F)

Epds Selection:

Assess impact using EPDS impact database:

Some of the Epds that were selected during the LCA calculation were chosen for diverse raisons and recognized assumptions:

1-Availability:

For The LCA evaluation, the building materials were manufactured in different countries in Europe, this led to the evaluation to be based on the EN 15978 standard for measuring the environmental sustainability of buildings from the European committee and the equivalent Norwegian counterpart standard NS3720, the goal is to have the possibility to access all epds from manufacturers from around Europe and not just from Norway,

2- Epds chosen depending on similar Material and component specifications (Appendix A).

That depends on the building material used in construction and their specific characteristics for example: density, usage purpose and manufacturer localization.

3- Norwegian Available EPD’s are privileged:

In this research, both case study buildings are located in Norway, thus both have been constructed under Norwegian regulations, in this case it is assumed that most or at least a high percentage of the building materials were locally manufactured for obvious economic and availability reasons: this means there is less transport for materials deliveries which tin return promotes local products.

Regardless the data collection allowed to amass some distinctive information about the source of some specific materials that were used for the construction of both buildings’ references. and for those not documented, European available environmental product declarations were used.

Table 5 mass of used materials in prefabricated wood building elements

Material inventory	Building A (Mjøstårnet)	Material inventory	Building B (Treet)
Massive Tre /Glulam	1320.9 m^3	Massive Tre /Glulam	460 m^3
CLT	418.54 m^3	CLT	222 m^3
Betong floor slabs	1375 m^3	Betong- slabs	415,8 m^3
Prefab floor Cassettes tra08	631,95 m^3	Prefab floor Cassettes tra08	x
Prefab wall panels	2503 m^3	Prefab wall panels	x
Steel Structural stiffeners	6,3m^3	Steel Structural stiffeners	6,3 m^3
Steel core piles	60 m	Steel core piles	5 m
Ground floor Concrete	192 m^3	Betong- foundation	529,2 m^3
External wood cladding	4904 m^2	External wood cladding	x
		Volumetric Modules (62apartements)	
Solid wood panel for Internal use	73,56 m^3	x	x
Rock wool insulation (Ext walls)	362,97 m^2	x	x
Gypsum (Int Walls, flooring-ceiling)	239,725 m^3	Gypsum	485,18 m^3
OSB	267,45 m^3	OSB	101,51 m^3
Mineral Rock wool insulation (Int walls, floors, ceilings)	1355.148 m^3	Mineral Wool (total int, Ext, floors, and ceilings)	4444,71 m^3
Wind stopper Basic	44.136 m^3	Wind stopper Basic	x
Timber Cladding	x	Timber Cladding	48,72 m^3
Moisture resistant	0.98 m^3	Moisture resistant	78,9 m^3

Particle Board 22mm	x	Particle Board 22mm	149,44 m^3
Ceiling Battens	x	Ceiling Battens	92,27 m^3
Aluminum facade cladding	x	Aluminum facade cladding	1888 m^2
Glass	1690 m2	Glass	1900 m^2

Table 6Main building component used in Treet in Bergen

Building Parts-Treet	Building Materials
Groundwork and foundation	Reinforced Concrete basement (parking) +Steel core piles (5 m depth into the rock bed)
Load bearing system	Glued laminated Timber +Steel structural stiffeners
External walls	Kodumaja volumetric Modules: - Timber members in walls, floors, and roof. - Roof sheathing - Subfloor -Thermal insulation - Membranes and barriers -Claddings
Inner walls	
Slabs	
Roof	
Stairs and elevator shaft	Cross laminated Timber
Heating System	Electricity, District heating

Table 7Main building components used in Mjøstårnet in Brumunddal

Building Parts-Mjøstårnet	Building Materials
Groundwork and foundation	Steel core piles (60 m depth into the rock bed)
Load bearing system	Glued laminated Timber +Steel structural stiffeners
External walls	Prefabricated Exterior timber Sandwich Panels (25-30 mm)
Inner walls	Prefabricated Interior timber Sandwich Panels (10-15 mm)
Slabs	Prefabricated Floor Cassettes Træ08
Roof	Prefabricated Concrete slabs (7 Top last floors)
Stairs and elevator shaft	Cross laminated Timber
Heating System	District heating, PV Panels

Transportation Machinery from manufacturers: Through this research, the transportation modes for a few main Construction elements were available and included in this evaluation, the Modules were Manufactured in Estonia and transported to Norway (Bergen) with the use of freighter shipments, it is mentioned that the modular volumetric constructions were transported divided between 3 boats trips back and forth to Bergen. Thus, the transport parameter was set to 3 times 2000 km (estimated distance between Bergen -Estonia). The CLT components were manufactured from Merk AS a German CLT producers and used a Truck which is assumed to be of type: Trailer combination, 40-ton capacity, 100% fill rate.

The construction materials components use in Mjøstårnet were mainly sourced locally; the Glued Laminated trusses were produced by Moelven Limtre in Lillehammer as well as the prefabricated sandwich panels for the exterior facades. the CLT and Prefabricated floor slabs Trå08 were produced in Sweden and transported by land.

8.3. Construction Process stage: (A4-A5)

Construction site scenarios

1.1.Excavation.:

Excavation is the process of digging, excavation will be understood as the process of excavating and removing volumes of earth or other materials for the conformation of spaces. Excavation is used in construction to create building foundations, reservoirs, and roads. Some of the different processes used in excavation include trenching, digging, and dredging and site development. The processes used will depend upon the structure that will result from the construction process. For construction work excavation services are important. We determine excavation method to use to find the volume. In this case we are dealing with a rectangular box because it describes a length, width, and depth.

Since Treet include a parking concrete basement with a total area of 920 m2, it is assumed the volume of the excavation is calculated following this methodology:

920 m2 x 5,432 m = 4997,5 m3

For Mjøstårnet, the building of 85 m high does not include a basement but instead the architects choose to implement piles as a stabilizing infrastructure that have depth that can reach down to 60 m. Although the ground floor slab is made of concrete as a fixating element that the glue laminated columns will sit and elevate the whole structure above the ground floor. Materials in the foundations will never be replaced, no matter assessment period length. For BREEAM UK Mat 1 IMPACT equivalent provide the data for site excavation fuel use here, choose resource Excavation works.

Deconstruction/demolition scenarios:

Since our building is assembled during the construction phase, The prefabricated elements also represent an opportunity to be dismantled and thus might be able to be reused and recycled. due to the ongoing developments of One click lca as a calculation tool, the available scenarios are restricted to a single option. The scenario selected consider only total demolition using electricity and diesel in the deconstruction process and the input the Gross Internal Area of the building in square meters.

Energy use on the site

The Energy use was assumed based on another study on GHG emission calculation from construction phase of Lia barnehage in Norway, which consists of onsite energy use for heating, cooling, ventilation, drying and lighting during the construction period. According to SKANSKA, all the energy used from the start of construction (10th April 2017) until the end (27th November 2017) is electricity, which has been supplied directly from the electricity grid. GHG emission factors from the ZEB research Centre have been used for electricity from the grid (0.132 kgCO2eq/kWh). The total electricity was quantified as 27700 Kwh. The Lia Barnehage has a heated floor area of 1600 m^2.

The GHG emissions associated with construction machinery include the type of machinery, Service hours and combustion of fossil fuels during operation. A crane and a Piles Drilling machinery were included for this study, the duration of use was assumed based of the construction period provided by the contractor.

The One Click LCA also take into consideration the time spent for drilling the piles for the foundation. the time data was not mapped out. Thus, the calculation was based on the Pile Construction Productivity Assessment equation:

$$\text{project drilling time} = \frac{N \bullet \text{TDT}}{60 \bullet \text{WH}} \quad \text{(days)}$$

where N = number of pile holes; TDT = total drilling time; and WH = working hours. Then, the outcome of project drilling time is calculated using Eq. (3) as follows:

Figure 29 calculation method to determine the total hours for steel core piles to be installed

If we assume that one pile drilling takes approximatively 30 mins (Depth value = 5 m) and a working day around 8 hours, we come to the result: 6,25 days for Treet (a total of 150 hours)

For Mjøstårnet:

If we assume that one pile drilling takes 6 hours (bigger Depth value = 60 m) for the second case project, we have a total of 58,5 days (1404 hours).

Hours for crane use:

Taking into consideration the duration from of the construction of the structure the start of construction until delivery of the projects. For Mjøstårnet: the building process started spring 2017. Opened 15th March 2019 so it lasted for approximatively 2 years, if we assume the working hours in one day are 8 hours, we come to the result of 5840 hours used for crane machinery during installation phase. For Treet, the construction process lasted for about 1 year: construction started spring 2014 and ended on autumn 2015. The total hours are assumed to be 4320 h.

Material uses on the site:

Material and Water use during construction on the site were not recorded and the data concerning these two phases are missing thus it was not included in our GHG emissions estimation.

Waste generated on the site

The construction waste includes material losses during the construction process, including the transportation processes to compensate for the loss of wasted products, and the processing of all waste up to an end-of-waste state or disposal of final residues. The default value for the waste disposal centers is set per default in One Click LCA Tool as 50 Km. It was difficult to get data for the production and transport of wasted materials used during the construction process. Thus, some values have been assumed based on a study that summaries the GHG emissions from the construction phase of Lia barnehage (a kindergarten located in Oslo, Norway). The GHG emission calculations associated with the construction waste consider the transport of waste to the treatment plant, waste processing (recycling or incineration) and waste disposal.

Figure 30 Plusshus Lia barnehage in Oslo, Norway. source (NIBE).

that additional materials be delivered alongside building materials, with all inputs connected to supplementary materials manufacturing processes being eliminated in order to compensate for product waste. The transportation of trash to the treatment facility, resource recovery (recycling or incineration), and waste disposal are all factored into the GHG emission estimations for construction waste. The distance between the construction site and the closest recycling and incineration plant, as well as the distance between the construction site and the nearest landfill, is assumed to be 50 kilometers.

Calculation period:

The building service life was set to 60 years.

According the EN/15978 the building LCA, the chosen calculation period is set to 60 years This is the default calculation period in most BREEAM and LEED assessments. BREEAM requires a 60-year study period for the purpose of compliance with this assessment issue to align with the BRE[9] Green Guide to Specification, which uses a 60-year period for quantifying the environmental impacts of building specifications and their replacement components.

[9] Building research establishment, UK centre of building science

8.4. Use stage: (b6-b7):

8.4.1. Inventory Building Energy Operations:

Energy Sources:

Energy use consists of onsite energy use for heating, cooling, ventilation, drying and lighting during the use stage B1.it is assumed that the energy supplied rely totally on the electricity grid .Even though both case studies are located near water sources and there is a high potential of integrating a water to air heat pump for heating purposes , there is no clear indication in any literature consulted about the possible use of this , Although both are connected to district heating for heating purposes and domestic water heating .

Energy demand calculations:

Simien simulations settings:

1.We used Simien to simulate the yearly energy needs for each referanser building using available U values for different construction elements (using the provided Thermal resistances in the European Technical Assessment of Kodu Maja building modules calculated according to EN ISO 6946:2017 [10]) as well as SFP (specific fan power for ventilation) values for low energy buildings.

2.The building is considered as a single zone (residential buildings) We also choose CAV[11] constant air Volume since we consider it as one single use zone instead of VAV (dedicated for multi zones) for calculations.

3. The periods for lightning and technical equipment use was set to 24 hours since it is a residential building.

4.Bergen was selected as the main climate location, with an energy supply sourced from the electric grid with apartments number adjusted to 62.

5. The [heated volume] was calculated to be more than 21 474,18 m3, the value was used based on the SN-NSPEK 3031:2021[12](Bygningers energiytelse Beregning av energibehov

[10] International standard Method of calculation of the thermal resistance and thermal transmittance of building components and building elements

[11] HVAC system for Heating, air conditioning and Ventilation

[12] Energy performance of buildings Calculation of energy needs and energy supply. NS: 2021.

og energiforsyning) Energy performance of buildings Calculation of energy needs and energy supply Norwegian specification.

6. The infiltration rate calculated for "Treet" as a passive house according to NS 3700. So, the infiltration rate should be 0.6 or better.

7. Thermal bridges were set to be 0.03 W/m2K according to NS 3700 as a passive house as well as the U-values for windows, walls, floors, and roofs are also set according to NS 3700 standard for passive house.

8. The ventilation rate is set to 1.5 m3/ (h m2) which is higher than the minimum requirements for a passive house.

9. The SFP OR The Specific fan power for ventilation is set also at 1,5 kW/(m3/s).

10.The Heat recovery is set to 80 % 80 (minimum requirement NS 3700) and according to other Zeb or low energy reference buildings, but the value could also be higher.

11. the Heat Transmittance for Treet were set for walls, floors, and roof to 0,16 m2. K/W, 0,12 m2. K/W and 0.13 m2. K/W respectively.

12. the Heat Transmittance for Mjøstårnet were set for walls, floors, and roof to 0,18 m2. K/W, 0,15 m2. K/W and 0.13 m2. K/W respectively according to the minimum’s Norwegian requirements (TEK, 2017)

8.4.2. Yearly Water consumption:

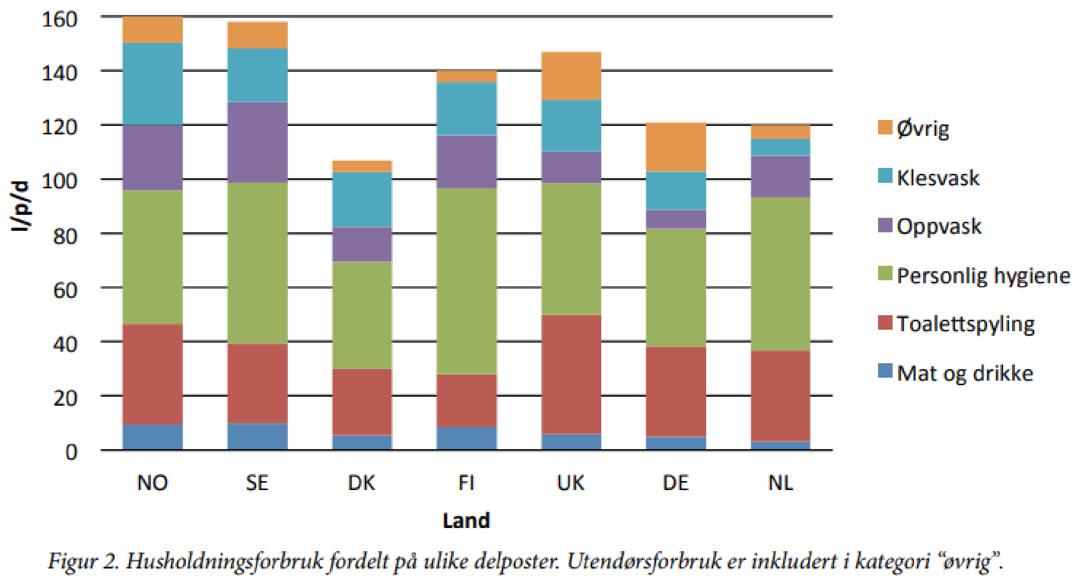


Figure 31Houshold water consumption in different cities, source (SSB)

Resource use of net fresh water (non-energy): The water consumption was calculated based on the report 'Vannforbruk I husholdninger' in Norway dating from 2015 comparing the water consumption in households between major cities in Europe per person (it is also worth mentioning that Households with a or few people have a higher specific water consumption than multi-family households /apartments building). so, considering this, based on the average family member number from SSB[13], the average family number of person in a family is 2,13. in this case, we multiplied the average number of persons per private household by (160 l) the individual water consumption in a day by 365 days (for yearly consumption) multiplied by the number of apartments in each building to have an approximate value of 7712,3 m3 for Treet domestic waters consumption

Mjøstårnet on the other hand includes a few but bigger appartements (36 apartments in total including the lofts and penthouses). So, the calculation was based on this equation:

160 L *365 days *2.13 *62 = 7712,3 m^3

160 L *365 days *2.13 *36 = 4478,112 m^3

[13] Sentral byrå Statistics, Norway.

9. Results and interpretation:

The preliminary results from One click Lca have provided us with the benchmarking of both buildings. Benchmarking is an environmental practice that allows us to compare the measured performance with the goal of informing with the improvement that could be undergone.

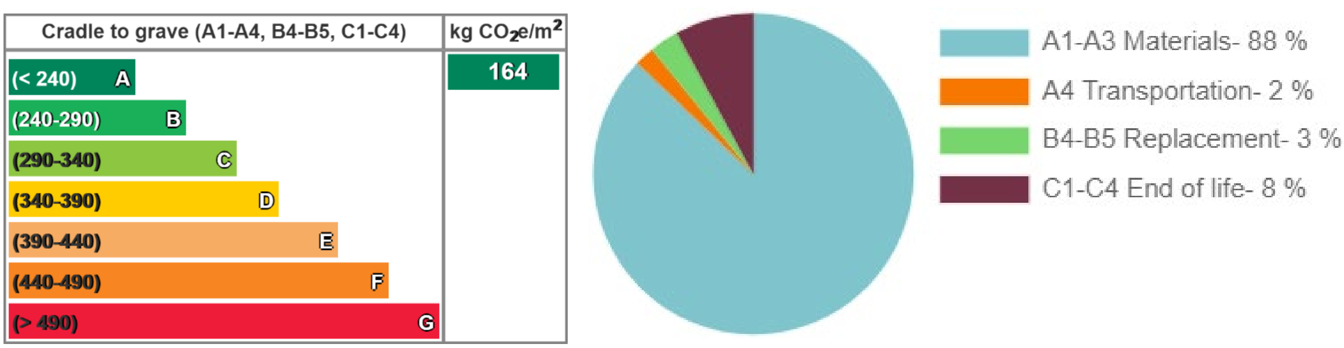
Buildings' energy performance benchmarking is a foundational element of an organization's energy management strategies. This practice has become a standard management procedure to quantify the energy costs and environmental and sustainability issues and raise awareness around the importance of environmental aspects and impacts of a building.

1. **Embodied carbon benchmarking:**

The buildings embodied carbon benchmarks are calculated for a fixed 60-year assessment period for all building materials and do consider the given quantities of materials, materials transportation within the provided distances, and material replacements required during the assessment period as well as the end-of-life processing.

The impacts do not include the recycling, reusing or disassembly impacts. The impacts are always calculated depending on the internal gross area.

Treet:



According to the results obtained after materials inputs, The Treet project has a benchmarking of A. the building use materials such as wood with low carbon emission for their production.

With a CO2 emission value of 164 kg Co_2 e/m^2, this is due mainly to the impact of materials and their low embodied carbon. 88 % of GHG impact is associated with the A1-A3 life cycle

Stage. The emissions associated with end-of-life stage deconstruction and demolition represent 8 % of the total embodied emissions, this could be lower since the modules could be disassembled and reused/recycled and contribute to promoting a circular life cycle.

Mjøstårnet:

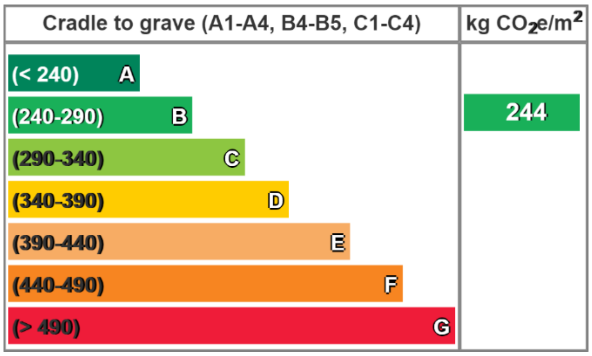


Figure 33 Building benchmarking excluding the embodied energy of Mjøstårnet

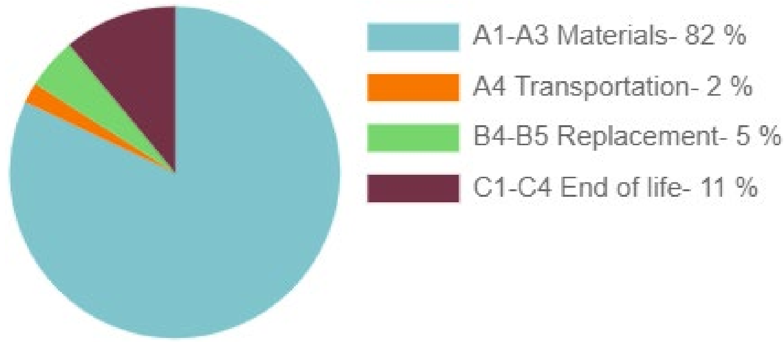


Figure 32 impact Proportions of different life cycle stage

For the Mjøstårnet case, the building Got a B benchmarking, with a Co2 emission value estimated to 244 Kg Co_2 e/m^{2,} which is higher than Treet's, the materials production impact is assessed to be responsible for 82 % of the GHG embodied emissions. The end-of-life stage embodied carbon represents 11 % of the total embodied carbon of the whole system boundary. which is slightly higher than the Treet project because of the possibility of a higher disassembly rate of multiple elements and parts of the buildings (walls, floors, panels.)

9.1. The embodied carbon emissions by Structure (A1.A3):

To evaluate the results obtained for both chosen case studies, we tried to compare the impact of different structures and ascertain which part of the construction is the most responsible for the GHG environmental impact.

Even though the results emphasized the impact of the two residential buildings on the production and construction stages, the structuring of the construction elements as a model allowed an investigation into the contribution of each building elements

The preliminary evaluation outcome shows that the concrete slabs introduced in the 8 top levels of Mjøstårnet as a necessary extra mass to stabilize the whole timber structure and reduce the horizontal deflections due to winds velocities, contributed the most to the embodied Co2 of the building by 51 % compared to Treet with a total of 3 Concrete slabs added on top of the power level which represents nearly 1/3 of Mjøstårnet impact on the same category.

Since this comparison paper has a focus on residential buildings, Mjøstårnet residential part happens to be situated on the top levels where the use of concrete slabs is the highest.

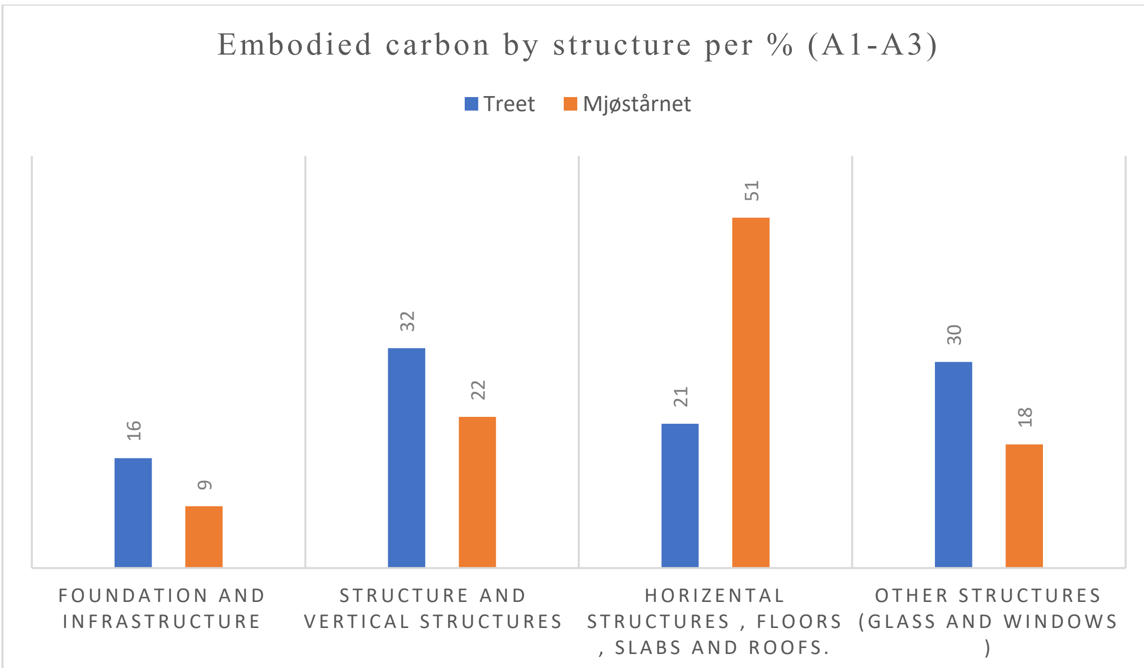


Figure 34 percentage of Embodied carbon by structure

On the other hand, for the vertical structure including exterior Facades, Treet embodied emissions are more consequent compared to Mjøstårnet, this could be justified due to the higher Thermal transmittance values to achieve A passive house standard and thus using high quantities of insulating materials such as rock wool insulations.

For the foundations, the results demonstrated that Treets concrete basement contributed the most to the total embedded carbon emissions (16%) almost 2 times higher than Mjøstårnet with (9%) contribution using Steel core piles fixated on a concrete floor slab instead.

9.2. GHG Emission from different life cycle stages:

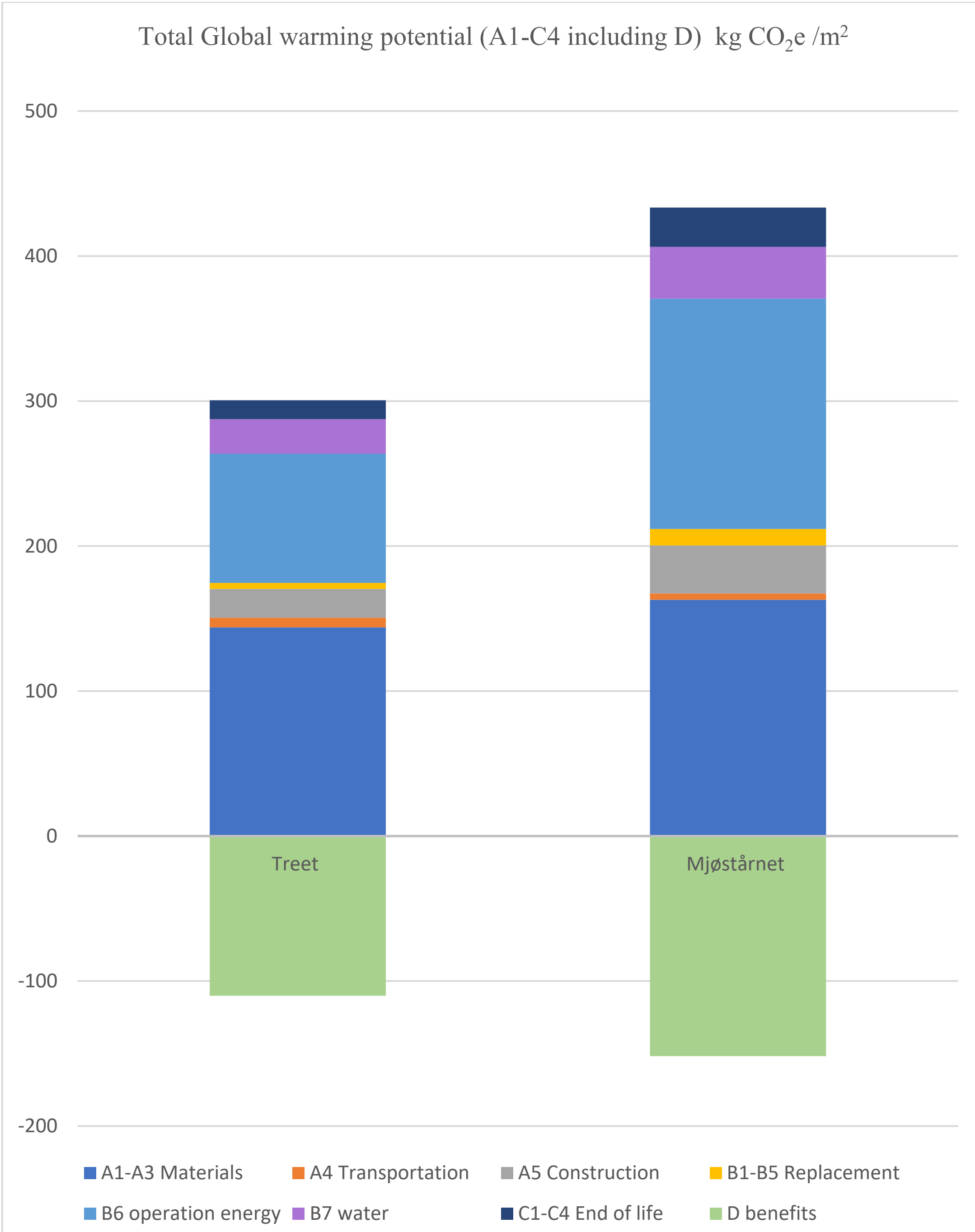


Figure 35 Total Global Warming potential KgCO2/m2

As the figure (34) shows that the total Gwp emissions including the energy consumption during service life differs significantly on case-by-case basis. For Treet, Module A1-3 accounts for

47, 8 % of the total GHG emissions, 29,6 % for B6 energy module. 2,7 % for A4 -transport to the building site- module, 6,7 % for A5 module, 4,7 % for B7 water use module, and 4,7 % for C1-4 module.

On the other hand, Mjøstårnet GWP for A1-A3, A4, A5, B6, B7 and C1-C4 accounts respectively for 42,7 %, 0.9 %, 7,1 %, 33,7%, 7,6% and 5.8 %. with a total of 470 kg of Co2 emitted per square meter for Mjøstårnet while Treet has a value of approximately 300 Kg Co_2/m^2 which highlights the significance of different prefabricated off-site methods.

In the next steps, we will try to analyze in-depth different Stages that have contributed to carbon emissions. In this report the environmental impact will include the environmental impact indicator of potential global warming due to emissions of greenhouse gases to air for climate change for fossil, biogenic and land use.

9.2.1. Greenhouse gas emissions for module A1-3 (material acquisition stage):

In module A1-A3, there seems to be greater potential to mitigate GHG emissions from the production of building components and elements in Treet compared to its counterpart IN Mjøstårnet. the potential of manufacturing completed prefabricated modules in the same factory could lead to fewer carbon emissions in module- A2 (transport of raw materials for assembly.

Effectively, the comparison shows that higher rates of prefabrication permit to have lower Co2 emissions during the production stage, however during the assessment we couldn't extract the emissions specific to electricity consumption due to the prefabrication process in the factory and therefore which sub-stage the mitigation is due. The Lower emissions in Treet Module production could be a consequence of 3 possible scenarios:

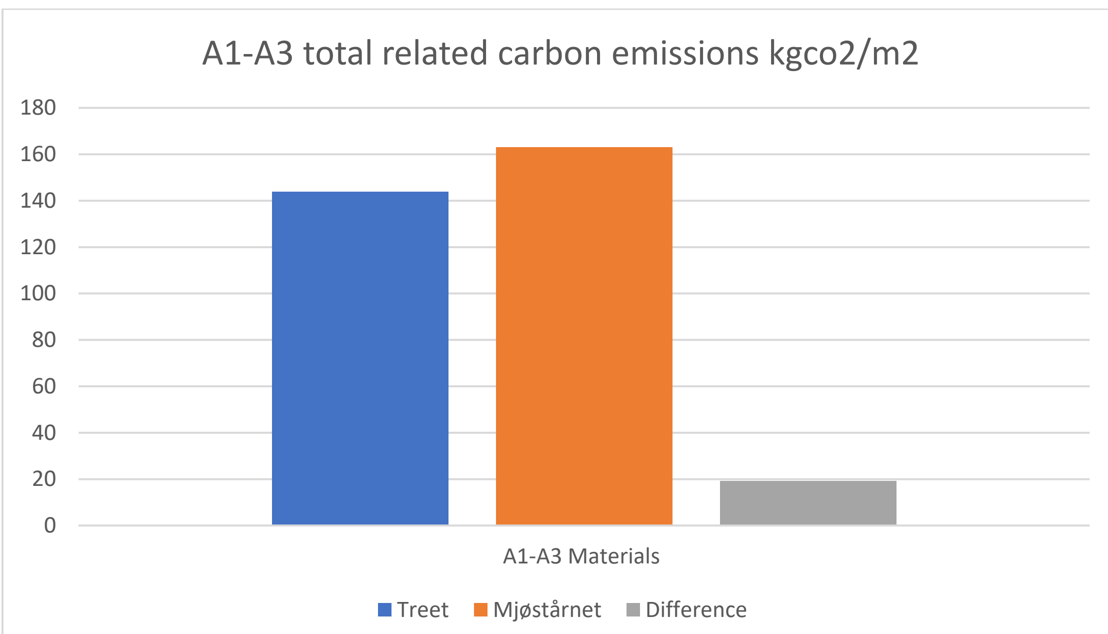
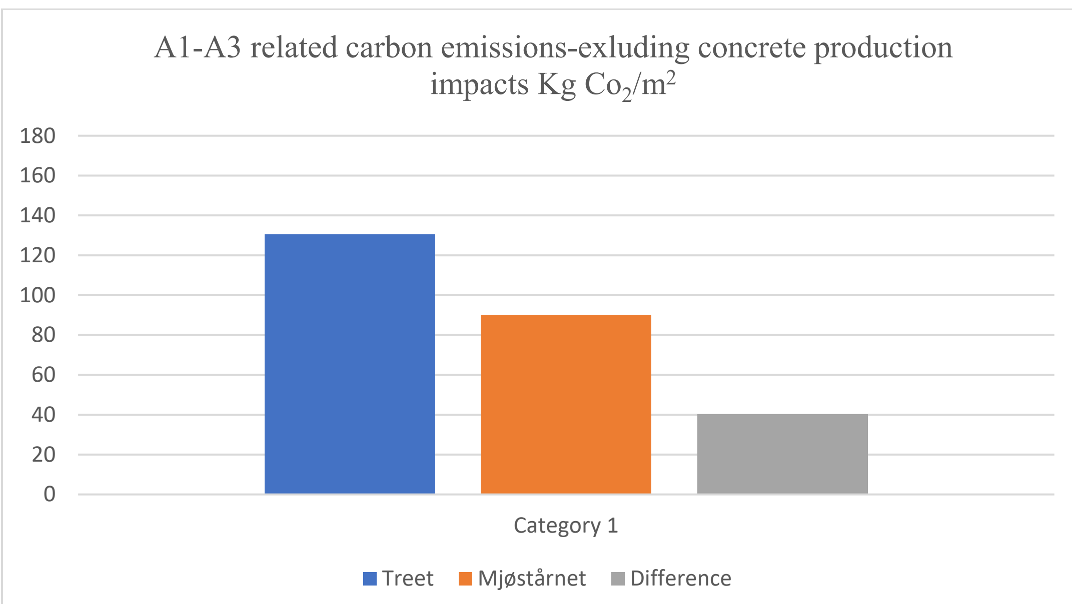


Figure 36 Production phase related carbon emissions

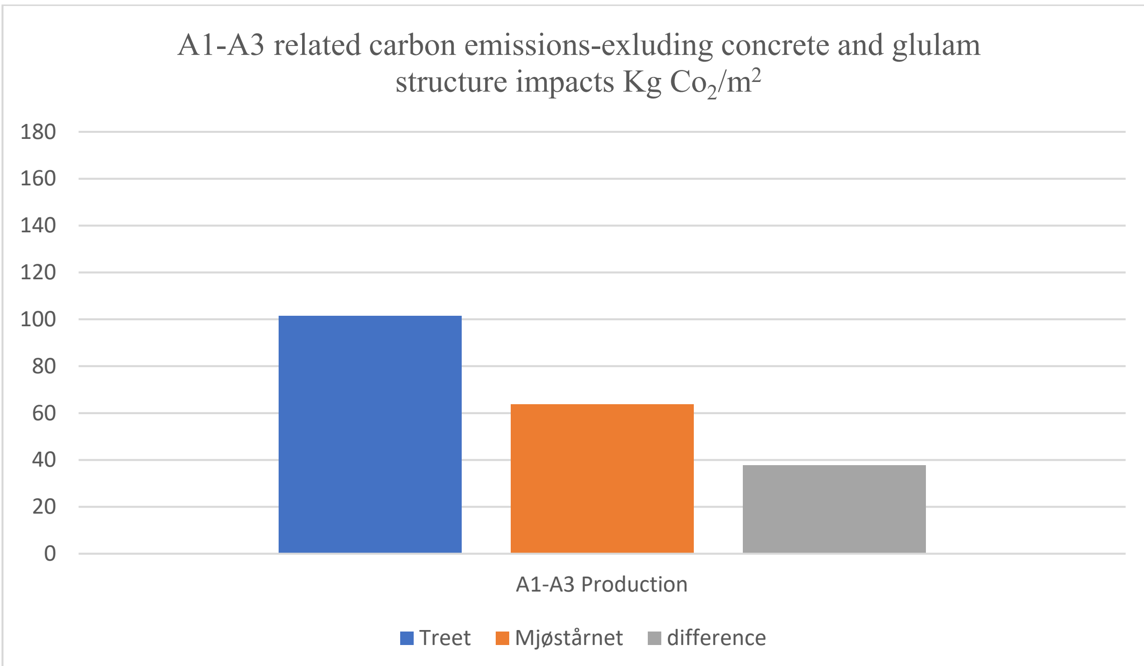
1. Concrete that was added to the load-bearing structure of both projects as an extra weight to stabilize and add stiffness to the structure.
2. lower transportation rate for raw product from suppliers to the manufacturer since only one manufacturer order different raw supplies to one specific located factory and assemble the whole module parts of a finished volumetric module (walls, slabs, and roofing). (Mjøstårnet case)
3. For the Manufacturing process, it is safe to presume that the assembly in factory of prefabricated building Element would significantly fluctuate the energy used for their off-site production. In this case, the tool One-click Lca does not allow us yet to determine which sub-stage in the production phase (A1-A3) influenced the increase in Co2 emission.

Thus, through an experiment investigation, we will try to evaluate the GHG emission from production A1-A3 excluding the production process of concrete and determine how the results would change in case the concrete related GHG emissions influence was dismissed. Concrete is a material which is composed of cement, aggregates, and water with different ratios.



This Figure shows GHG emissions for module A1-3 of the reference buildings, the results show that if we exclude the concrete from the evaluation, the Treet would be responsible for more GHG with a value of 760615.6 Kg Co2, which is 25 % higher than Mjøstårnet when in the production phase. While Mjøstårnet carbon emissions drop by half when excluding concrete masses.

Naturally, this increase is assumed to do with high levels of off-site prefabrication of Volumetric modules that requires more energy consumption to assemble in factories during the manufacturing stage. In this case, Modules employed in Treet are 95 % prefabricated off-site in the factory and represent a greater potential to contribute the most to GHG during the production stage. But then we have to consider the duality of the prospect of using wood waste from production as biofuel and that would actually reduce the carbon emission from off-site prefabricated modular system.



After observing an important use of glulam structural element in Mjøstårnet due to height and wider foot area that require more support, another experimentation excluding both glulam and concrete was undergone, this choice was made to narrow down the impact of Modular and panelized systems. Here we can notice that the Panels used in Mjøstårnet reduced the carbon emissions compared to the modular system in Treet.

9.2.2. Transport to site and construction process (A4-A5):

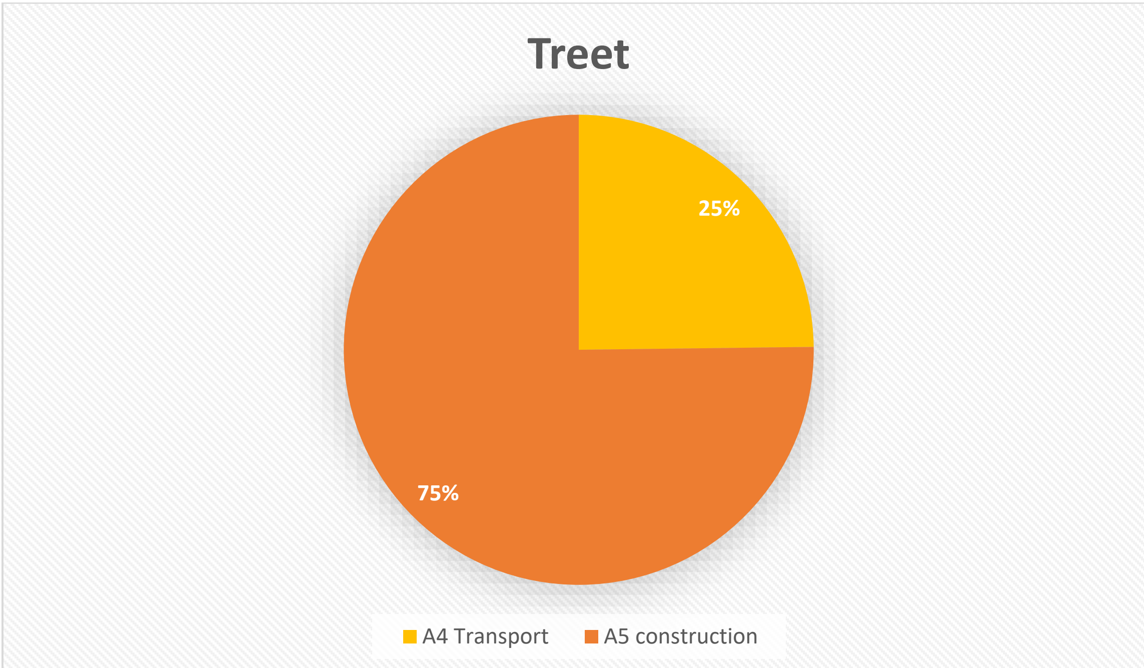


Figure 37 carbon emission Percentage from A4-A5 Module

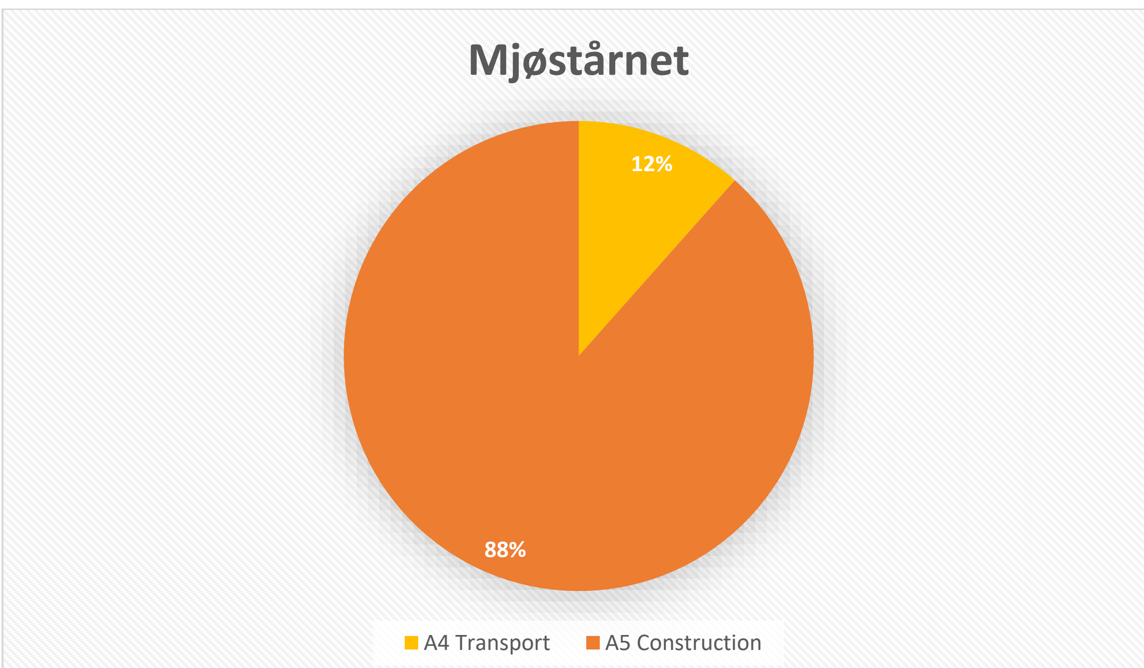


Figure 38 carbon emission Percentage from A4-A5 Module

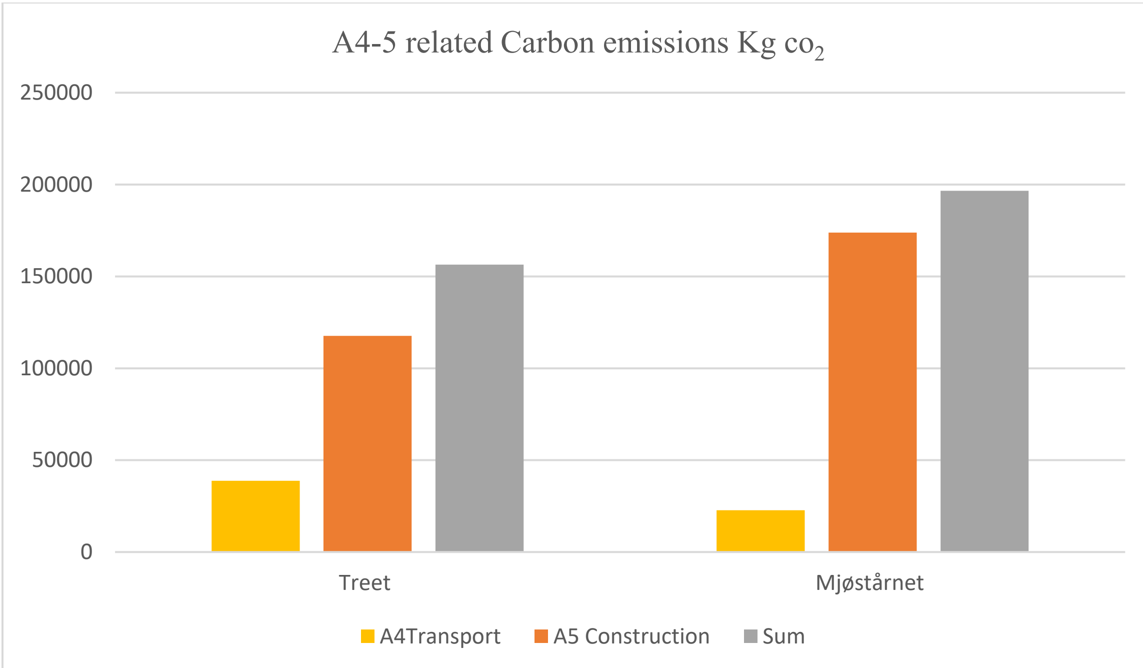


Figure 39 Emissions difference between Mjøstårnet and Treet

In the A4-5 module, the potential to mitigate the GHG emissions during transport and construction installation is higher with use of finished modules in Treet. since the volumes offer the possibility to stack the volumes up on top of each other which can take less than 20 mins.

The A4-5 electricity use during the construction process was based on a previous study on Lia Barnehage in Oslo[14], a prefabricated kindergarten with a heated area of approximately of 1600 $m^{2.}$ the electricity use was then assumed depending on each of the reference buildings area (5830 and 6400 m^2 respectively) to be more proportionate to each project BRA.

In this evaluation, the distance between the locations of the factories and building site is taken into consideration to calculate G to S (gate to site) emissions.

This detailed experimentation of GHG emissions estimation during transport and construction put light on the optimization capacity of Prefabricated volumetric modules compared to panelized components.

[14] Selamawit Mamo Fufa (2018) GHG emission calculation from construction phase of Lia barnehage

The impact of Transport-A4 in Treet project is more consequent partly due to the longer delivery distances of modules /CLT elements from manufacturers from other European countries.

As shown in figure (19) The Carbon emissions from the transportation of Mjøstårnet prefabricated panels to the building site are half as much as Treet value. this is partly due to locally sourced materials.

9.2.3. Energy use during lifetime (B1-B7):

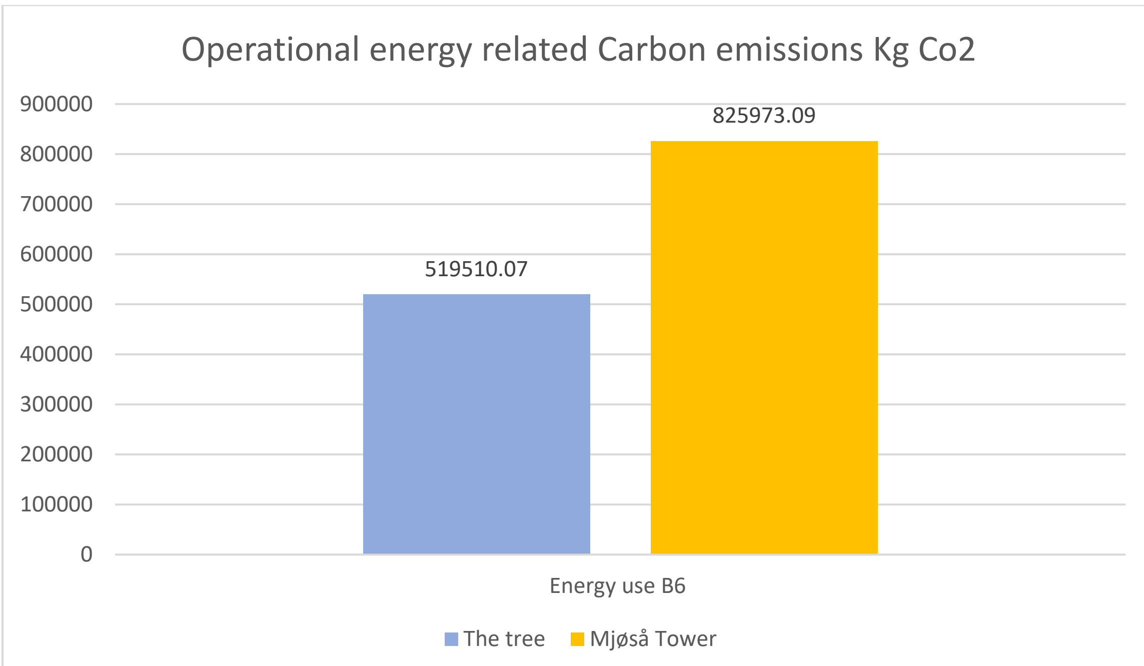


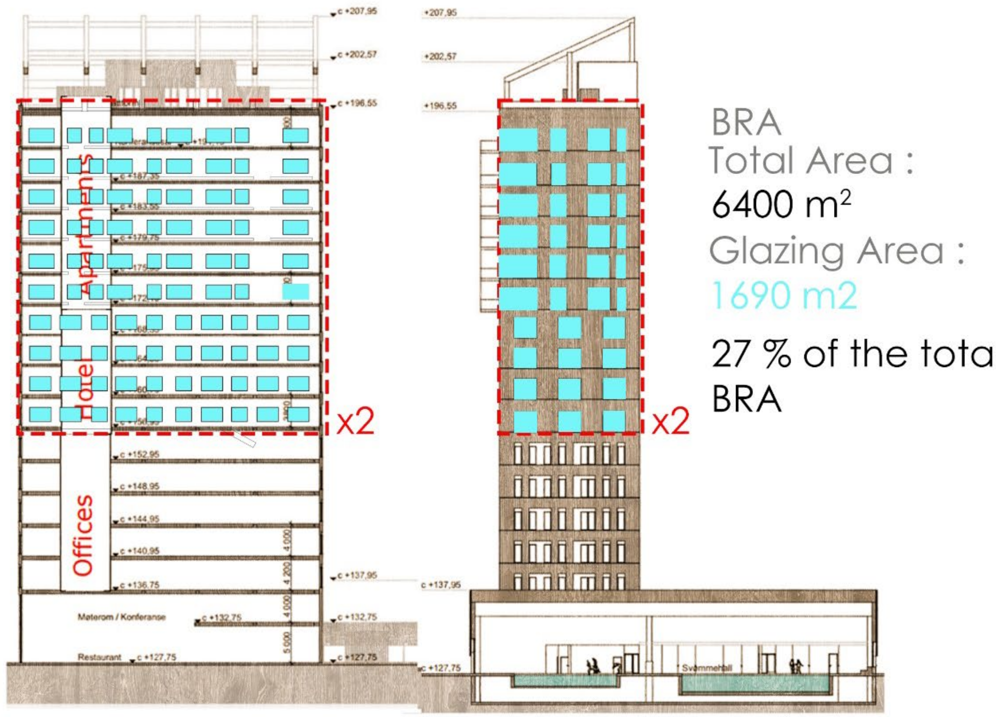
Figure 40 Operational energy related carbon emissions KgCo2

We can observe a sizeable gap when it comes to energy consumption when comparing the two study cases. for Mjøstårnet the total annual energy demands is 501778 kwh which emits the equivalents of 825973.09 Kg Co2 within the building lifetime. Whereas Treet's energy demands are 360115 kwh per year and is responsible for 519510.07 KgCo2 pf carbon emission during the building service life.

Although the result from Simien indicates different values for example Treet represent a yearly Co2 emissions of 39 630 kg CO_2 the equivalent of 8,8 Kg CO_2/ m^2. this represents 2 340 000 kg CO_2 over a 60-year time frame. Almost 3 times the value obtained from One click LCA. this could be due to different Electricity resourcing. The value provided by One click LCA is 0.0287 kg CO2e / kWh while in SIMIEN it is 0,13 kg Co_2 /Kwh.

Analyzing the results from One click LCA, the gap is most probably due to the difference in fenestration ratios of these two buildings, Mjøstårnet windows are designed to be much bigger than the Tree Project to allow direct view to Mjösa Lake. (Magnus Berge, Judith Thomsen) (2012) in Bergen on the other hand, since it rains the equivalent of 3 m of rain yearly, the architects added a glass facade on the outer side of balconies which could be considered as a double façade that can contribute to lower heating needs in the occupied spaces and thus explain why the Treet project has less energy demands. The energy demands cover heating, cooling, ventilation, lighting, and electrical utilities.

Another perspective to consider is the difference is the heat transfer characteristics, As Treet is better insulated and airtight than Mjøstårnet. (Appendix B, C).



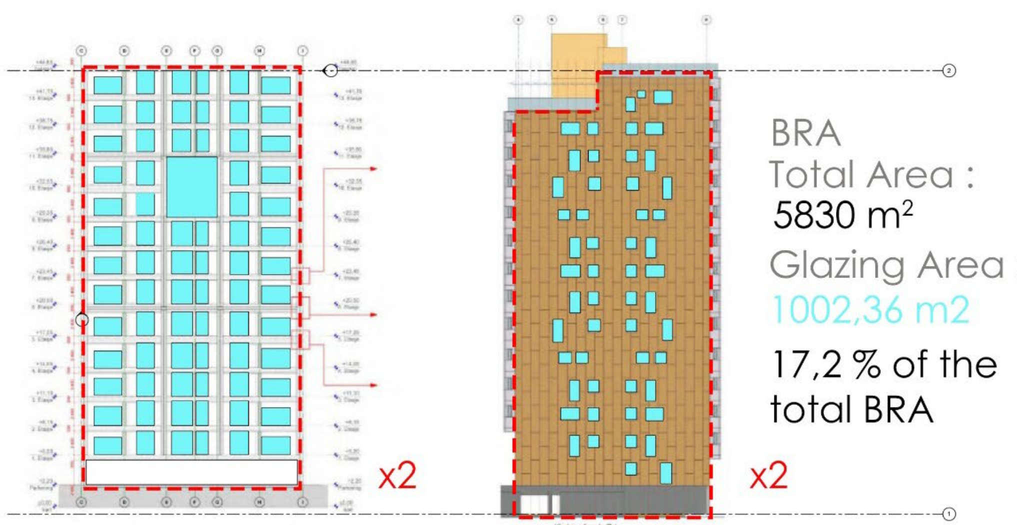
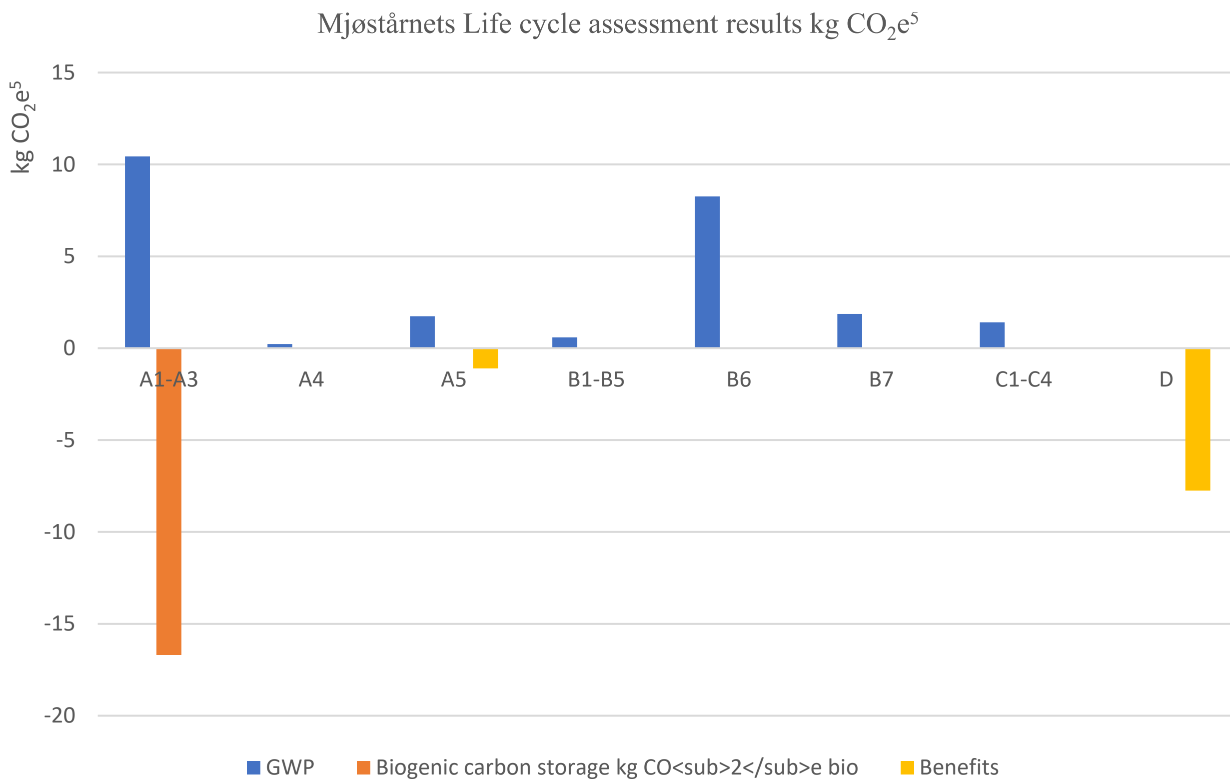
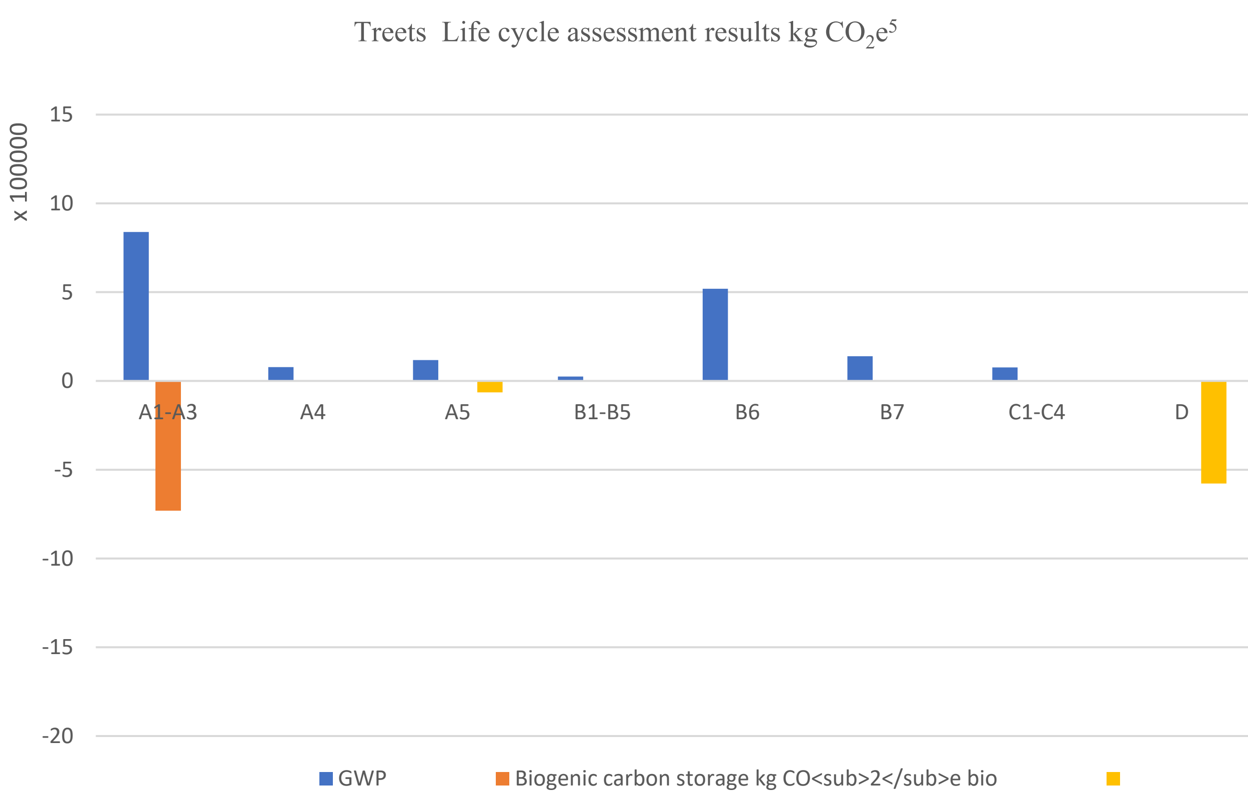


Figure 41 windows Area ratios per BRA

9.3.Carbon Uptake compared to emitted:

Figure 42 life cycle assessment carbon intake and emitted





Timber structures confine approximatively 1 ton of CO2 per 1 m^3 of wood, this way of capturing the Carbon could be an opportunity to transform the construction industry and encourage the application of Timber as a sustainable and durable product. To differentiate the duality between operational and embodied carbon, we can observe the results obtained from our comparison study with focus on these two dimensions using Life cycle assessment method.

When considering Mjøstårnet, the results shows that it emits more GHG emission than Treet throughout its service lifetime, nevertheless it has a very high rate of embodied CO2 from the use of raw materials products such as Mass Timber.

The embodied carbon in trees Modules is very low and the reason can be related to the higher use of rock wool products (insulation) as a recurrent component in the walls, floors, and ceiling composite elements in hopes to achieve a passive house standard.

If we consider Mjøstårnet panelized system as open panels with massive CLT elements, then it would explain the consequent embodied carbon or renewable primary energy as raw material it represents.

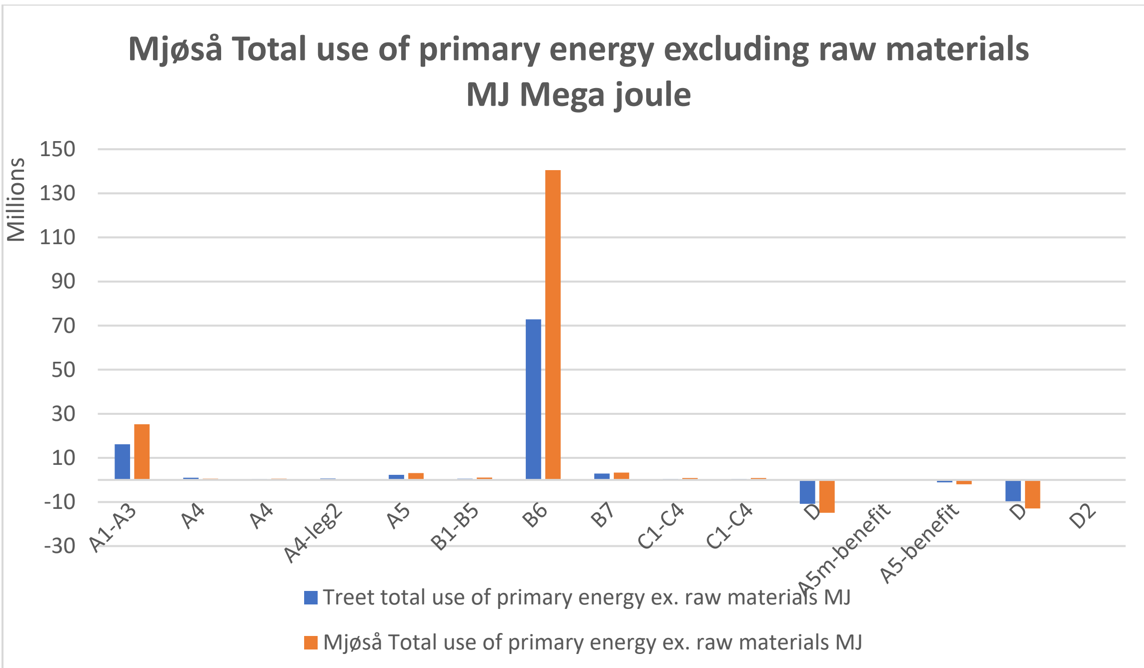
In C1-c4 the carbon emissions have a small value since the wood waste generated during demolition will not be sent to landfills, but the wood elements represent combustible energy source that is accounted for in phase D instead of end-of-life C1-C4. (Appendix F, G)

Beyond the system boundary Benefits from the material reuse:

Reusing building materials may result in considerable resource savings as well as other environmental benefits such as a reduction in landfill trash and the energy required to produce new materials.

Module D contains the benefits and loads beyond the asset life cycle (system boundary). This information module provides transparency for the environmental benefits or loads resulting from reusable products, recyclable materials and/or useful energy carriers leaving a product system e.g., as secondary materials or fuels or in form of exported energy.

During A5 construction phase, the construction operations generate waste from unfitted elements or wood pellets. Through wood waste processing, this biomass could generate renewable energy and help meet the target for climate change goals. In addition, After the possible dismantling of Panels / Modules during disposal stage (C1-C4) when the building reaches the end of its service life, reuse, and recycling opportunities will give a second life to used construction element and integrate the reused products in other projects which will further minimize their carbon footprint.



The last figure shows the sum of non-renewable primary energy (energy carrier) excluding non-renewable primary energy resources used as raw materials and renewable primary energy excluding renewable primary energy resources used as raw material. which basically means this is the quantification of all RPEE and NRPE used for the construction of this building from gate to grave life cycle. Construction Machinery that uses non-renewable energy carriers such as oil or gas will contribute to increase the total of the energy that is in its primary form.

The advantage with wood products for example is if burned it could be considered as a renewable primary energy carrier and generate electricity using wood waste such as pellets as biofuel which is a carbon neutral energy source.

This clearly indicate that the consumption of Primary energy as an energy resource in its first form is observed to have the highest rate for operational energy of the building during the B6 module which is resultant of the electricity demands during the building lifetime, followed by the production stage use of primary energy. this result does not show the proportion of renewable primary energy and non-renewable primary energy but only indicate totals. in addition, it does not include renewable primary energy as energy carrier from raw materials such wood waste, or pellets generated during production, construction, and end of life phases. which then the results could be expected to have higher values.

9.4. Circularity:

The circularity score of Mjøstårnet has a percentage of 39 % slightly higher than Treets final circularity score with 30 %.

This includes the material query and data collected with information that documents the rate of virgin, recycled, renewable, reused materials (Some products have the recycled, renewable, or reused percentage defined with a default value) which can be based either on the product or the type of product. Waste defines the construction site wastage for the material. Defaults are set based on typical wastage and will vary based on the construction process, building and design (One click LCA tool, 2021).

Mjøstårnet:

The percentage of materials recovered 23,9 %: includes Renewables and Recycled materials.

The percentage of virgin Material: 76,1%

With the percentage of material return 54,4 %: which includes 50 % of Downcycling process and 50 % of the score used for energy as well as the full score of materials reused or recycled excluding the Score of materials disposed.

Treet:

The percentage of materials recovered 24,9 %: includes Renewables and Recycled materials.

The percentage of virgin Material: 75,1 %

With the percentage of material return 36 %: which includes 50 % of Downcycling process and 50 % of the score used for energy as well as the full score of materials reused or recycled excluding the Score of materials disposed.

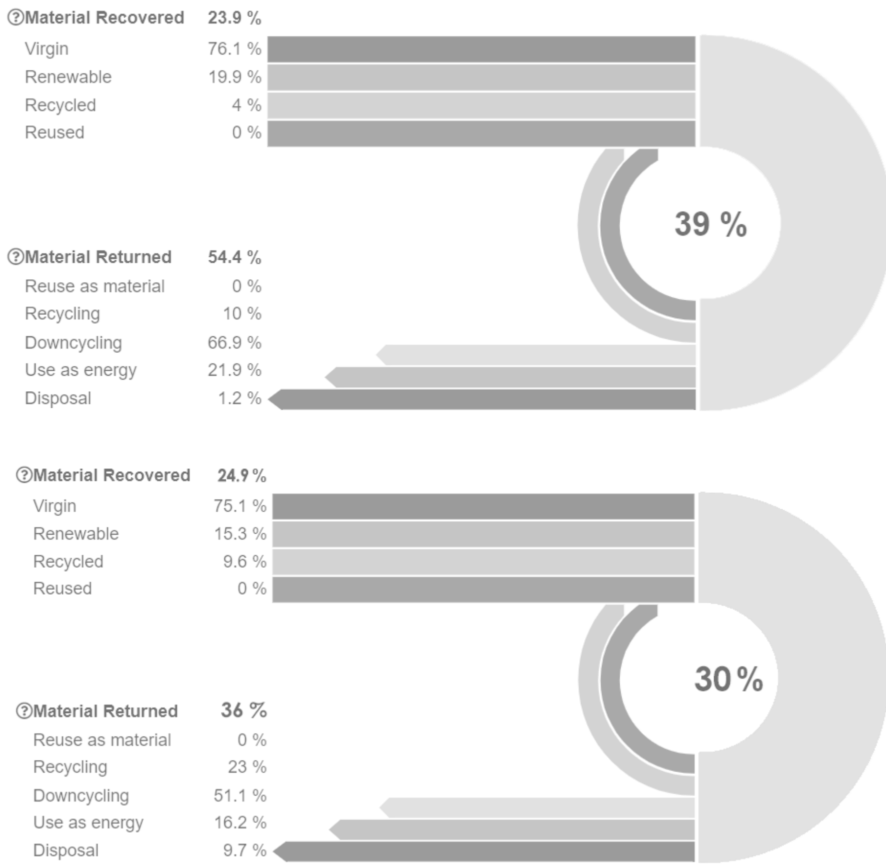


Figure 43 Circularity scores

Table 8 26 Building circularity for Mjøstårnet

	Project name	Design name	Indicator name			
	Mjøstårnet - Brumunddal	Mjøstår net	Building Circularity			
Section	**Result category**	**Total tons**	**Virgin tons**	**Renewabl e tons**	**Recycled tons**	**Reused tons**
A1-A3	Construction Materials	5476.33	4292.8 2	1008.61	174.9	0
A5	Construction site - material wastage	249.58	67.26	169.21	13.11	0
B4-B5	Material replacement and refurbishment	204.98	151.44	2.29	51.24	0
Totals Materials Used	Total	5930.89	4511.5 3	1180.11	239.25	0

Table 9 Building circularity for Treet

	Project name	Design name	Indicator name			
	Treet-Bergen Apartment buildings	7 - Treet-Bergen	Building Circularity			
Section	**Result category**	**Total tons**	**Virgin tons**	**Renewable tons**	**Recycled tons**	**Reused tons**
A1-A3	Construction Materials	3092.08	2353.41	452.81	285.86	0
A5	Construction site - material wastage	222.29	121.24	75.86	25.2	0
B4-B5	Material replacement and refurbishment	139.1	117.75	0	21.35	0
Totals Materials Used	Total	3453.48	2592.39	528.67	332.42	0

9.5. Carbon Social costs implications:

Treet Social cost of carbon is estimated to be 855690.14 kr (currency changed to kr) with 1 ton of carbon costing 487 kr. Mjøstårnet social cost of carbon is estimated to be 1195993.96 kr.

Prefabrication has the capacity to Reduce the costs by reducing by 30 % the construction costs, time and a 60 % reduction in defect.

If a building design's emissions can be reduced by using different materials or processes, then investing in different materials or measures that could be justified by making economic saving and pursuing emissions reductions.

Energy measures can be integrated in the preliminary design that can actually rise the costs during design phase but provide a higher energy saving on the long term during the building lifetime by applying renewable energy sources and sustainable low carbon raw materials.

Both Projects are located Near water supply (lake and river) that provide the opportunity to integrate a water source heat pump that could save tremendous amount of energy and related carbon emissions for space heating.

Discussion:

Both Panelized and modular Timber prefabricated system represent an opportunity to encourage the development of high-rise wooden buildings market in the construction industry. They minimize construction work time frame and optimize safety during assembly. wood as a flexible Biogenic material offer the possibility of off-site prefabrication with the advantage of using waste generated during manufacturing as biofuel. Although Panelized systems require 25 % less energy for production (A1-A3) than modules if we exclude the concrete values. On the other hand, Volumetric Modules have a certain range of flexibility when it comes to material transportation and installation in the building site which causes 20 % less related carbon emissions than a Panelized system.

Nevertheless, a good Insulation plays a consequent role in the mitigation of operational carbon emissions same as the architectural design and fenestration ratios that are important indicators for energy demands reduction. In prefabricated Volumetric modules, the insulation can be pre-defined to match any environmental certifications e.g., NS 3720 with specific heat transference rate. Since the modules are solid, there is little potential for airflow through the system. As a result, an extremely tight building envelope can be achieved.

The concrete was Another important structural decision that played a role in the fluctuation in the embodied carbon. the different type of infrastructure foundations had different impacts concerning the total embodied carbon accountability: a reinforced concrete basement dedicated for parking for Treet scored higher carbon emissions than a 60 m steel core piles in Mjøstårnet. Even though Steel has similar GHG related emissions as concrete during their production, steel is however easier to reuse and recycle than concrete since it has the ability to be melted and molded again. Using One click LCA Tool, results shows that Metals and Steel could be recovered up to 92 % while using only 8 % of virgin materials for each new cycle. The same is not applied to concrete where it requires 100 % virgin materials for their production (Appendix F, G)

In addition, stabilizing the structure is essential for an improved indoor environment for light structured high rise buildings.it becomes evident that the added concrete on the top levels of wood high rise building has an important structural and comfort benefits. but it also increases the Gwp emissions related to the concrete manufacturing process.

Through the different lifetime Phases study of the reference buildings service life, the results as shown in figure (35), demonstrate that the Modules used in Treet achieve less energy consumption and emit less carbon during the installation process compared to the panelized system, however a panelized CLT system offers more possibilities to store biogenic carbon. Another interesting point is that the benefits of panelized systems at their end-of-life stage D and carbon input are more substantial than volumetric modules as shown in figure (42). The lower use of Rock wool insulation which is a non-combustible material would explain the higher rate of benefits at the buildings end of life phase. but it is a double-edged sword as insulation also saves Co2 emissions during the building operation lifetime. But as demonstrated based on results shown in figure (40), the extra use of Rock wool in prefabricated Modules saves 306 463 Kg Co2 of carbon emitted from operational energy during the building lifetime compared to a 197 530 KgCo2 as benefits from the building end of life.

The circularity assessment in figure (43) indicate that Mjøstårnet materials obtained a higher score for circularity which means that a panelized system design is an effective way to reduce waste at the end the building life service. This could be explained by higher rate of disassembly of separated wall and floor panels that ultimately offers a wider range for reuse options than a standards volumetric room.

Concluding Remarks:

This study provided a detailed examination of greenhouse gases due to the impact of wooden high-rise buildings and the new construction applications with their associated carbon emissions relative to each life cycle stages, moreover two different timber prefabrication systems were investigated based on two reference buildings.

The results show Modular construction's total GWP global warming impact is 30% less than a panelized system figure (35) . By Considering the life cycle stages in the production stage modular system had significant impact with 31% higher carbon emissions than a panelized system (excluding the concrete use), The Panelized system has a higher mitigation impact on carbon emissions with a 40% reduction in GHG due to transport processes.

Modular systems also optimize the installation and time efficient as it doesn't require on site intensive machinery. Furthermore, the emissions from different construction prefabricated systems were studied based on several different scenarios and assumptions. In addition, Results shows that panelized systems present higher benefits rate at the end of life than volumetric prefabricated modules but also a higher ability to store CO_2 responsible for global warming. To conclude, the results depend on the holistic construction approach and methodologies, for instance structures, foundation and infrastructures influence the final outcome of this study. even though the popularity of tall buildings built with Timber is one the rise in the construction industry, the use of concrete is still omnipresent and part of the process as a structural requirement.

Prefabrication seems to also be an exploitable opportunity to achieve circularity within the building sector. with significant potential for reuse in Panelized system. a prefabricated system that ensures the creation of materials banks rather than a fixed asset found in linear production practices.

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Appendix A

Kodumaja building modules

Annex A2

Material and component specifications

Material / component	Specification (None specified dimensions shall be according to Annex 3 or specifications worked out separately for each delivery))	Reaction to fire class according to EN 13501-1
Structural components		
Timber members in walls, floors and roof	Untreated structural grade timber class C30, C24, C18 and C16 according to EN14081/EN 338, and according to specific calculations. Maximum moisture content 18%	D-s2, d0
I-beams	Masonit I-beams according to ETA-12/0018	D-s2, d0
Roof sheathing	18 mm particleboard type P5 according to EN 13986 or equivalent, formaldehyde class E1	D-s2, d0
Subfloor	22 mm particleboard type P6 according to EN 13986, formaldehyde class E1	D-s2, d0
Insulation materials		
Thermal insulation	Saint-Gobain Isover mineral wool insulation, CE-marked according to EN 13162 and certificate no. C248/03 issued by VTT(Technical Research Centre of Finland), with the following declared thermal conductivities: Type KL-A35: λ_D = 0,035 W/mK for insulation between studs and beams (density ≥ 16 kg/m^3). Type RKL: λ_D = 0,031 W/mK for additional insulation of external walls (density ≥ 60 kg/m^3) Type VKL: λ_D = 0,032 W/mK for underside of suspended ground floors (density ≥ 130 kg/m^3) or similar mineral wool insulation.	A1
Membranes and barriers		
Water vapour control layer	0,2 mm polyethylene Rani MOBar, according to certificate no.3189/90 issued by SP Technical Research Institute of Sweden and SINTEF Technical Approval no. 20201	F
Breather paper / Wind barrier	Tyvek 2460B in conformity with CE marking according to EN 13859-2 and SINTEF Technical Approval no. 2043	E
Claddings and linings		
External cladding	Min. 19 mm timber boards with quality equivalent to NS 3186	D-s2, d0
External wall sheathing	9 mm OSB boards type OSB/3 according to EN 13986, formaldehyde class E1	D-s2, d0
Internal linings	- 10 mm particleboard type P1 according to EN 13986, formaldehyde class E1 - OSB/3 ECO strand board panels according to EN 13986 and EN 300 and SINTEF Technical Approval no. 20155 - 12,5 mm gypsum board type A according to EN 520 - 12,5 mm and 15 mm gypsum board type DF according to EN 520	D-s2, d0 D-s2, d0/ D_{FL}-s1 A2-s1, d0 A2-s1, d0
Fasteners		
Mechanical fasteners and connectors	Mechanical fasteners and connectors for external use shall be protected by hot dip galvanization or have equivalent protection against corrosion	A1
Glue for floor sheathing	CascolLin Object 3459, Casco Proff Solid 3460	NPD
Sealant for façade for interior/exterior application	Silicon - Soudal Silirub AL	E
Wet rooms		
Concrete floor slab	Mira 6998 betomix Quick Weber Vetonit 5400 Kiilto 70 Topcem pronto Heikki Haru Oy/Mapei	A1
Membrane for wet zones	Mira 4400 Multicoat og 4410 Vapourstop according to ETA-09/0156	F
Floor screed	Mira X-plan floor screed according to EN 13813	A1
Internal lining	12,5 mm gypsum board type A or DF according to EN 520	A2-s1, d0
Water pipes	Roth Multipex® Rørsystem according to SINTEF Technical Approval no. 2556	NPD
Drain pipes	Uponor HTP PP drain pipes according to InstaCert 4010, 4032, 4048, 4064	NPD
Gullies	Vieser PP gullies according to EN 1253 and SINTEF certificate no. 0444 Vieser PP spacer for gullies according to EN 1253 and SINTEF certificate no. 0456	NPD

Appendix B

Simien yearly results:

Mjøstårnet:

Energibudsjett		
Energipost	Energibehov	Spesifikt energibehov
1a Romoppvarming	153360 kWh	30,0 kWh/m²
1b Ventilasjonsvarme (varmebatterier)	23668 kWh	4,6 kWh/m²
2 Varmtvann (tappevann)	152494 kWh	29,8 kWh/m²
3a Vifter	28032 kWh	5,5 kWh/m²
3b Pumper	102 kWh	0,0 kWh/m²
4 Belysning	58307 kWh	11,4 kWh/m²
5 Teknisk utstyr	89702 kWh	17,5 kWh/m²
6a Romkjøling	0 kWh	0,0 kWh/m²
6b Ventilasjonskjøling (kjølebatterier)	0 kWh	0,0 kWh/m²
Totalt netto energibehov, sum 1-6	505666 kWh	98,8 kWh/m²

Levert energi til bygningen (beregnet)		
Energivare	Levert energi	Spesifikk levert energi
1a Direkte el.	345039 kWh	67,4 kWh/m²
1b El. til varmepumpesystem	0 kWh	0,0 kWh/m²
1c El. til solfangersystem	1133 kWh	0,2 kWh/m²
2 Olje	0 kWh	0,0 kWh/m²
3 Gass	0 kWh	0,0 kWh/m²
4 Fjernvarme	155606 kWh	30,4 kWh/m²
5 Biobrensel	0 kWh	0,0 kWh/m²
6. Annen energikilde	0 kWh	0,0 kWh/m²
7. Solstrøm til egenbruk	-0 kWh	-0,0 kWh/m²
Totalt levert energi, sum 1-7	501778 kWh	98,0 kWh/m²
Solstrøm til eksport	-0 kWh	-0,0 kWh/m²
Netto levert energi	501778 kWh	98,0 kWh/m²

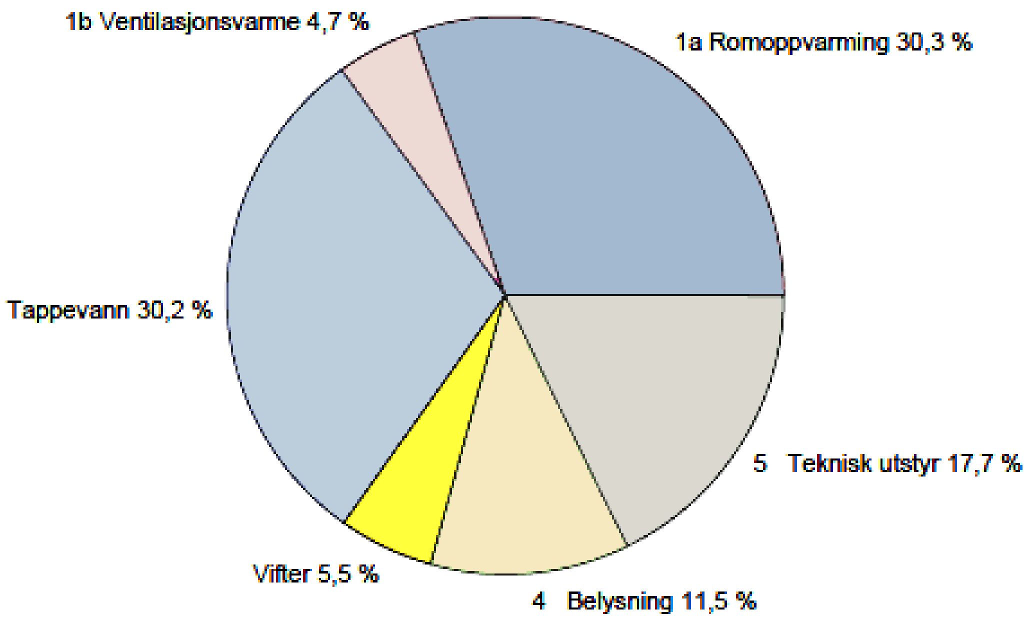
Dokumentasjon av sentrale inndata (1)		
Beskrivelse	Verdi	Dokumentasjon
Areal yttervegger [m²]:	6227	
Areal tak [m²]:	10	
Areal gulv [m²]:	640	
Areal vinduer og ytterdører [m²]:	1369	
Oppvarmet bruksareal (BRA) [m²]:	5120	
Oppvarmet luftvolum [m³]:	22528	
U-verdi yttervegger [W/m²K]	0,16	
U-verdi tak [W/m²K]	0,12	
U-verdi gulv [W/m²K]	0,08	
U-verdi vinduer og ytterdører [W/m²K]	0,80	
Areal vinduer og dører delt på bruksareal [%]	26,7	
Normalisert kuldebroverdi [W/m²K]:	0,03	
Normalisert varmekapasitet [Wh/m²K]	83	
Lekkasjetall (n50) [1/h]:	0,60	
Temperaturvirkningsgr. varmegjenvinner [%]:	80	

Dekning av energibudsjett fordelt på energikilder						
Energikilder	Romoppv.	Varmebatterier	Varmtvann	Kjølebatterier	Romkjøling	El. spesifikt
El.	22,5 kWh/m²	4,6 kWh/m²	0,0 kWh/m²	0,0 kWh/m²	0,0 kWh/m²	34,4 kWh/m²
Olje	0,0 kWh/m²	0,0 kWh/m²	0,0 kWh/m²	0,0 kWh/m²	0,0 kWh/m²	0,0 kWh/m²
Gass	0,0 kWh/m²	0,0 kWh/m²	0,0 kWh/m²	0,0 kWh/m²	0,0 kWh/m²	0,0 kWh/m²
Fjernvarme	0,0 kWh/m²	0,0 kWh/m²	29,8 kWh/m²	0,0 kWh/m²	0,0 kWh/m²	0,0 kWh/m²
Biobrensel	0,0 kWh/m²	0,0 kWh/m²	0,0 kWh/m²	0,0 kWh/m²	0,0 kWh/m²	0,0 kWh/m²
Varmepumpe	0,0 kWh/m²	0,0 kWh/m²	0,0 kWh/m²	0,0 kWh/m²	0,0 kWh/m²	0,0 kWh/m²
Sol	7,5 kWh/m²	0,0 kWh/m²	0,0 kWh/m²	0,0 kWh/m²	0,0 kWh/m²	0,0 kWh/m²
Annen	0,0 kWh/m²	0,0 kWh/m²	0,0 kWh/m²	0,0 kWh/m²	0,0 kWh/m²	0,0 kWh/m²
Sum	30,0 kWh/m²	4,6 kWh/m²	29,8 kWh/m²	0,0 kWh/m²	0,0 kWh/m²	34,4 kWh/m²

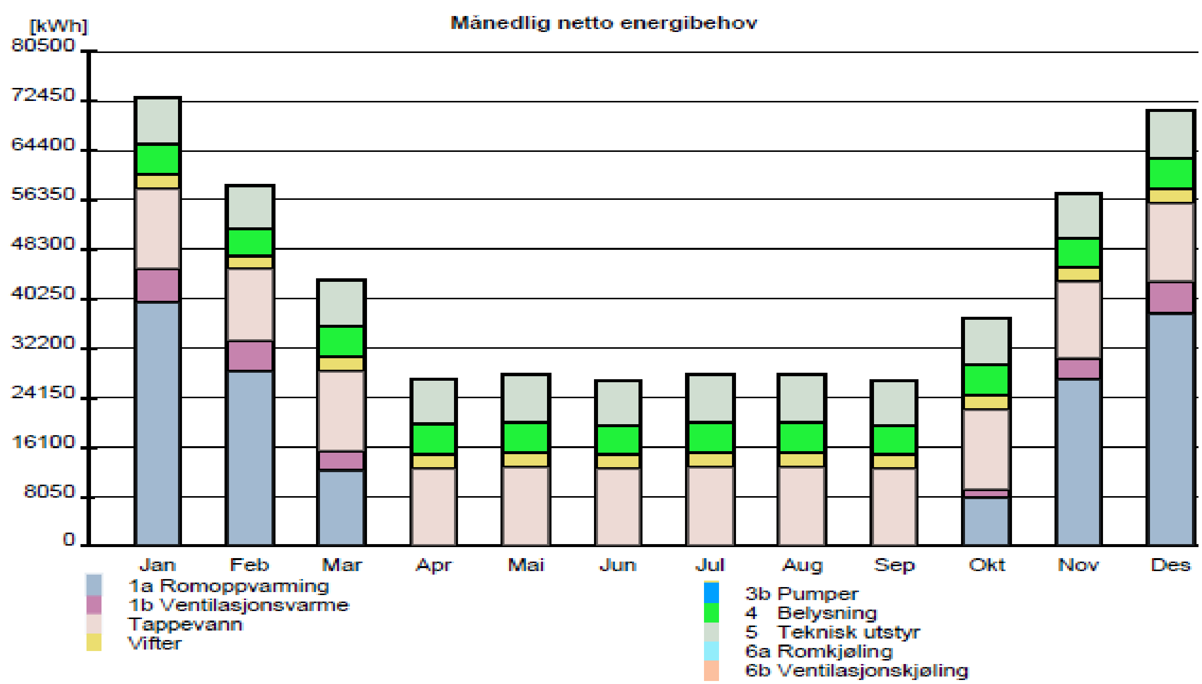
Årlige utslipp av CO2		
Energivare	Utslipp	Spesifikt utslipp
1a Direkte el.	44855 kg	8,8 kg/m²
1b El. til varmepumpesystem	0 kg	0,0 kg/m²
1c El. til solfangersystem	147 kg	0,0 kg/m²
2 Olje	0 kg	0,0 kg/m²
3 Gass	0 kg	0,0 kg/m²
4 Fjernvarme	11670 kg	2,3 kg/m²
5 Biobrensel	0 kg	0,0 kg/m²
6. Annen energikilde	0 kg	0,0 kg/m²
7. Solstrøm til egenbruk	-0 kg	-0,0 kg/m²
Totalt utslipp, sum 1-7	56673 kg	11,1 kg/m²
Solstrøm til eksport	-0 kg	-0,0 kg/m²
Netto CO2-utslipp	56673 kg	11,1 kg/m²

Kostnad kjøpt energi		
Energivare	Energikostnad	Spesifikk energikostnad
1a Direkte el.	276031 kr	53,9 kr/m²
1b El. til varmepumpesystem	0 kr	0,0 kr/m²
1c El. til solfangersystem	906 kr	0,2 kr/m²
2 Olje	0 kr	0,0 kr/m²
3 Gass	0 kr	0,0 kr/m²
4 Fjernvarme	116705 kr	22,8 kr/m²
5 Biobrensel	0 kr	0,0 kr/m²
6. Annen energikilde	0 kr	0,0 kr/m²
7. Solstrøm til egenbruk	-0 kr	-0,0 kr/m²
Årlige energikostnader, sum 1-7	393642 kr	76,9 kr/m²
Solstrøm til eksport	0 kr	0,0 kr/m²
Netto energikostnad	393642 kr	76,9 kr/m²

Årlig energibudsjett



1a Romoppvarming	153360 kWh
1b Ventilasjonsvarme (varmebatterier)	23668 kWh
2 Varmtvann (tappevann)	152494 kWh
3a Vifter	28032 kWh
3b Pumper	102 kWh
4 Belysning	58307 kWh
5 Teknisk utstyr	89702 kWh
6a Romkjøling	0 kWh
6b Ventilasjonskjøling (kjølebatterier)	0 kWh
Totalt netto energibehov, sum 1-6	505666 kWh



Appendix C

Simien yearly results: Treet:

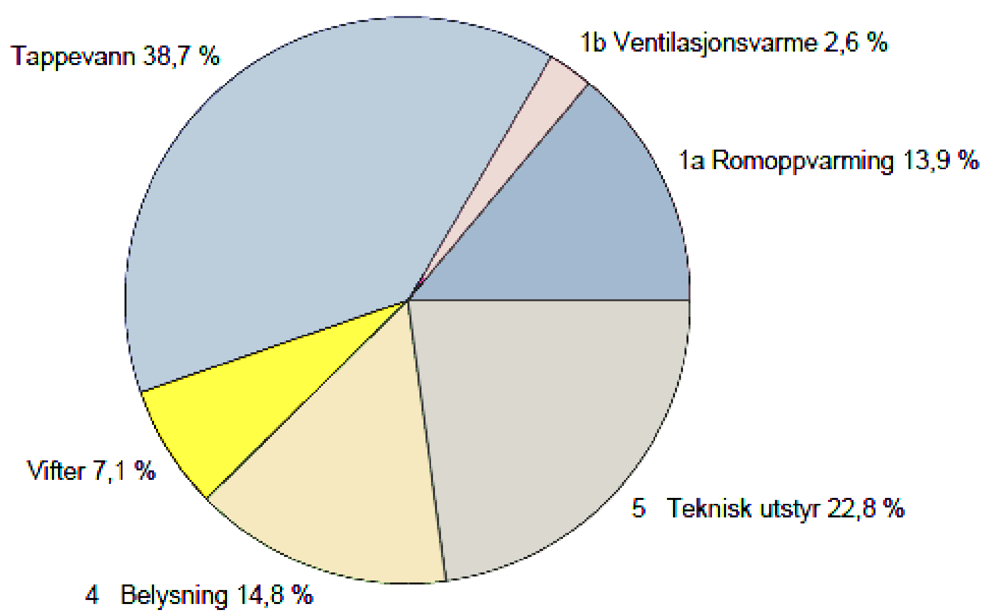
Energibudsjett		
Energipost	Energibehov	Spesifikt energibehov
1a Romoppvarming	48158 kWh	10,7 kWh/m²
1b Ventilasjonsvarme (varmebatterier)	9069 kWh	2,0 kWh/m²
2 Varmtvann (tappevann)	133997 kWh	29,8 kWh/m²
3a Vifter	24645 kWh	5,5 kWh/m²
3b Pumper	42 kWh	0,0 kWh/m²
4 Belysning	51235 kWh	11,4 kWh/m²
5 Teknisk utstyr	78858 kWh	17,5 kWh/m²
6a Romkjøling	0 kWh	0,0 kWh/m²
6b Ventilasjonskjøling (kjølebatterier)	0 kWh	0,0 kWh/m²
Totalt netto energibehov, sum 1-6	346003 kWh	76,9 kWh/m²

Levert energi til bygningen (beregnet)		
Energivare	Levert energi	Spesifikk levert energi
1a Direkte el.	229489 kWh	51,0 kWh/m²
1b El. til varmepumpesystem	0 kWh	0,0 kWh/m²
1c El. til solfangersystem	0 kWh	0,0 kWh/m²
2 Olje	0 kWh	0,0 kWh/m²
3 Gass	0 kWh	0,0 kWh/m²
4 Fjernvarme	130626 kWh	29,0 kWh/m²
5 Biobrensel	0 kWh	0,0 kWh/m²
6. Annen energikilde	0 kWh	0,0 kWh/m²
7. Solstrøm til egenbruk	-0 kWh	-0,0 kWh/m²
Totalt levert energi, sum 1-7	360115 kWh	80,0 kWh/m²
Solstrøm til eksport	-0 kWh	-0,0 kWh/m²
Netto levert energi	360115 kWh	80,0 kWh/m²

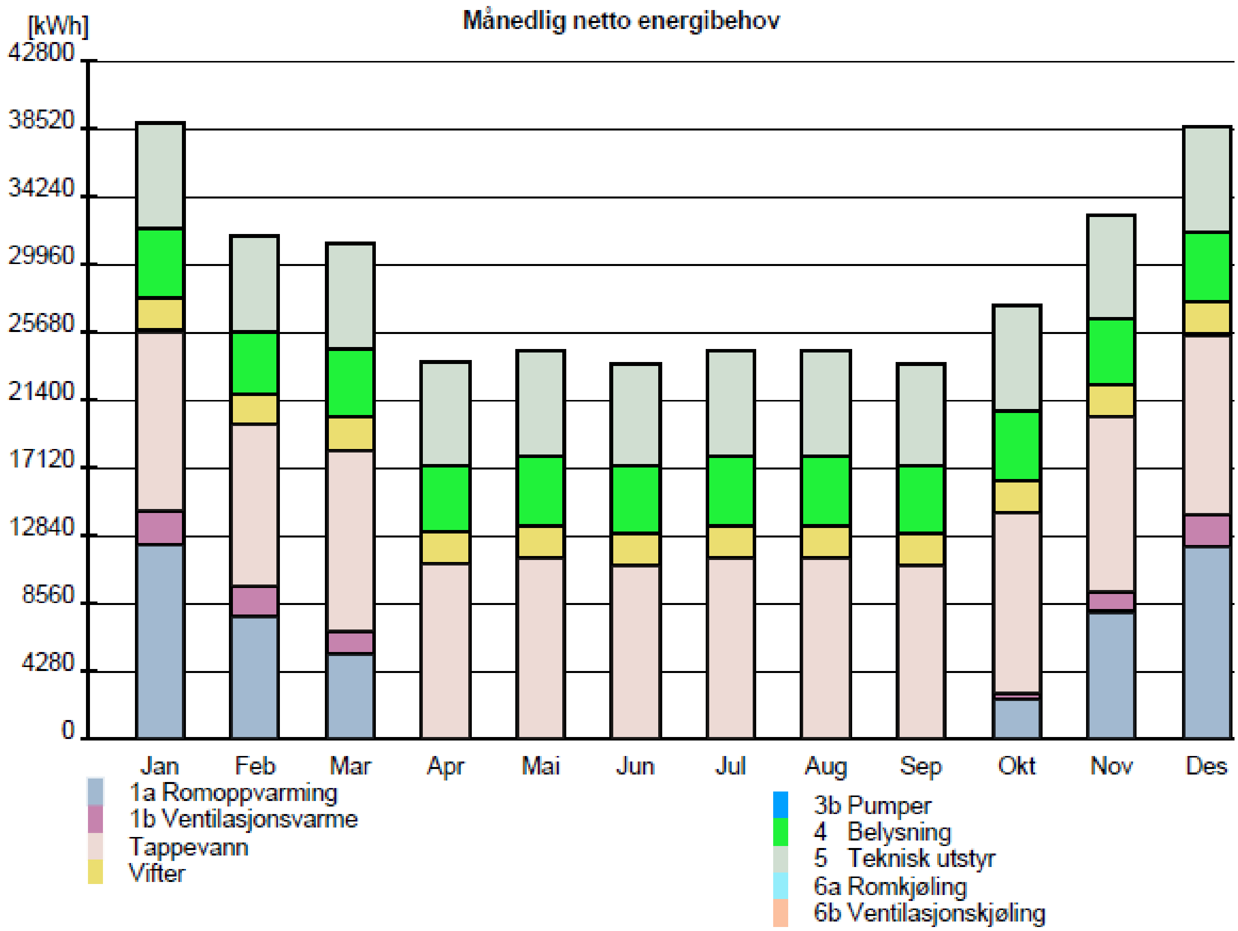
Årlige utslipp av CO2		
Energivare	Utslipp	Spesifikt utslipp
1a Direkte el.	29834 kg	6,6 kg/m²
1b El. til varmepumpesystem	0 kg	0,0 kg/m²
1c El. til solfangersystem	0 kg	0,0 kg/m²
2 Olje	0 kg	0,0 kg/m²
3 Gass	0 kg	0,0 kg/m²
4 Fjernvarme	9797 kg	2,2 kg/m²
5 Biobrensel	0 kg	0,0 kg/m²
6. Annen energikilde	0 kg	0,0 kg/m²
7. Solstrøm til egenbruk	-0 kg	-0,0 kg/m²
Totalt utslipp, sum 1-7	39630 kg	8,8 kg/m²
Solstrøm til eksport	-0 kg	-0,0 kg/m²
Netto CO2-utslipp	39630 kg	8,8 kg/m²

Kostnad kjøpt energi		
Energivare	Energikostnad	Spesifikk energikostnad
1a Direkte el.	183591 kr	40,8 kr/m²
1b El. til varmepumpesystem	0 kr	0,0 kr/m²
1c El. til solfangersystem	0 kr	0,0 kr/m²
2 Olje	0 kr	0,0 kr/m²
3 Gass	0 kr	0,0 kr/m²
4 Fjernvarme	97970 kr	21,8 kr/m²
5 Biobrensel	0 kr	0,0 kr/m²
6. Annen energikilde	0 kr	0,0 kr/m²
7. Solstrøm til egenbruk	-0 kr	-0,0 kr/m²
Årlige energikostnader, sum 1-7	281560 kr	62,6 kr/m²
Solstrøm til eksport	0 kr	0,0 kr/m²
Netto energikostnad	281560 kr	62,6 kr/m²

Årlig energibudsjett



1a Romoppvarming	48158 kWh
1b Ventilasjonsvarme (varmebatterier)	9069 kWh
2 Varmtvann (tappevann)	133997 kWh
3a Vifter	24645 kWh
3b Pumper	42 kWh
4 Belysning	51235 kWh
5 Teknisk utstyr	78858 kWh
6a Romkjøling	0 kWh
6b Ventilasjonskjøling (kjølebatterier)	0 kWh
Totalt netto energibehov, sum 1-6	346003 kWh



Appendix D

Treet Material list:

The Volumes were extracted using Revit material takeoff plugin, for most the structure, floors, and walls we used the masses and volumes but sometimes the epds chosen only had m^2 Area units, o therefore we used the total areas for internal walls, if the internal wall had two layers of gypsum, the area is multiplied x2. Example in Mjøstårnet: 6434 *2 = 12868 m^2

For the modules used in Treet, the sum of the modules was multiplied by the total numbers of modules used in apartments.

Walls

<Wall Material Takeoff >

A	B	C
Material: Name	Material: Volume	Material: Area
Gypsum Wall Boar	0.19 m^3	15 m^2
Gypsum Wall Boar	0.26 m^3	20 m^2
Gypsum Wall Boar	0.15 m^3	12 m^2
Gypsum Wall Boar	0.29 m^3	22 m^2
Gypsum Wall Boar	0.29 m^3	22 m^2
Gypsum Wall Boar	0.84 m^3	65 m^2
Gypsum Wall Boar	1.37 m^3	105 m^2
Gypsum Wall Boar	0.25 m^3	19 m^2
Gypsum Wall Boar	0.25 m^3	19 m^2
Gypsum Wall Boar	0.29 m^3	23 m^2
Gypsum Wall Boar	0.16 m^3	12 m^2
	4.35 m^3	
Mineral wool	3.62 m^3	44 m^2
Mineral wool	4.90 m^3	60 m^2
Mineral wool	2.92 m^3	36 m^2
Mineral wool	0.78 m^3	11 m^2
Mineral wool	0.78 m^3	11 m^2
Mineral wool	3.08 m^3	32 m^2
Mineral wool	5.01 m^3	53 m^2
Mineral wool	0.66 m^3	9 m^2
Mineral wool	0.67 m^3	10 m^2
Mineral wool	0.79 m^3	11 m^2
Mineral wool	0.43 m^3	6 m^2
	23.64 m^3	
OSB Oriented stran	0.13 m^3	15 m^2
OSB Oriented stran	0.18 m^3	20 m^2
OSB Oriented stran	0.11 m^3	12 m^2
OSB Oriented stran	0.29 m^3	16 m^2
OSB Oriented stran	0.47 m^3	26 m^2
	1.19 m^3	
Timber cladding	0.30 m^3	15 m^2
Timber cladding	0.40 m^3	20 m^2
Timber cladding	0.24 m^3	12 m^2
	0.93 m^3	

<Wall Material Takeoff >

A	B	C
Material: Name	Material: Area	Material: Volume
Gypsum Wall Boar	10 m^2	0.13 m^3
Gypsum Wall Boar	99 m^2	1.29 m^3
Gypsum Wall Boar	31 m^2	0.40 m^3
Gypsum Wall Boar	12 m^2	0.15 m^3
Gypsum Wall Boar	10 m^2	0.13 m^3
Gypsum Wall Boar	19 m^2	0.25 m^3
Gypsum Wall Boar	4 m^2	0.05 m^3
Gypsum Wall Boar	8 m^2	0.10 m^3
Gypsum Wall Boar	9 m^2	0.11 m^3
Gypsum Wall Boar	12 m^2	0.15 m^3
Gypsum Wall Boar	8 m^2	0.11 m^3
		2.87 m^3
Mineral wool	31 m^2	2.53 m^3
Mineral wool	50 m^2	4.71 m^3
Mineral wool	15 m^2	1.07 m^3
Mineral wool	6 m^2	0.41 m^3
Mineral wool	5 m^2	0.34 m^3
Mineral wool	10 m^2	0.67 m^3
Mineral wool	2 m^2	0.13 m^3
Mineral wool	4 m^2	0.27 m^3
Mineral wool	4 m^2	0.30 m^3
Mineral wool	6 m^2	0.41 m^3
Mineral wool	4 m^2	0.29 m^3
		11.14 m^3
OSB Oriented stran	10 m^2	0.09 m^3
OSB Oriented stran	25 m^2	0.45 m^3
		0.54 m^3
Timber cladding	10 m^2	0.21 m^3
		0.21 m^3

Figure 44 2 Bedrooms modules

Treet Material list:

Floors and Ceilings:

<Ceiling Material Takeoff>

A	B	C
Material: Name	Material: Area	Material: Volume
Gypsum Wall Boar	75 m²	1.96 m³
	75 m²	1.96 m³
Mineral wool	150 m²	21.81 m³
	150 m²	21.81 m³
Moisture resistant	75 m²	1.35 m³
	75 m²	1.35 m³
OSB Oriented stran	75 m²	0.60 m³
	75 m²	0.60 m³

<Floor Material Takeoff>

A	B	C
Material: Name	Material: Area	Material: Volume
Air	75 m²	6.77 m³
	75 m²	6.77 m³
Ceiling battens	75 m²	1.58 m³
	75 m²	1.58 m³
Gypsum Wall Boar	75 m²	1.96 m³
	75 m²	1.96 m³
Mineral wool	150 m²	31.59 m³
	150 m²	31.59 m³
Particle board 22 m	150 m²	2.56 m³
	150 m²	2.56 m³

<Ceiling Material Takeoff>

A	B	C
Material: Name	Material: Area	Material: Volume
Gypsum Wall Boar	47 m²	1.23 m³
	47 m²	1.23 m³
Mineral wool	94 m²	13.69 m³
	94 m²	13.69 m³
Moisture resistant	47 m²	0.85 m³
	47 m²	0.85 m³
OSB Oriented stran	47 m²	0.38 m³
	47 m²	0.38 m³

<Floor Material Takeoff>

A	B	C
Material: Name	Material: Area	Material: Volume
Air	47 m²	4.25 m³
	47 m²	4.25 m³
Ceiling battens	47 m²	0.99 m³
	47 m²	0.99 m³
Gypsum Wall Boar	47 m²	1.23 m³
	47 m²	1.23 m³
Mineral wool	94 m²	19.82 m³
	94 m²	19.82 m³
Particle board 22 m	94 m²	1.60 m³
	94 m²	1.60 m³

Appendix E

Mjøstårnet Material list:

<Multi-Category Material Takeoff>		
A	B	C
Material: Name	Material: Area	Material: Volume
CLT STAIRS AND	159 m²	31.78 m³
	2094 m²	418.54 m³
External walls	528 m²	211.33 m³
	3323 m²	1314.22 m³
Timber cassettes	527 m²	157.99 m³
Timber cassettes	527 m²	157.99 m³
Timber cassettes	527 m²	157.99 m³
Timber cassettes	527 m²	157.99 m³
	2106 m²	631.95 m³
Glulam massiv tre	71 m²	8.37 m³
Glulam massiv tre	71 m²	8.37 m³
Glulam massiv tre	71 m²	8.37 m³
Glulam massiv tre	71 m²	8.37 m³
Glulam massiv tre	71 m²	8.37 m³
Glulam massiv tre	71 m²	8.37 m³
	9705 m²	1320.91 m³
Prefabricated beton	676 m²	202.78 m³
Prefabricated beton	676 m²	202.78 m³
Prefabricated beton	676 m²	202.78 m³
Prefabricated beton	676 m²	202.78 m³
Prefabricated beton	676 m²	202.78 m³
Prefabricated beton	676 m²	202.78 m³
Prefabricated beton	530 m²	159.04 m³
	4586 m²	1375.72 m³
Glass	3 m²	0.02 m³
Glass	3 m²	0.02 m³
Glass	5 m²	0.03 m³
Glass	9 m²	0.05 m³
Glass	9 m²	0.05 m³
	1681 m²	9.95 m³
Timber Walls internal	12 m²	1.83 m³
Timber Walls internal	15 m²	2.32 m³
Timber Walls internal	4 m²	0.54 m³
Timber Walls internal	16 m²	2.42 m³
Timber Walls internal	9 m²	1.33 m³
Timber Walls internal	14 m²	2.17 m³
	6463 m²	969.42 m³

Appendix F

Once click LCA results: Life cycle assessment summary

	Project name	Design name	Indicator name					
	Mjøstårnet - Brumunddal	2 - Mjøstårnet	Life-cycle assessment, EN-15978					
Section	**Result category**	**Global warming kg CO₂e**	**Acidification kg SO₂e**	**Eutrophication kg PO₄e**	**Ozone depletion potential kg CFC 11e**	**Formation of ozone of lower atmosphere kg Ethane**	**Total use of primary energy ex. raw materials MJ**	**Biogenic carbon storage kg CO₂e bio**
A1-A3	Construction Materials	1.04E+06	3.16E+03	1.23E+03	5.30E-02	3.37E+03	2.53E+07	1.67E+06
A4	Transportation to site	2.27E+04	8.85E+01	1.92E+01	4.30E-03	1.76E+00	5.79E+05	
A4	Transportation to site	2.27E+04	8.85E+01	1.92E+01	4.30E-03	1.76E+00	5.79E+05	
A5	Construction/installation process	1.74E+05	2.67E+02	5.44E+01	3.00E-02	2.69E+01	3.13E+06	
B1-B5	Maintenance and material replacement	5.88E+04	1.91E+02	3.04E+01	4.80E-03	9.82E+00	1.11E+06	
B6	Energy use	8.26E+05	5.54E+03	1.58E+03	7.40E-02	2.07E+02	1.41E+08	
B7	Water use	1.86E+05	1.30E+03	3.73E+03	1.90E-02	5.46E+01	3.36E+06	
C1-C4	End of life	1.41E+05	3.19E+02	1.07E+02	1.50E-03	2.43E+01	8.75E+05	
C1-C4	Deconstruction	1.41E+05	3.19E+02	1.07E+02	1.50E-03	2.43E+01	8.75E+05	
D	External impacts (not included in totals)	-8.85E+05	-1.03E+03	-1.12E+02	1.50E-03	-5.94E+01	-1.49E+07	
A5-benefit	Construction site - material wastage - benefit	-1.10E+05	-1.10E+02	-1.59E+01	1.10E-04	-1.08E+01	-1.94E+06	
D	Installed Materials - benefit	-7.75E+05	-9.17E+02	-9.59E+01	1.40E-03	-4.85E+01	-1.29E+07	

Appendix G

Once click LCA results: Life cycle assessment summary

	Project name	Design name	Indicator name					
	Treet-Bergen Apartment buildings	7 - Treet-Bergen	LCA EN-15978					
Section	**Result category**	**Global warming kg CO^{2}/ e**	**Acidification kg SO^{2}/ e**	**Eutrophication kg PO₄e**	**Ozone depletion potential kg CFC11e**	**Formation of ozone of lower atmosphere kg Ethane**	**Total use of primary energy ex. raw materials MJ**	**Biogenic carbon storage kg CO₂e bio**
A1-A3	Construction Materials	8.39E+05	4.81E+03	6.28E+02	2.25E+00	5.64E+02	1.62E+07	7.30E+05
A4	Transportation to site	3.88E+04	4.31E+02	6.59E+01	7.30E-03	1.00E+01	9.90E+05	0.00E+00
A4	Transportation to site	1.56E+04	4.68E+01	1.00E+01	2.90E-03	1.63E+00	3.39E+05	
A4-leg2	Transportation to site - leg 2	2.32E+04	3.84E+02	5.58E+01	4.50E-03	8.37E+00	6.52E+05	0.00E+00
A5	Construction/installation process	1.18E+05	1.84E+02	3.74E+01	2.00E-02	1.83E+01	2.30E+06	
B1-B5	Maintenance and material replacement	2.43E+04	8.11E+01	1.60E+01	2.00E-03	7.95E+00	5.74E+05	
B6	Energy use	5.60E+05	1.81E+03	3.49E+02	6.00E-02	8.80E+01	7.65E+07	
B7	Water use	1.39E+05	7.52E+02	3.80E+02	1.50E-02	3.38E+01	2.93E+06	
C1-C4	End of life	7.63E+04	1.63E+02	5.19E+01	9.00E-04	1.52E+01	4.48E+05	
C1-C4	Deconstruction	7.63E+04	1.63E+02	5.19E+01	9.00E-04	1.52E+01	4.48E+05	
D	External impacts (not included in totals)	-6.42E+05	-1.31E+03	-1.53E+02	-1.20E-03	-9.59E+01	-1.08E+07	
A5-benefit	Construction site - material wastage - benefit	-6.42E+04	-9.10E+01	-1.23E+01	-3.30E-05	-8.09E+00	-1.12E+06	
D	Installed Materials - benefit	-5.78E+05	-1.22E+03	-1.41E+02	-1.10E-03	-8.78E+01	-9.69E+06	

Main > Mjøstårnet - Brummundal > Mjøstårnet > Life-cycle assessment, EN-15978 > Input data : Building materials

Mjøstårnet

Building materials | Energy consumption, annual | Water consumption, annual | Construction site operations | Building area | Calculation period

Material	Country	Data source	Type	Upstream	CO2e	Unit	Properties
Filter:	Filter:	Filter:	Filter:	Filter:	Filter:	Filter:	Filter:

Sa

Fill in the material consumptions by material type. You may fill in all materials lumped together, or on separate rows for example by type of structure. Unless instructed otherwise, use gross amounts (incl. losses). Materials can be added in any section. Material selection help.

Completeness (-) and plausibility checker (grade: A)

LCA Checker overall grade: A. Grade is based on data you have provided. ×

LCA Checker overall grade: A

LCA Checker checks the embodied impacts plausibility. These results reflect plausibility for 6200.0 m^2 project of type new construction, whole building with frame type timber frame with scope consisting of foundations and substructure, structure and enclosure, finishings and other materials. To edit these parameters open LCA Parameters query. The result is intended as indicative of the plausibility; and exceptions may occur.

No.	Check description	Project value	Threshold value	Typical value	Unit	Type	Validated ?
1	**Roofing bitumen mass credible:** Has no materials	0.0	0.5 - 4		kg/m^2	✗	
2	**Replacements share credible:** Project has unusual amount of replacements	5.634	10 - 100		%	✗	
3	**Gypsum board mass credible:** Value seems unusual but is within allowable deviation range	41.483	3 - 40		kg/m^2	⚠	
Validated checks							
4	**Structure mass credible**	914.098	greater than 150		kg/m^2	✓	
5	**Finishes mass credible**	22.178	greater than 10		kg/m^2	✓	
6	**Embodied carbon credible**	243.553	150 - 1000		kg CO_2e/m^2	✓	
7	**Project mass credible**	1092.56	300 - 3500		kg/m^2	✓	
8	**Ready mix and reinforcement ratio**	3.064	1 - 7		%	✓	
9	**Too few materials to be credible**	33	greater than 20		nr.	✓	
10	**Too dominant single material**	44.71	less than 50		%	✓	
11	**Project mass credible (timber frame)**	936.276	200 - 1000		kg/m^2	✓	
12	**Insulation mass credible**	13.628	1 - 21		kg/m^2	✓	
13	**Gypsum board and plaster mass credible (no cement)**	44.929	0.0 - 80		kg/m^2	✓	
14	**Glass and openings mass credible**	12.668	2 - 25		kg/m^2	✓	
15	**Vertical materials mass**	238.767	50 - 700		kg/m^2	✓	
16	**Horizontal materials mass**	675.33	100 - 1300		kg/m^2	✓	
17	**Embodied carbon credible (timber frame)**	200.73	80 - 350		kg CO_2e/m^2	✓	
18	**Wood mass credible (wood frame)**	213.19	35 - 220		kg/m^2	✓	
19	**Mortar mass credible**	3.446	0.4 - 50		kg/m^2	✓	
20	**Glass mass credible**	12.668	1 - 13		kg/m^2	✓	
21	**Brick mass credible**	0.0	0.0 - 100		kg/m^2	✓	

Help

1. Foundations and substructure

108 Tons CO_2e - 4 %

Materials in the foundations will never be replaced, no matter assessment period length. For BREEAM UK Mat 1 IMPACT equivalent provide the data for site excavation fuel use here, choose resource Excavation works.

Foundation, sub-surface, basement and retaining walls Create a group · Move materials · Add to compare

Start typing or click the arro

Resource	Quantity		CO_2e	Comment	Transport, kilometers	Transport, leg 2, kilometers	Service li
Concrete ground slab asse	640	m^2	84t - 3%		Data by constituent	Data by constituent	Data by c
Steel pipe pile filled with	60	m	24t - 0,99%		Data by constituent	Data by constituent	Data by c

2. Vertical structures and facade

379 Tons CO_2e - 15 %

External walls and facade Create a group · Move materials · Add to compare

Start typing or click the arro

Resource	Quantity				CO_2e	Comment	Transport, kilometers		Transport, leg 2, kilometers
External wood cladding, from pine,	4905	m2	21	mm	40t - 2%		130	Trailer combination, 40	Not defined
Rock wool insulation, L = 0.037 W/m	9810	m2	37	mm	12t - 0,5%		70	Trailer combination, 40	Not defined
Solid wood panel for Internal us	4905	m2	15	mm	21t - 0,8%		130	Trailer combination, 40	Not defined
Plastic vapour control layer, 0.	4905	m2	0.2	mm	2,1t - 0,1%		110	Trailer combination, 40	Not defined
Fibre cement board, 1300 kg/m3,	4905	m2	9	mm	5,5t - 0,2%		70	Trailer combination, 40	Not defined
Oriented strand board (OSB), generi	4905	m2	15	mm	3,2t - 0,1%		130	Trailer combination, 40	Not defined

Columns and load-bearing vertical structures Create a group · Move materials · Add to compare

Start typing or click the arro

Resource	Quantity		CO_2e	Comment	Transport, kilometers		Transport, leg 2, kilometers
Glued laminated timber (Glulam), 42	1320.9	m3	168t - 7%		130	Trailer combination, 40	Not defined

Internal walls and non-bearing structures Create a group · Move materials · Add to compare

Start typing or click the arro

Resource	Quantity				CO_2e	Comment	Transport, kilometers		Transport, leg 2, kilometer
Cross laminated timber (CLT), 470 k	427.81	m3			30t - 1%		130	Trailer combination, 40	Not defined
Rock wool insulation, unfaced, L =	12926	m2	37	mm	16t - 0,7%		70	Trailer combination, 40	Not defined
Gypsum board, moistureproof, 12.5 m	12926	m2	12,5	mm	73t - 3%		70	Trailer combination, 40	Not defined
Oriented strand board (OSB), generi	12926	m2	15	mm	8,4t - 0,3%		130	Trailer combination, 40	Not defined

3. Horizontal structures: beams, floors and roofs

591 Tons CO_2e - 24 %

Floor slabs, ceilings, roofing decks, beams and roof Create a group · Move materials · Add to compare

Start typing or click the arro

Resource	Quantity				CO_2e	Comment	Transport, kilometers		Transport, leg 2, kilometer
CLT slab floor assembly,	481	m^2			20t - 0,8%		Data by constituent		Data by constituent
Timber (LVL) flooring panel	631,95	m^2			29t - 1%		Data by constituent		Data by constituent
Hollow core concrete slab + rein		m3					70	Trailer combination, 40	Not defined
Rock wool insulation, L = 0.038 W/m	5120	m2	38	mm	29t - 1%		70	Trailer combination, 40	Not defined
Gypsum board, moistureproof, 12.5 m	5120	m2	12,5	mm	29t - 1%		70	Trailer combination, 40	Not defined
Suspended balcony floor concrete	1375	m3			485t - 20%		70	Trailer combination, 40	Not defined

Other structures and materials Create a group · Move materials · Add to compare

Start typing or click the arro

Resource	Quantity		CO_2e	Comment	Transport, kilometers		Transport, leg 2, kilometers
Structural steel profiles, generic,	6,30	m3	32t - 1%		110	Trailer combination, 40	Not defined

Windows and doors Create a group · Move materials · Add to compare

Start typing or click the arro

Resource	Quantity		CO_2e	Comment	Transport, kilometers		Transport, leg 2, kilometers
Aluminium frame glass façade system	1600	m2	157t - 6%		60	Trailer combination, 40	Not defined

Finishes and coverings Create a group · Move materials · Add to compare

+ Click to input data

Main > Treet-Bergen Apartment buildings > Treet-Bergen > Life-cycle assessment, EN-15978 > Input data : Building materials

Treet-Bergen

Building materials | Energy consumption, annual | Water consumption, annual | Construction site operations | Building area | Calculation period

Material	Country	Data source	Type	Upstream	CO2e	Unit	Properties	
Filter:	Filter:	Filter:	Filter:	Filter:	Filter:	Filter:	Filter:	Save

Fill in the material consumptions by material type. You may fill in all materials lumped together, or on separate rows for example by type of structure. Unless instructed otherwise, use gross amounts (incl. losses). Materials can be added in any section. Material selection help.

Completeness (-) and plausibility checker (grade: B)

LCA Checker overall grade: B. Grade is based on data you have provided.

LCA Checker overall grade: B

LCA Checker checks the embodied impacts plausibility. These results reflect plausibility for 5830.0 m^2 project of type new construction, whole building with frame type other/mixed frame with scope consisting of foundations and substructure, structure and enclosure, finishings and other materials, external areas, services. To edit these parameters open LCA Parameters query. The result is intended as indicative of the plausibility; and exceptions may occur.

No.	Check description	Project value	Threshold value	Typical value	Unit	Type	Validated ?
1	**Insulation mass credible:** Insulation mass is unusual	53.367	1 - 21		kg/m^2	✗	
2	**Gypsum board mass credible:** Gypsum board mass is unusual	92.555	3 - 40		kg/m^2	✗	
3	**Foundation mass credible:** Foundation has unusually low amount of materials	1.565	greater than 100		kg/m^2	✗	
4	**Too few materials to be credible:** Project has unusually little data	18	greater than 20		nr.	✗	
5	**Embodied carbon credible:** Value seems unusual but is within allowable deviation range	128.487	150 - 1000		kg CO_2e/m^2	⚠	
Validated checks							
6	**Structure mass credible**	280.792	greater than 150		kg/m^2	✓	
7	**Project mass credible**	312.288	300 - 3500		kg/m^2	✓	
8	**Too dominant single material**	37.669	less than 50		%	✓	
9	**Project mass credible (mixed frame)**	286.864	200 - 1900		kg/m^2	✓	
10	**Glass and openings mass credible**	6.072	2 - 25		kg/m^2	✓	
11	**Vertical materials mass**	130.447	50 - 700		kg/m^2	✓	
12	**Horizontal materials mass**	150.345	100 - 1300		kg/m^2	✓	
13	**Embodied carbon credible (mixed frame)**	114.855	100 - 800		kg CO_2e/m^2	✓	
14	**Glass mass credible**	6.072	1 - 13		kg/m^2	✓	
15	**Brick mass credible**	0.0	0.0 - 100		kg/m^2	✓	
16	**Finishes mass credible**	10	greater than 10		kg/m^2	⚠	
17	**Services mass credible**	10	greater than 2		kg/m^2	⚠	
18	**External areas mass credible**	10	greater than 10		kg/m^2	⚠	
19	**Replacements share credible**	10	10 - 100		%	⚠	
20	**Gypsum board and plaster mass credible (no cement)**	9	0.0 - 80		kg/m^2	⚠	
21	**Mortar mass credible**	10	0.4 - 50		kg/m^2	⚠	

Help

1. Foundations and substructure 2 Tons CO_2e

Materials in the foundations will never be replaced, no matter assessment period length. For BREEAM UK Mat 1 IMPACT equivalent provide the data for site excavation fuel use here, choose resource Excavation works.

Foundation, sub-surface, basement and retaining walls Create a group Move materials Add to compare

Start typing or click the arro

Resource	Quantity		CO_2e	Comment	Transport, kilometers		Transport, leg 2, kilometers	
Steel pipe pile fillled with	5	m	2t - 0,1%		Data by constituent		Data by constituent	
Ready-mix concrete, normal strength		m3			70	Concrete mixer truck		Not defined
Ready mix concrete for infrastructu	0	m3			50.0	Concrete mixer truck		Not defined

2. Vertical structures and facade 294 Tons CO_2e - 18 %

External walls and facade Create a group Move materials Add to compare

Start typing or click the arro

Resource	Quantity		CO_2e	Comment	Transport, kilometers		Transport, leg 2, kilometers	
Insulation, Rockwool/mineral woo	1325,46	m3	38t - 2%	Modules - walls	200	Trailer combination, 40	2000	Ship, Big bulk
Gypsum plaster board, regular, gene	256.2	m3	72t - 5%	Modules - walls	70	Trailer combination, 40	2000	Ship, Big bulk
Oriented strand board (OSB), generi	66.41	m3	3,8t - 0,2%	Modules- walls	130	Trailer combination, 40	2000	Ship, Big bulk
Burnt timber cladding (Yakisugi), 1	48,72	m3	3,9t - 0,2%	Modules - walls	130	Trailer combination, 40	2000	Ship, Big bulk
Insulation, Rockwool/mineral woo	1845.21	m3	53t - 3%	Modules - Floors	200.0	Trailer combination, 40	2000	Ship, Big bulk
Gypsum plasterboard, 12.5 mm, 9 kg/	114.49	m3	19t - 1%	Modules - Floors	70	Trailer combination, 40	2000	Ship, Big bulk
Gypsum plasterboard, fire and moist	78.90	m3	17t - 1%	Modules - Floors	70	Trailer combination, 40	2000	Ship, Big bulk
Particleboard, type P2, 28mm, 18.4k	149.44	m3	22t - 1%	Modules - Floors	130	Trailer combination, 40	2000	Ship, Big bulk
Glass facade, size: 3.60 x 7.20m		m2		Glass cladding	60	Trailer combination, 40		Not defined
Aluminium facade cladding, for rear		m2			40	Trailer combination, 40		Not defined
Aluminium cladding, for facade, 6.8	1888	m2	65t - 4%		40	Trailer combination, 40		Not defined

Columns and load-bearing vertical structures Create a group Move materials Add to compare

Start typing or click the arro

Resource	Quantity		CO_2e	Comment	Transport, kilometers		Transport, leg 2, kilometers	
Glued laminated timber (Glulam), 42	0	m3		Load Bearing structure	130	Trailer combination, 40	440	Not defined

Internal walls and non-bearing structures Create a group Move materials Add to compare

Start typing or click the arro

3. Horizontal structures: beams, floors and roofs 224 Tons CO_2e - 14 %

Floor slabs, ceilings, roofing decks, beams and roof Create a group Move materials Add to compare

Start typing or click the arro

Resource	Quantity		CO_2e	Comment	Transport, kilometers		Transport, leg 2, kilometers	
Cross-laminated timber (CLT), 460 k	222	m3	39t - 2%	Stairs and elevator shaft	130	Trailer combination, 40	1500	Trailer combination
Gypsum plaster board, regular, gene	114.49	m3	30t - 2%	Modules - Ceilings	70	Trailer combination, 40		Delivery van, 1,2 to
Insulation, Rockwool/mineral woo	1274.04	m3	34t - 2%	Modules - Ceilings	200.0	Trailer combination, 40		Delivery van, 1,2 to
Gypsum plasterboard, for outdoors a	78.9	m3	34t - 2%	Modules - Ceilings	70	Trailer combination, 40		Not defined
OSB (oriented strand board) boards,	35,1	m3	5,9t - 0,4%	Modules - Ceilings	130	Trailer combination, 40		Not defined
Hollow core concrete slab + rein		m3		Modules - Roof stabilizing	70	Trailer combination, 40		[illegible] 19 t
Hollow core concrete slab, HD/F32,	415,8	m3	81t - 5%		70	Trailer combination, 40		

Help

Windows and doors Create a group Move materials Add to compare

Start typing or click the arro

Resource	Quantity		CO_2e	Comment	Transport, kilometers		Transport, leg 2, kilometers	
Aluminium frame glass façade system	1900	m2	252t - 16%		60	Trailer combination, 40		Not defined

Finishes and coverings Create a group Move materials Add to compare

+ Click to input data

Building Circularity - Key Material Groups

Result category	Total tons	Virgin %	Materials Recovered %	Disposal %	Downcycling and use as energy %	Recycling and reuse as material %	Materials Returned %	Circularity %	
Concrete	3 921	100	0		100		50	25	Details
Metals	75	8	92			100	100	96	Details
Bricks and ceramics									Hide empty
Gypsum-based	234	77	23		8	92	96	60	Details
Insulation	71	32	68	96	4		2	35	Details
Glass	66	100	0			100	100	50	Details
Wood and biogenic	1 109	9	91		100		50	70	Details
Earth masses and asphalt									Hide empty
Other materials	1	100	0		100		50	25	Details

Figure 46 key Materials circularity, Mjøstårnet

Building Circularity - Key Material Groups

Result category	Total tons	Virgin %	Materials Recovered %	Disposal %	Downcycling and use as energy %	Recycling and reuse as material %	Materials Returned %	Circularity %	
Concrete	1 715	100	100		100		100	100	Details
Metals	13	98	100			100	100	100	Details
Bricks and ceramics									Hide empty
Gypsum-based	540	90	100			100	100	100	Details
Insulation	311	25	100	100				50	Details
Glass	35	100	100			100	100	100	Details
Wood and biogenic	478	5	100		100		100	100	Details
Earth masses and asphalt									Hide empty

Figure 47 Key Materials Circularity, Treet.

Appendix H: Used software

Online Software for Life cycle and circularity assessment (Limited Student educational access)

BIM (buildings information modelling software) accessible with student license, used for 3D modeling and material inventory data source.

Software used for energy use simulation and indoor climate in buildings.

Standards:

- ISO 21678(2020): Sustainability in buildings and civil engineering works Indicators and benchmarks — Principles, requirements, and guidelines
- Norge Standards NS-EN 15978 (2011) Sustainable buildings - Assessment of the environmental performance of buildings - Calculation method, which is the full name of the standard, sets calculation rules for assessing the environmental performance of new and existing buildings.
- Norge Standards NS-EN 15804 (2012): Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products
- Norge Standards NS-3700 (2013): Criteria for passive houses and low energy buildings- Residential buildings.
- Norge Standard NS-3720 (2018): Method for greenhouse gas calculations for buildings.

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