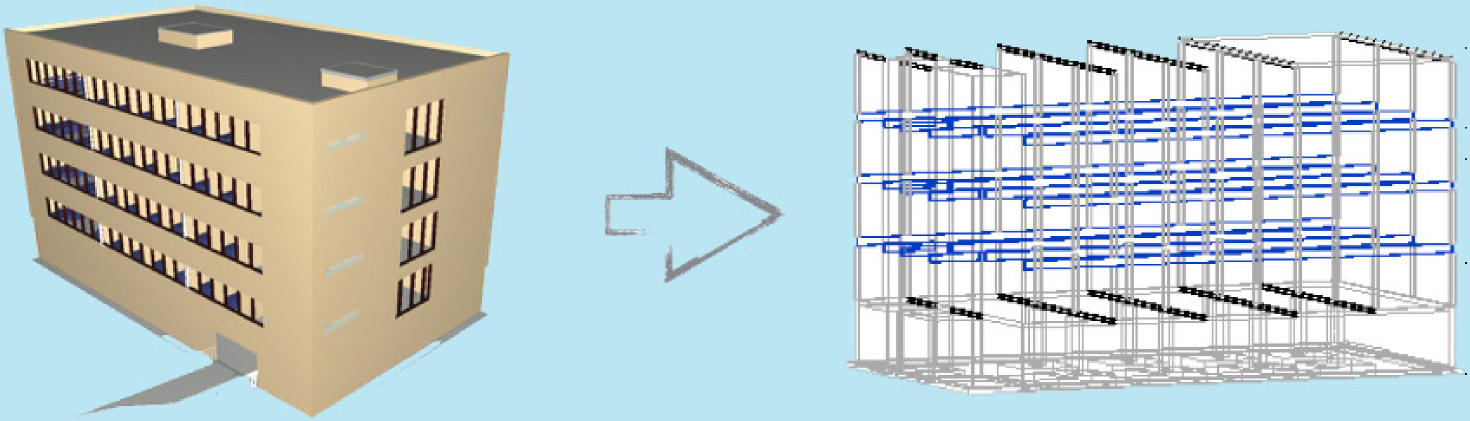
ZEB Project report 20 – 2015

Tobias Barnes Hofmeister, Torhildur Kristjansdottir, Berit Time and
Aoife Houlihan Wiberg

Life Cycle GHG Emissions from a Wooden Load-Bearing Alternative for a ZEB Office Concept

The Research Centre on
Zero Emission Buildings



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Abstract

A major contributor to global greenhouse gas emissions is the production of concrete and steel for the construction industry. This report presents a comparison of the life cycle GHG impact of a concrete and steel load-bearing structure with a wood load-bearing alternative. The basis for the comparison is a theoretical ZEB office concept of a four story Norwegian office building.

The wooden structure causes approximately half the emissions of the concrete and steel structure. The results show that end-of-life emissions account for less than 10% of the overall GHG emissions from the load-bearing systems life cycle.

Contents

1. INTRODUCTION AND BACKGROUND **6**

2. CONSTRUCTION ALTERNATIVES **8**

2.1 BASE CASE – LOADBEARING STRUCTURE WITH CONCRETE AND STEEL 8
2.1.1 Base Case – Detailed Floor Construction *9*
2.2 WOOD CASE – LOADBEARING STRUCTURE 9
2.2.1 Wood Case – Detailed Floor Construction *11*
2.3 MATERIAL INVENTORY AND DATA SOURCES 12

3. METHODOLOGY **13**

3.1 BOUNDARIES 13
3.2 MATERIAL INVENTORY 14
3.3 PRODUCT STAGE EMISSION DATA 16
3.4 WASTE SCENARIOS 16
3.4.1 End-of-life emissions data *16*
3.4.2 End of life scenario modeling *17*

4. RESULTS **20**

5. DISCUSSION **23**

6. CONCLUSION **24**

7. REFERENCES **25**

1. Introduction and background

Two concept studies have been carried out at the Research Centre on Zero Emission Buildings with the goal of achieving the ZEB-OM level. The ZEB-OM level can be defined according to Dokka et al. (2013)and (Kristjansdottir et al., 2014) as:

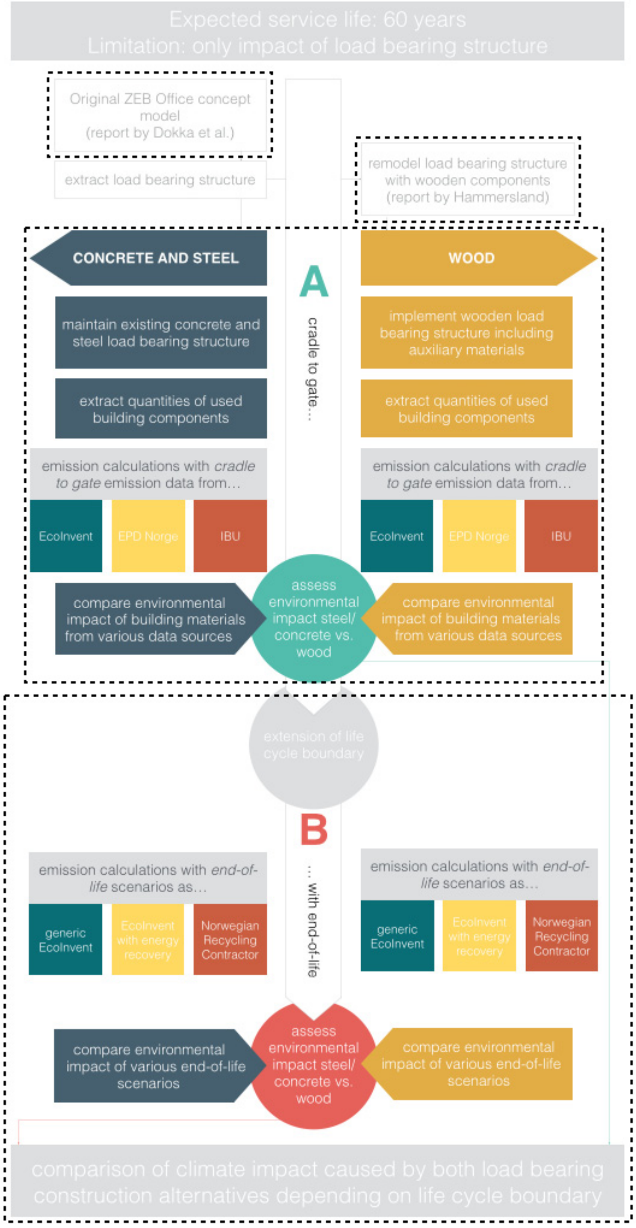
“Emissions related to all operational energy (O) use plus embodied emissions from the materials (M) and technical installations shall be compensated for with on-site renewable energy generation. The M refers to the emissions from the product phase of the materials and components and a scenarios for the replacements over a life cycle of 60 years.”

The concept studies were a theoretical office concept study presented in (Dokka, et al. 2013) and a residential concept study presented in (Houlihan Wiberg, et al. 2014). These concept studies were limited regarding the material emission calculations. The concept studies looked at traditional material solutions that are common today with no innovative design solution or material choices to reduce emissions. Also, the concept studies did not include a scenario for the end of life emissions, as this was not defined within the boundaries of the ZEB-OM level. In the ZEB office concept study the bearing structure was a traditional solution with concrete and reinforcement steel, with slab structures.

The results from the office concept study showed that material emissions accounted for a large share of the total emissions. Also, the results showed that the emissions from the load bearing structures were a large contributor. The ambition level ZEB-OM was not met, thus emphasizing the need for alternative solutions and material choices.

This study looks at material emissions from the original ZEB office concept and compares it with emissions from an alternative wooden load bearing structure. Furthermore, the study includes three end-of-life emission scenarios for the load-bearing alternatives. Firstly a scenario, calculating end of life emissions based on end-of-life treatment data from Ecoinvent Version 2.2 (Dokka 2007), secondly a scenario that looks at the effects of incineration of used construction wood in a municipal incineration plant, and thirdly a scenario based on information from the Norwegian recycling industry. The wooden alternative has been dimensioned by Hammersland (Hammersland 2013).

A selection of relevant material databases was considered used for the inventory of the analysis in (Barnes Hofmeister and Thorkildsen 2014). Data from Ecoinvent was chosen since it was used in the original ZEB office concept model. However, since the model should be placed in Norway in order to understand the local impact, the database of Norwegian approved Environmental Product Declarations (EPDs) from the Norwegian EPD-foundation proved to be a useful resource. Institut Bauen und Umwelt e.V. (IBU) was used as third data set, because it provided an interesting accounting approach using negative values for wood, accounting for it as a carbon sink during the construction process. This approach however, led to tremendous CO_2 savings on a cradle to gate basis, distorting a clear understanding. The outcome showed an incomplete and distorted picture. Especially, only a limited amount of data was available from the Norwegian EPD foundation (www.epd-norge.no). Similarly, IBU was equally lacking material information. Ecoinvent proved to be the most comprehensive data source, offering information for all required materials. Furthermore it was confirmed that emission data from different sources could not be compared directly. The work that has been carried out is presented in Figure 1.



PREVIOUS WORKS

1. Creation of ZEB office concept model (Dokka et al.)
2. Changed load bearing structure (Hammersland)
3. Comparison of emission data sources (Barnes Hofmeister and Thorkildsen)
4. Evaluation of material end-of-life emissions for wooden and conventional load bearing structure (this report)

Figure 1 Previous work done regarding the emission calculations of cases based on the ZEB office concept model.

2. Construction Alternatives

This assessment is carried out as a comparative study between the initial concept study proposed by Dokka et al. (2013) and a predominantly wooden alternative adapted by Hammersland (2013). Hammersland takes the Original ZEB Office concept model and dimensions major parts of the loadbearing structure with wood trusses and glue-laminated beams and columns. It details on load analysis to make a realistic design with the same performance criteria and room program as the base case. The wooden alternative, however, maintains concrete and steel for foundation works and technical shafts in reduced quantities within the structure. Emission analysis has been the overarching goal of this work. Subsequently dimensioning was carried out in order to provide comparable functions. Neither the reference structure nor the wood case has been optimized from a statics perspective.

2.1 Base Case – Loadbearing Structure with concrete and steel

The load-bearing structure follows a very traditional approach using concrete slabs supported by steel beams and columns (Figure 2). The building envelope is placed on the outside of this load-bearing skeleton. The building rests on a basement and foundations both made of reinforced concrete. The slabs are hollow core elements.

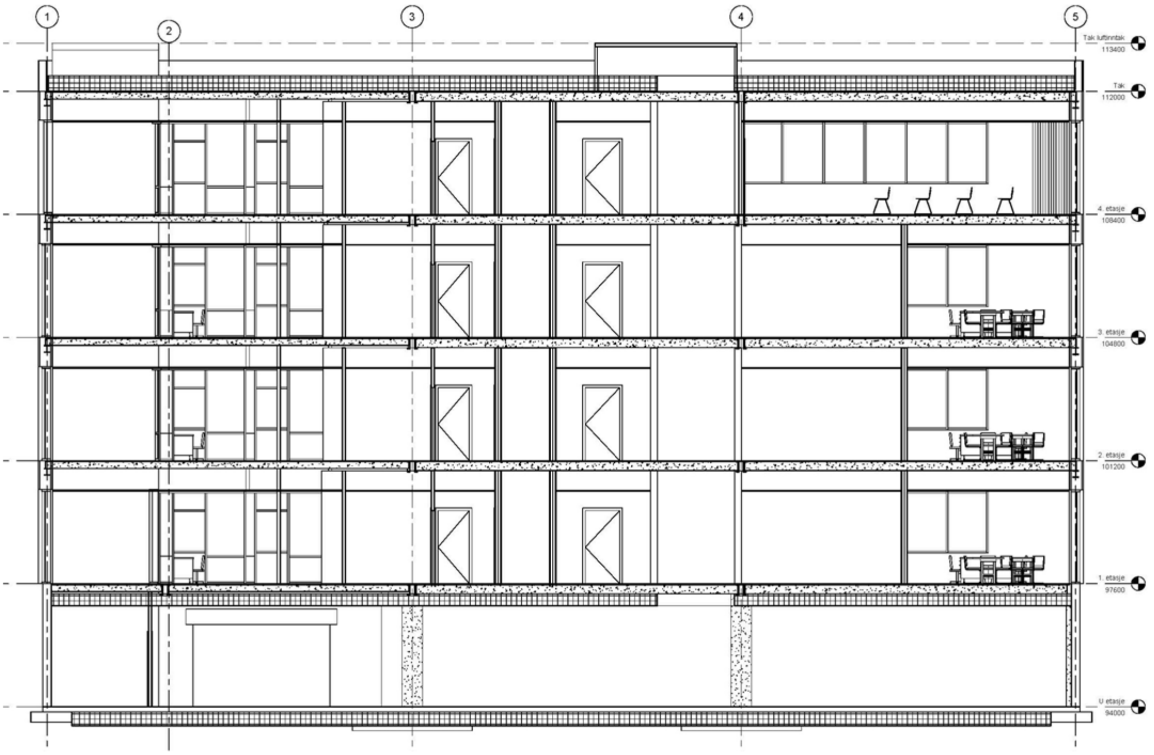


Figure 2 Section along east-west axis showing a traditional load-bearing structure of concrete slabs supported by steel beams and columns resting on a reinforced concrete foundation.

2.1.1 Base Case – Detailed Floor Construction

The detail in Figure 3 shows the original floor build-up for the ZEB office building. The load-bearing element is 200 mm reinforced concrete with a 30 mm concrete finish. The 630 mm air gap is used for technical equipment and ventilation system.

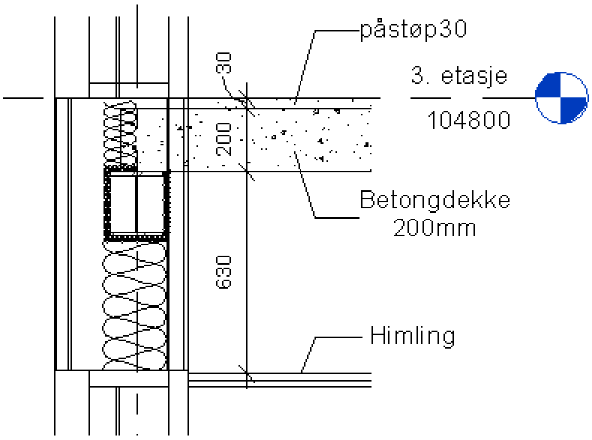


Figure 3 Detail extracted from the Revit model of the ZEB office building (Betongdekke – refers to hollow core elements)

2.2 Wood Case – Loadbearing Structure

The altered loadbearing structure consists of wood trusses resting on glue-laminated beams and columns. Figure 4 to Figure 11 are taken from Hammersland's report (Hammersland 2013) illustrating the build-up of the wooden load-bearing structure. The east-west section in

Figure 4 outlines the wooden load-bearing structure of wooden trusses supported by glue-laminated beams and columns. The illustration on the right shows a plan of the roof construction, which is partly realized as wooden ceiling and partly in concrete due to the size of the meeting room, which was not to be interrupted by load bearing columns. Figure 5 further details the floor construction consisting of wooden trusses resting upon glue-laminated beams. The flooring material itself consists of oriented strand boards (OSB) covering the truss construction, creating a continuous surface.

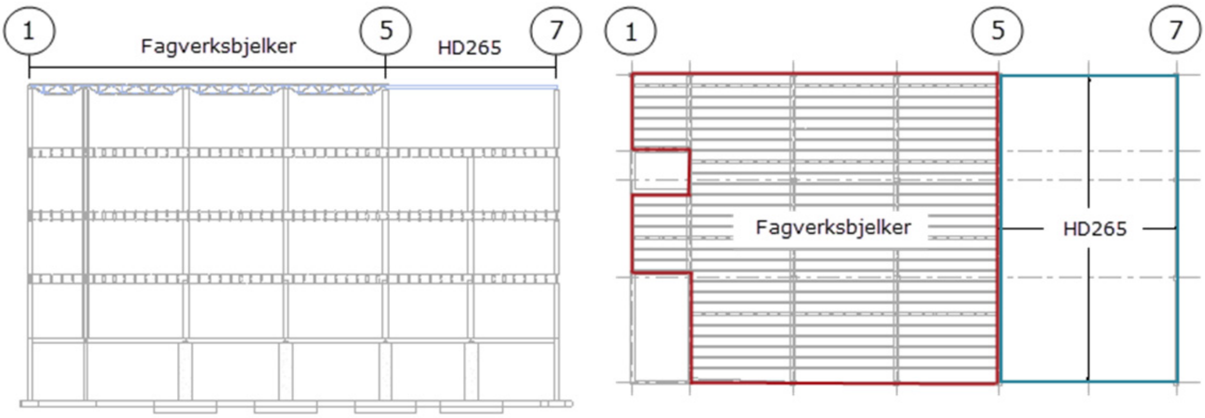


Figure 4 Section along east-west axis showing the wooden load-bearing structure of wooden trusses supported by glue laminated beams and columns and a detailed plan of the roof construction showing in red the part constructed in wood and blue the concrete ceiling

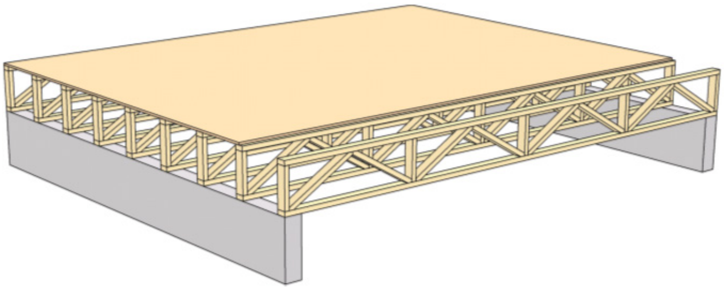


Figure 5 Schematic arrangement of wood trusses on top of glue-laminated beams covered by OSB boards.

Figure 6 and Figure 7 show in more detail the arrangement of glue-laminated beams in the floor and ceiling constructions. Figure 8 and Figure 9 detail the layout of glue-laminated columns supporting the individual floors against the reinforced concrete basement.

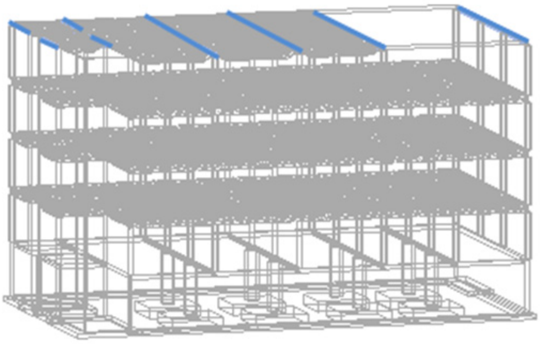


Figure 6: Glue-laminated beams in the roof construction.

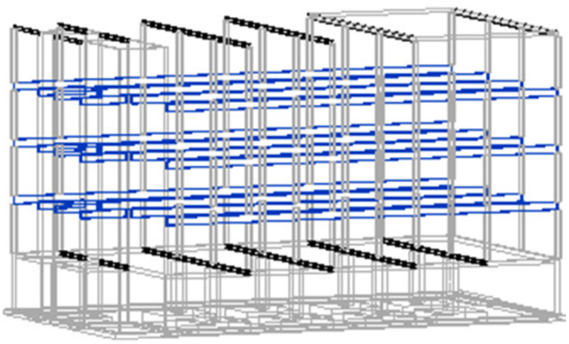


Figure 7: Glue-laminated beams in the floor construction.

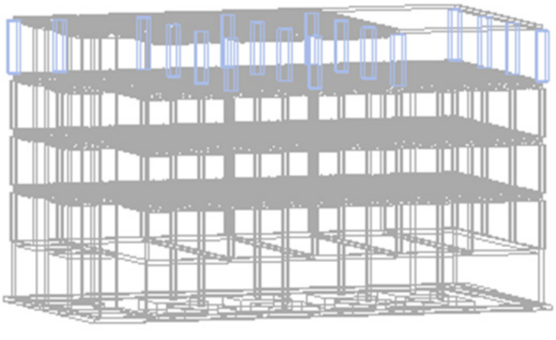


Figure 8: Glue-laminated columns supporting the beams of the roof construction.

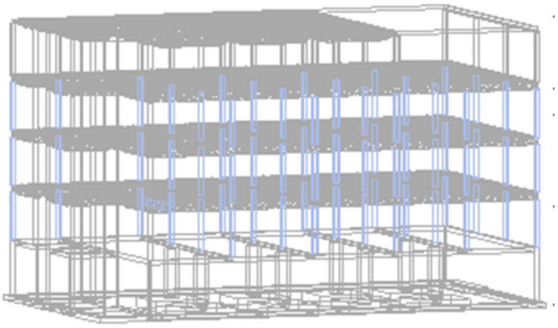


Figure 9: Glue-laminated columns supporting floors 1 to 3 against the basement.

For structural reasons the elevator shaft, the staircase and the ceiling over the meeting room, as well as the basement (walls, columns, floor and ceiling) are kept as concrete components (Figure 11). However, the foundations are reduced in size since the wooden structure is lighter than the traditional concrete and steel one. In order to take wind loads a steel cross is implemented in the east façade of the building.

Figure 10 shows the reduced size of the foundations illustrating additionally the foundation underneath the basement walls and the support for the steel cross taking wind loads on the east façade.

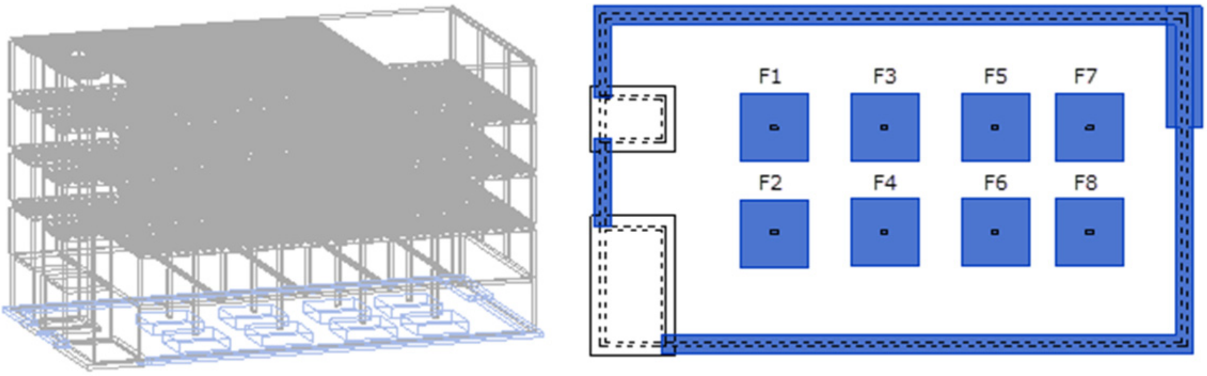


Figure 10 Reduced size of foundations due to lighter structure with additional support underneath the steel cross taking wind loads on the east façade.

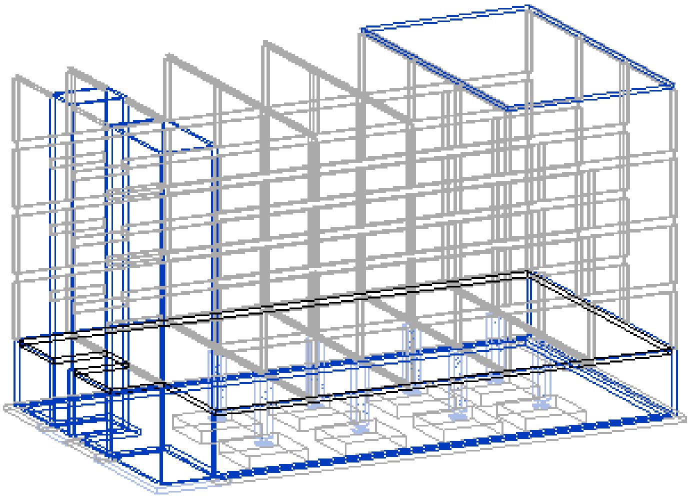


Figure 11 Illustration of remaining concrete elements for structural reasons.

2.2.1 Wood Case – Detailed Floor Construction

The wooden alternative for the floor is a timber structured floor, where the structural element is a wooden truss. For dimensions and build-up of the floor a wood truss producer proposed the composition shown in Figure 12. The producer used actual plans for the ZEB office building in order to arrange a feasible setup to achieve required qualities of acoustics and fire protection, which are mandatory for office buildings.

In the ceiling there are two gypsum boards, giving the structure sufficient protection during a fire. Due to the issues of sound spreading through wood sound, impact plates are added underneath and overtop the truss-OSB chip-board ceiling. Sound impact plates are typically made from mixed cell polyurethane foam, while the product Silencio, also intended to mitigate sound penetration, is made of wood fibre. The truss will be prefabricated, allowing an efficient building process.

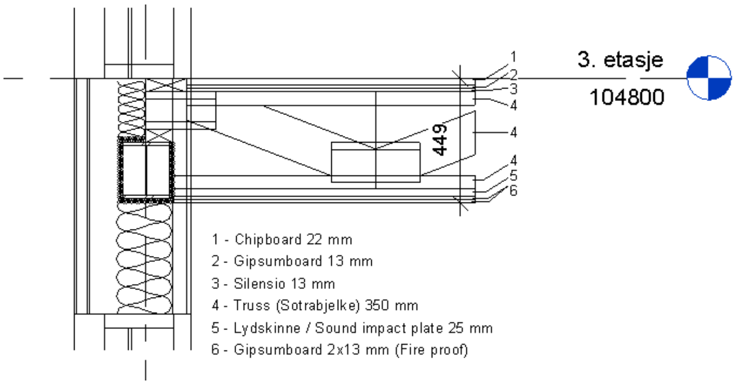


Figure 12 Detailed floor construction around wooden trusses as structural element.

2.3 Material Inventory and Data Sources

Hammersland´s report (Hammersland 2013) offers material quantities required for the construction of the load-bearing structure. However, it does not specify details concerning floor constructions. A wood truss producer delivered a proposal of how the floor looks in detail. For the emission calculations the two aspects have been combined. Table 1 shows all material types used in both structural alternatives. The load-bearing structure of the Original ZEB Office concept model is only composed of four materials while the one of the wooden alternative structure consists of nine different materials.

Table 1 Overview of materials present in each version of the compared load-bearing structures. (Data sources: OI – ZEB Office concept inventory, HR – Hammersland's report (Hammersland 2013), HC –- hand calculation based on values from Hammersland's report and ZEB Office concept inventory, TP – calculation based on detailed information from a wood truss producer).

Material	**Base Case**	**Wood Case**
Concrete	OI	HR
Reinforcing steel	OI	HR and HC
Structural timber		HR
Glue-laminated beams/ columns		HR
OSB chipboards		HR
Nail plates		HR
Steel studs	OI	
Gypsum plaster boards	OI	TP
Wood fibreboard		TP
Sound impact plates		TP

3. Methodology

The general methodology within the concept studies is to use a life cycle approach with the functional unit of 1 m^2 of the total 1980 m^2 heated floor area (BRA) over the estimated service lifetime of 60 years for the whole building. There is a clear distinction in the concept studies between material emissions and emissions due to operational energy use. This study only considers material emissions related to the loadbearing structure. In contrast to the initial study by Dokka et al. (2013) this assessment disregards all emissions from other building components and focuses solely on comparing the emissions related to a significantly wooden vs. a steel/ concrete loadbearing structure. As a consequence it is impossible to make any comments about whether a certain ZEB ambition level can be achieved or not.

3.1 Boundaries

The present case study is based on the same assumptions for the service lifetime as the initial concept building proposed by Dokka et al. and that there will not be any replacements necessary in the loadbearing structure over the service lifetime (Dokka et al. 2013).

Figure 13 visualizes the life cycle stages considered in the initial concept study (dotted black box) and the expanded boundaries for this study (dotted red box). The initial concept building study considered only material emissions from the product phase (A1-A3) over the lifetime of 60 years. The boundaries of this study are extended to include scenarios for the end-of-life stages waste processing (C3) and disposal (C4). Also, since wood can further be used as an energy source, a scenario for future reuse, material recycling and energy recovery (D) has been calculated.

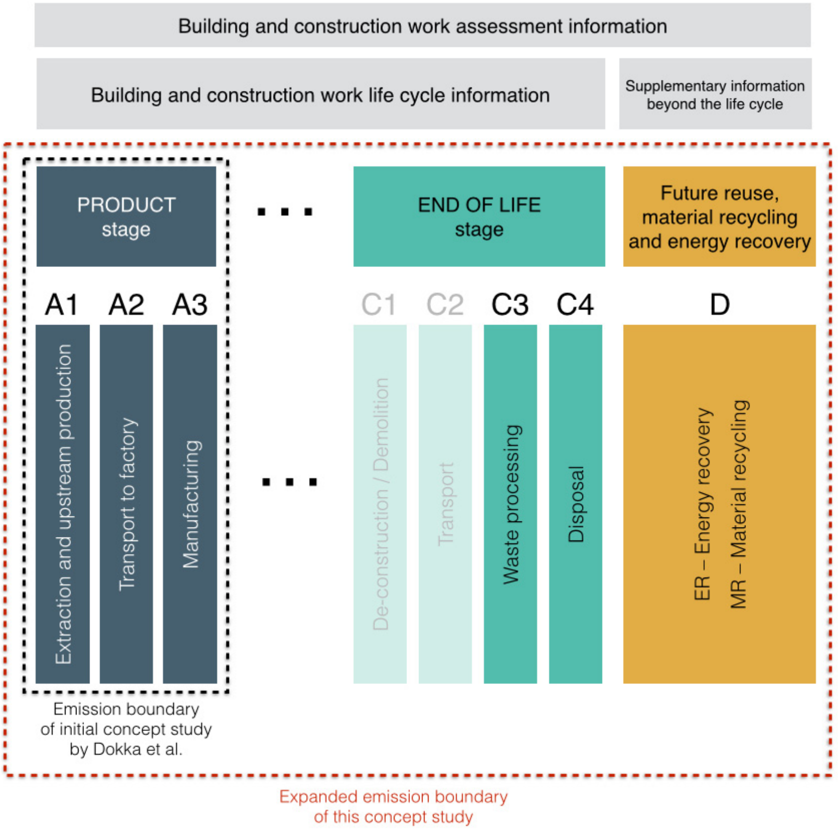


Figure 13 Accounted life cycle stages in Dokka et. al.'s (2013) initial concept study compared to the extended boundaries used in this study (Illustration based on EN 15978)

3.2 Material inventory

Table 2 shows all material quantities for the different load-bearing options. The load-bearing structure of the Original ZEB Office concept model is only composed of four materials, while the one of the wooden alternative structure consists of nine different materials.

The material quantities for the concrete and steel load-bearing structure of the base case are extracted from the excel spreadsheet which was the base for the work of Dokka et al. (2013). In the wood case all major components are taken from Hammersland´s report (Hammersland 2013). However, since Hammersland´s work did not go into detail concerning the floor/ceiling build up, material quantities for gypsum plaster boards, sound impact plates and wood fibreboards are derived from information provided by the wood truss producer. A comparison of material quantities used in the structure of the initial concept study (base case) and the adapted structure (wood case) is shown in Table 2.

Table 2 Estimated material quantities for the base case and wood case load-bearing structure.

Material	**Base Case [m^3]**	**Wood Case [m^3]**
Structural timber	0	70
Glulam beams/columns	0	19
Chip boards	0	43
Nail plates	0	0,2
Steel studs	0,3	0
Gypsum plaster boards	32	65
Sound impact plates	0	44
Silencio (wood fibreboard)	0	19
Reinforcing steel	19	5
Concrete foundation	*104*	*33*
Concrete inner load-bearing walls	*134*	*134*
Concrete in columns	*3*	*3*
Concrete in slab structures	*524*	*125*
Concrete in outer walls	*109*	*109*
Concrete total	874	408
TOTAL	**925**	**673**

Figure 14 and Figure 15 visualize the quantities of the different alternatives in more detail. Compared to the base case the wooden alternative requires 25% less construction material by volume and 50% less by weight. Furthermore, Figure 15 clearly indicates that concrete constitutes by far the mayor construction material in both cases. This is due to maintaining a concrete basement and foundations also in the wooden construction alternative. Additionally, Figure 15 displays the much wider spread of material variety in the wood case.

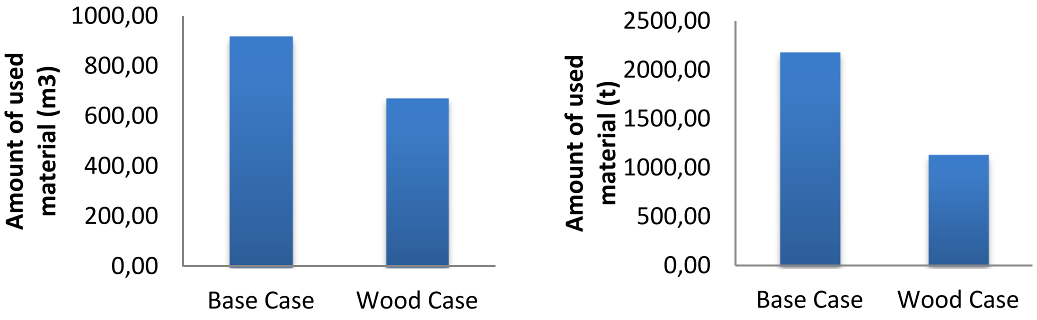


Figure 14 Compounded material quantities used in the base case and wood case. The diagram on the left shows m^3, while the one on the right shows ton (t).

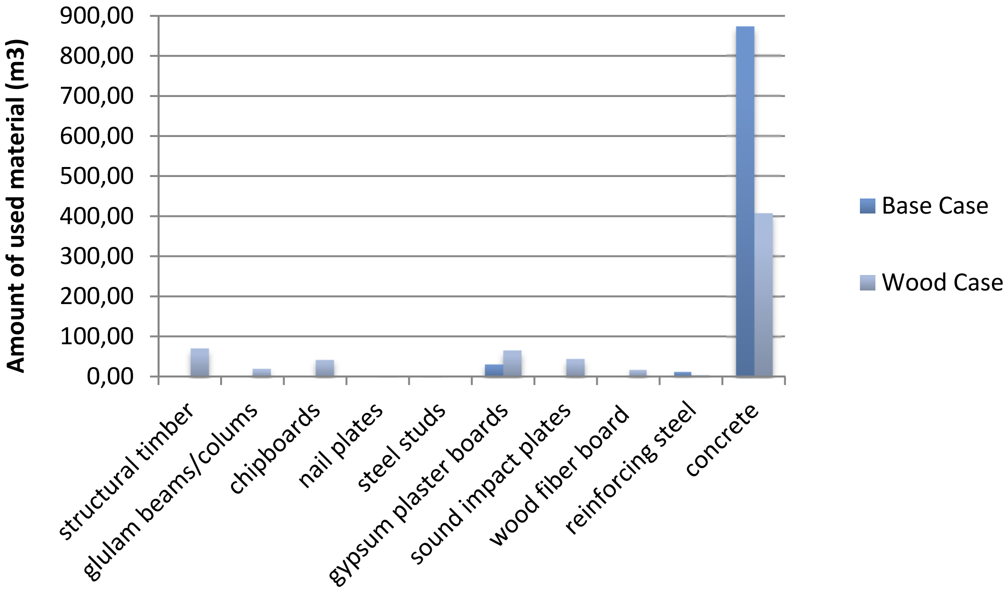


Figure 15 Detailed split of all materials used in the base case and in the wood case.

3.3 Product stage emission data

Table 3 lists the emission factors used for the different materials included in this analysis. All emission factors are converted to $kgCO_2/m^3$ with the respective densities provided by EcoInvent. For materials which were already used in the original ZEB office concept study by Dokka et al. (2013), the same emission factors are used in this analysis.

Table 3 Overview of extracted product stage emission factors.

Material	Emissions ($kg CO_2/m^3$)	Reference
Structural timber	104	Sawn timber, softwood, planed, kiln dried at plant/ RER U
Glulam beams/columns	205	Glued laminated timber indoor use, at plant / RER U
Chip boards	312	Oriented Strand Board, at plant / RER U
Nail plates / steel studs	27554	Steel, low-alloyed, at plant / RER U + steel product manufacturing, average metal working /RER U
Gypsum plaster boards	274	Gypsum plaster board, at plant/ CH U
Sound impact plates	129	Polyurethane, rigid foam, at plant/ RER U
Wood fibre board	56	Fibber board soft, at plant (u=7%)/CH U
Reinforcing steel	11383	Reinforcing steel, at plant/RER U
Concrete	261	Concrete, normal, at plant/ CH U

3.4 Waste Scenarios

In order to gain understanding of the environmental impact of the various end-of-life treatments three scenarios are investigated.

Generic EcoInvent: This scenario follows the recommended end-of-life treatment for building materials described in table 3.18 in Part V – Building Material Disposal of the report collection affiliated with SimaPro (Doka 2007). There will be no energy recovery from waste materials treated with the process of municipal incineration.

EcoInvent with Energy Recovery: This scenario is congruent with Generic EcoInvent, but considers energy recovery from municipal incineration.

Norwegian Recycling Contractor: For a better apprehension of the end-of-life of the building within the Norwegian framework, data has been gathered from a Norwegian recycling contractor regarding typical end-of-life treatments. The provided process descriptions were modelled with SimaPro S 8.0.1Multiuser Classroom in order to attain emission data. The recovered energy substitutes fossil fuel that leads to factored-in emission savings. For a clear picture of the building material lifetime emissions, product stage emissions were added to the end-of-life emissions.

3.4.1 End-of-life emissions data

The data used for the assessment of the end-of-life emissions of specific materials have been extracted from EcoInvent Version 2.2. Unit processes from the professional database of SimaPro S 8.0.1 Multiuser Classroom were used to calculate the environmental impact of the building material production as well as end-of-life.

All material emission values are calculated using the IPCC 2007 GWP100 method developed by IPCC 2007 (Solomon et al. 2007) built into Simapro. Table 4 shows the SimaPro unit processes used to model the building component emissions. The data quality for the product stage (A1–A3) shows high standards due to a typically large sample size of data from central European companies. For the end-of-life state there is not a complete set of data. Particularly wood products are underrepresented. The only two applicable end-of-life processes for wood describe untreated waste wood, which best represents structural timber, and wood fibreboards. The process for untreated waste wood, however, is also used to assess the end-of-life impact of glue-laminated timber and chipboards. Similarly SimaPro offers only one end-of-life process for steel, particularly reinforcement steel. Therefore, data for nail plates and steel studs are approximated using the process for reinforcement steel.

Table 4 EcoInvent process names chosen for respective building materials used in both load-bearing structure alternatives and energy carriers substituted through waste wood products.

Material	Product stage process name	End-of-life stage process name
Structural Timber	Sawn timber, softwood, planed, kiln dried at plant / RER U	Disposal, building, waste wood, untreated, to final disposal / CH U
Glue-laminated Timber	Glued laminated timber indoor use, at plant/ RER U	Disposal, building, waste wood, untreated, to final disposal / CH U
Chipboard (OSB)	Oriented strand board, at plant / RER U	Disposal, building, waste wood, untreated, to final disposal / CH U
Nail Plate/ Steel Stud	Steel, low-alloyed, at plant / RER U + Steel product manufacturing, average metal working / RER U	Disposal, building, reinforcement steel, to sorting plant / CH U
Reinforcement Steel	Reinforcing steel, at plant / RER U	Disposal, building, reinforcement steel, to sorting plant / CH U
Concrete	Concrete, normal, at plant / CH U	Disposal, building, concrete, not reinforced, to sorting plant / CH U
Gypsum Plaster Board	Gypsum plaster board, at plant / CH U	Disposal, building, plaster board, gypsum plaster, to recycling / CH U
Wood Fibreboard	Fibreboard soft, at plant (u = 7 %) / CH U	Disposal, building, wood fibreboard, to final disposal / CH U
Sound Impact Plate	Polyurethane, rigid foam, at plant / RER U	Disposal, building, polyurethane foam, to final disposal / CH U
Fuel Oil	Heat, heavy fuel oil, at industrial furnace 1MW / CH U	
Natural Gas	Heat, natural gas, at industrial furnace >100 kW / RER U	

3.4.2 End of life scenario modeling

All three scenarios are based on material emission data gathered from EcoInvent. EcoInvent provides three end-of-life options for each listed building material. The boundaries for each of these options vary strongly, influencing the quantity of emissions accounted for (compare Figure 16). The lowest emissions result from *Option A – Direct recycling* since the boundary only includes the emissions for demolition with immediate material sorting. Gypsum plasterboards can be treated in such a fashion. Reinforced concrete as well as steel studs and nail plates are counted for using *Option B – (Partial) recycling after sorting*, since these materials have to be separated from one another before recycling. *Option C – Disposal without recycling* causes highest emission values since it will be disposed completely, either by landfilling or by incineration. All wooden building materials are accounted for in this manner since municipal incineration is at present the most feasible option (Fjeldheim 2011).

It is assumed that all materials can be separated from one another. Thus it is possible to calculate respective end-of-life emissions following the material quantities used during the construction process.

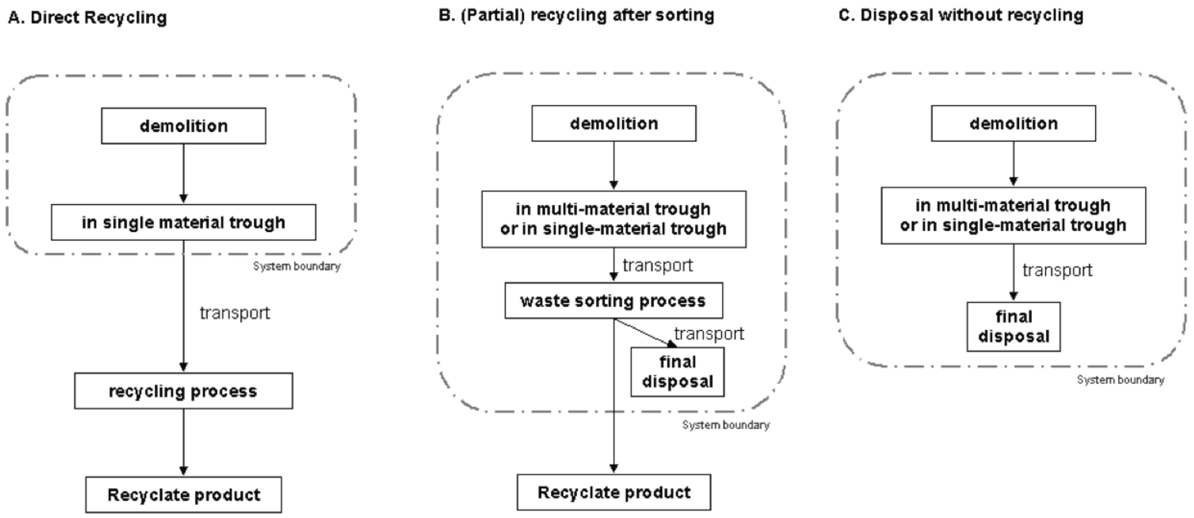


Figure 16 End-of-life scenario boundaries used in EcoInvent (Doka 2007).

In Norway municipal incineration is coupled with district heating. The energy recovery from wood is based on supplementary fossil fuels used in Norwegian district heating plants in 2004 (Thyholt 2006). It is assumed that backup fossil fuels are needed in cases where there is not enough organic matter or household waste to incinerate. Therefore, it is furthermore assumed that combustible construction waste can substitute fossil fuels for the sake of energy production. In 2004 the supplementary firing in Norwegian district heating plants consisted of 4% natural gas and 8% fuel oil (Thyholt 2006). This composition matches the average value for the Norwegian district heating system from 1998 to 2007 (Lien 2013).

The emission factors for 1 MJ heat production from fuel oil and natural gas respectively are extracted from EcoInvent. Subsequently, a new emission factor representing the composition of 1/3 natural gas and 2/3 fuel oil is computed. This emission factor per MJ of heat production is used to calculate emissions in case of no availability of a wood substitute.

Table 5 shows the waste treatment options considered in the three studied scenarios. The difference in data between *Generic EcoInvent* and *EcoInvent with energy recovery* is that wood substitutes backup fossil fuel for district heating in the second scenario, which leads to emission savings. The scenario *Norwegian recycling contractor* differs from *EcoInvent with energy recovery* in the sense that gypsum plasterboards are landfilled since the only gypsum recycling facility is south of Oslo, which often limits the economic potential for gypsum recycling. Furthermore, demolition wood in Norway is typically sold to private enterprises, which use it as a fuel oil substitute.

Table 5 End-of-life treatment for respective materials in all three scenarios

Material	**Generic EcoInvent**	**EcoInvent with Energy Recovery**	**Norwegian Recycling Contractor**
Structural Timber	Municipal incineration, no energy recovery	Municipal incineration, with energy recovery	Bioenergy for businesses
Glue-laminated Timber	Municipal incineration, no energy recovery	Municipal incineration, with energy recovery	Municipal incineration, with energy recovery
Chipboard (OSB)	Municipal incineration, no energy recovery	Municipal incineration, with energy recovery	Municipal incineration, with energy recovery
Nail Plate/ Steel Stud	To sorting plant	To sorting plant	To sorting plant
Reinforcement Steel	To sorting plant	To sorting plant	To sorting plant
Concrete	To sorting plant	To sorting plant	To sorting plant
Gypsum Plaster Board	Recycling	Recycling	Landfilled
Wood Fibreboard	Municipal incineration, no energy recovery	Municipal incineration, with energy recovery	Municipal incineration, with energy recovery
Sound Impact Plate	Municipal incineration, no energy recovery	Municipal incineration, with energy recovery	Municipal incineration, with energy recovery

4. Results

The analysis shows that compared to the production stage emissions, the end-of-life emissions add less than 10 % to the overall balance (8% base case, 9% wood case).

Figure 17 shows the comparison of the three scenarios plotted together with only the cradle-to-gate emissions (production stage A1–A3). It is apparent that the wooden structure (wood case) causes almost 50% less emissions compared to the original ZEB office concept model (base case) in concrete and steel. This trend is the same in all three scenarios.

The total emissions (all in this report considered life cycle stages) for the base case only vary in the third scenario. The reason is that gypsum plasterboards are landfilled instead of recycled, causing a slightly higher impact. For the wood case, however, the emissions fluctuate from scenario to scenario. The scenario based on information from the Norwegian recycling contractor shows the lowest emissions due to larger fossil fuel emissions being substituted with demolition wood (wood replacing fuel oil in private enterprises). The wood products from the scenario *EcoInvent with energy recovery* substitute emissions caused by a mixture of fuel oil and natural gas, which are slightly lower than the ones of pure fuel oil.

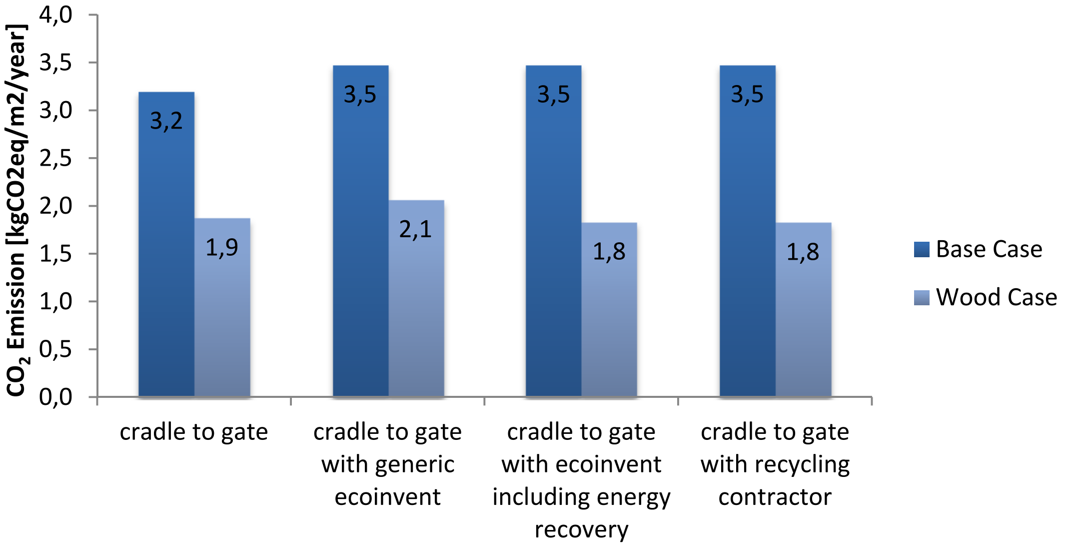


Figure 17 Three end-of-life scenarios including product stage emissions compared to only cradle-to-gate emissions.

Figure 17 shows the overall emissions from all considered life cycle stage, while Figure 18 only shows emissions related to stages C3, C4 and D. Comparing the data for all three scenarios it becomes obvious that wood as energy carrier substituting fossil fuels leads to negative end-of-life emissions. Despite higher emissions due to landfilling of gypsum plasterboards (four times higher compared to recycling) the *Norwegian recycling contractor* scenario has the largest emission savings due to demolition wood substituting fuel oil in private enterprises (Figure 18). Considering that a possible future situation in the Norwegian energy sector might be that demolition wood will not substitute fossil fuels, but rather emissions from heat pumps driven by electricity, the benefits of wood as laid out here may decrease.

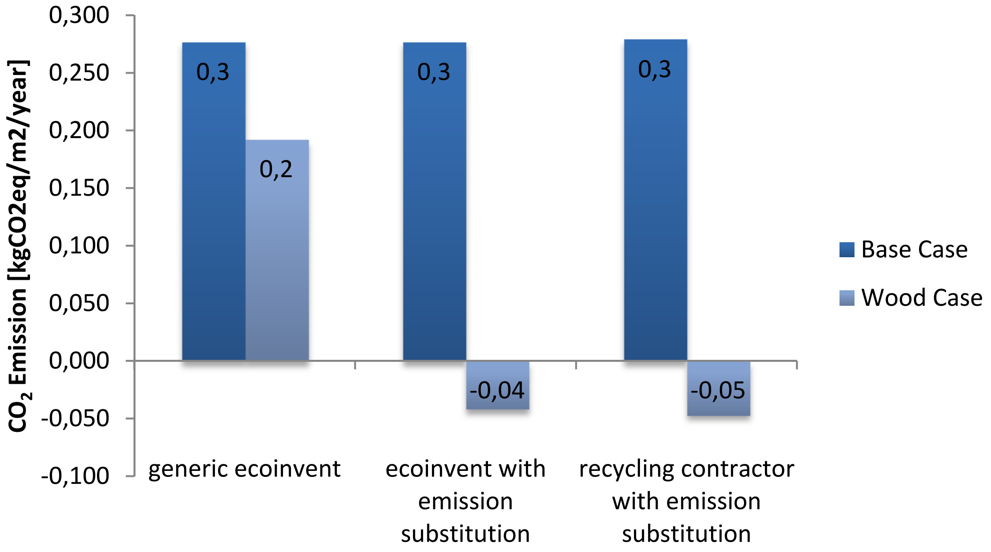


Figure 18 End-of-life emissions for all three scenarios showing negative emissions in case fossil fuels are substituted with wood.

Since the emission from the end-of-life stages are in the order of one magnitude smaller than the production stage emissions, it becomes clear how crucial it is to be conservative with respect to the material use in buildings, regardless of whether the structure is made of wood or concrete and steel. As Figure 19 shows, especially concrete and steel have a tremendous impact compared to all other materials. In both models concrete is the strongest emission driver. Although the major environmental impact is caused during the product stages (A1-A3), the end-of-life of concrete causes the major fraction of emissions among all end-of-life processes (C3 and C4).

Combustible materials substituting fossil fuels drive negative emissions as shown in Figure 18. This will of course only be feasible as long as the back-up fuels in district heating systems are fossil fuels.

Overall, the fossil fuel mixture of 1/3 natural gas and 2/3 fuel oil has 18 times (20 times for pure fuel oil) higher emissions than the end-of-life procedure for wooden building materials including municipal incineration. In the case of wood fibreboards, the emissions are almost comparable (0,8 times the emissions of substituted fossil fuel) due to chemical adhesives used to bind the fibres into solid boards.

The assessment, however, also showed that incineration is not preferable in any case. While wood products are favourable to fossil fuels, the sound impact plates used in the wooden constructions, made of polyurethane foam, cause four times higher emissions than the substituted fossil fuel.

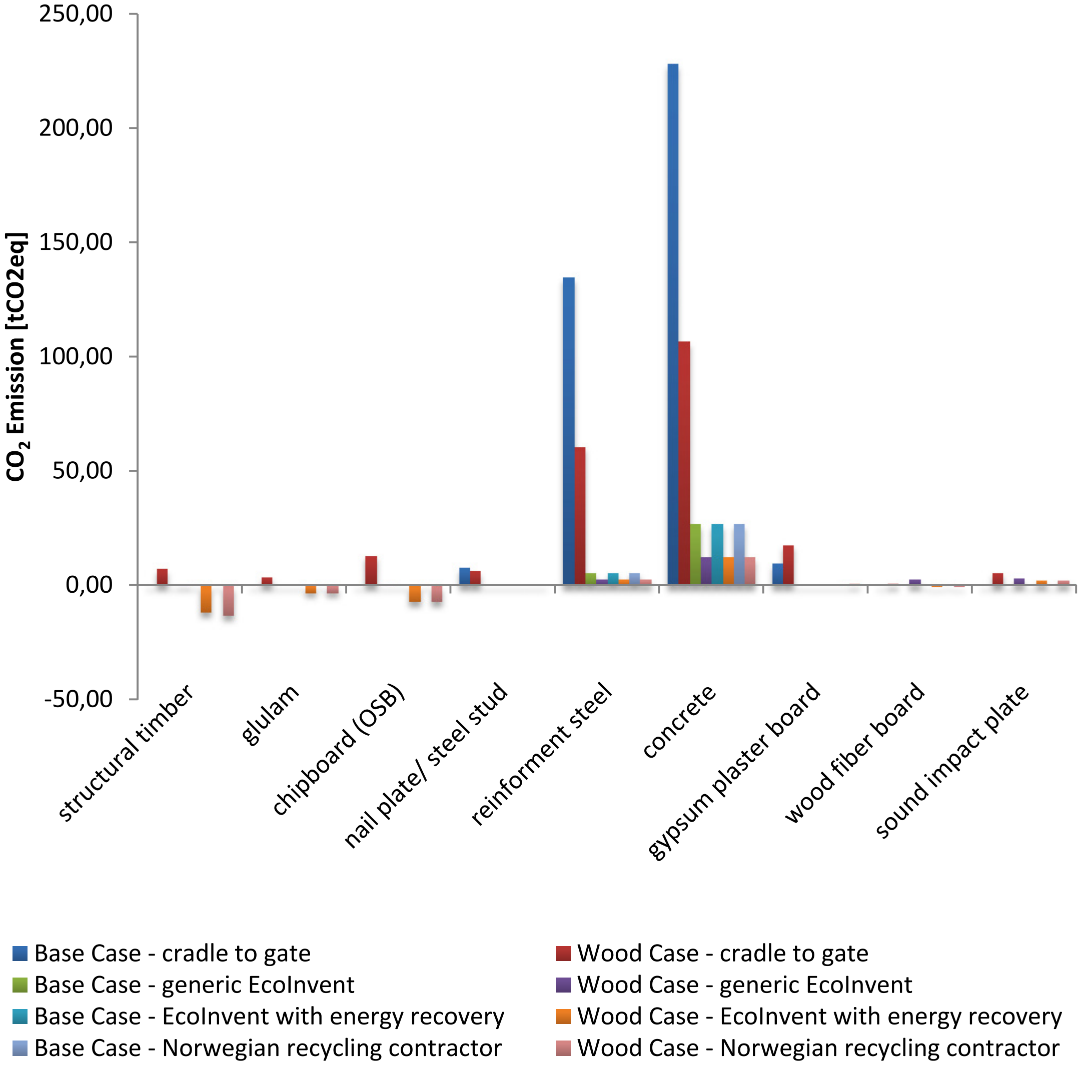


Figure 19 Emission contribution by material category.

5. Discussion

The analysis clearly shows that emissions from the production process outweigh any emissions from the materials end-of-life treatment. This means that the material choice plays a major role in locking-in emissions. Therefore, it is crucial to reduce the required construction material quantity.

Since the original ZEB office model concept was modelled after a typical four-story office building including a basement for parking, the same structure has been used in the alternative wooden load-bearing structure. Due to lower weight the reinforced concrete foundations and basement walls are downsized in the wood case. However, the emission picture is still dominated by the emission of these two materials. In order to really minimize emission in the wooden construction it should be considered to not assume that there is a basement underneath or to use a different technology (e.g. solid wood based basement, e.g. a combination of concrete, steel and wood). If, hypothetically, in a simplified approach there would be no concrete and steel used in the wooden construction, its product stage emissions would shrink to 55 t CO_2 (equal to 25 % of the emissions including concrete and steel) while the end-of-life energy reclamation would yield 20 t CO_2 savings (four-times more than including concrete and steel). The total emissions on the boundary of cradle-to-gate including the end-of-life over a 60-year lifetime would be 35 t CO_2. In order to put these figures into perspective it is helpful to compare the building emissions with typical road transport emissions. The U.S. Environmental Protection Agency states typical passenger car emissions to 5 t CO_2 per year, the environmental impact of the wood case would equal seven years of driving a car (U. S. Environmental Protection Agency 2011). This implies that by reducing the amount of concrete and steel to a minimum, it would be feasible to achieve a ZEB-balance above the currently achieved ZEB-O level as determined for the ZEB office concept model (Dokka et al. 2013).

In order to gain a better understanding of the overall building, in the next steps a thorough ZEB-balance should be established going beyond the changes within the load-bearing structure. Furthermore, it is necessary to take a closer look at emissions related to the cladding and its surface treatments, predominantly paints.

In this very first examination on how different end-of-life processes impact the building emissions, all numerical data has been extracted from EcoInvent (www.ecoinvent.ch). Especially in case of the Norwegian recycling contractor this data might not be accurate enough, since it was only possible to find information about the specific processes, but with no insights into specific emission values. In future examinations it would be recommended to find more precise numerical values either from Norwegian processes or via the means of Norwegian EPDs. Up to this day Norwegian EPDs, however, were insufficient in their data variety to sufficiently model especially the wooden load-bearing structure.

With respect to building material recycling, future research should expand the boundary condition from the building to a larger economic area, since concrete, for example, can replace crushed rock in road sub bases or newly extracted aggregate in fresh concrete mixtures. However, emission saving from these processes will be invisible when keeping the boundary on the building itself. Furthermore, current construction practice in casting elements together or permanently gluing surface protection on floors etc., limits the recycling potential. While this assessment assumes a perfect recycling potential, industry practice has to be altered to construct buildings in a way that keeps the ease of an end-of-life disassembling process in mind.

Considerations of the building's lifetime may impact its environmental load. Quantitatively looking at our current built environment, it seems that masonry buildings can last longer than lighter wooden structures. With more scientific insight, an alteration of assumed lifetimes for lighter and heavier buildings might be necessary to better represent their true environmental impact.

6. Conclusion

The analysis shows that compared to the production stage emissions, the end-of-life emissions add less than 10 % to the overall balance (8 % base case, 9 % wood case). At the same time, concrete and steel prove to be the responsible for 75 % of the production stage emissions even in the building with the wooden load-bearing structure. Most of the concrete and reinforcing steel is utilized in the basement. However, advantageous thermal properties of reinforced concrete in terms of thermal mass are inaccessible in such a configuration. Therefore, choosing the right construction is crucial.

The life cycle emissions and potential emission saving are strongly dependent on the chosen system boundary. Especially in terms of concrete, down-cycling to gravel for road construction is a possible option. In terms of wood, the emission saving strongly depends on the type of fuel substituted by demolished construction wood. These are only two aspects. However, it is clear that especially end-of-life emission, but also production stage emissions, are strongly influenced by the system boundary, and more importantly the interdependencies and possible synergies within the system. Therefore, assessing a building's life cycle emissions in the context of a larger «ecosystem» might open untapped potentials.

The study shows that it is crucial to keep product life cycle emission in mind while initially conceptually designing a building, since upstream alterations, such as replacing a concrete and steel load-bearing structure with a wooden one, might result in only minor benefits. The study also shows that reducing production stage emissions is highly relevant, since even energy recovery in an end-of-life scenario only will result in about a 20% energy yield.

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APPENDICES

	Construction Scenario								
	ECOInvent							Cradle to Gate OZEB	Cradle to Grave WZEB
Material	**Functional unit**	**density (kg/m3)**	**Source**	**ected service life (ye**	**Source**	**cradle to gate - GWP (kg CO2 eq/FU)**	**Source**	**Emission (kg CO2 eq)**	**Emission (kg CO2 eq)**
structural timber	1 m3	490	Konstruktionsvollholz KVH, Überwachtungsgemeinschaft Konstruktionsvollholz e.V., EPD-ÜKH-2012111-D	60	Norwegian planed strucutral timber (crude wood) Treindustrien NEPD nr: 084E rev1	104	sawn timber, softwood, planed, kiln dried at plant/ RER U	**0,00**	**7282,08**
glulam	1 m3	470	standard glulam bear	60	standard glulam bear	205,000	Glued laminated timber indoor use, at plant, RER U	**0,00**	**3913,45**
chipboard (OSB)	1 m3	600	Fritz Egger GmbH & Co OG Holzwerkstoffe, Eurostrand OSB, EPD-EHW-2012113-D	> 50	Fritz Egger GmbH & Co OG Holzwerkstoffe, Eurostrand OSB, EPD-EHW-2012113-D	312,000	Oriented Strand Board, at plant RER U	**0,00**	**13260,00**
nail plate/ steel stud	1 kg	7850	Akkon steel structures systems Co., EPD-AKK-2012111-E	60	Norgips Norge AS, Deklaration nr: 00178N	3,51	nail plate = steel, low-alloyed, at plant/RER U + steel product manufacturing, average metal working/RER U	**7821,68**	**6337,31**
reinforment steel	1 kg	7850	Outokumpu Oyj, stainless steel rebar product, EPD-OUT-2013-0160-CBD1-EN	1000	Outokumpu Oyj, stainless steel rebar product, EPD-OUT-2013-0160-CBD1-EN	1,45	reinforcing steel, at plant/RER U	**134657,88**	**60678,41**
concrete	1 m3	2358	Informationszentrum Betong GmbH, Beton der Druckfestigkeitsklasse C35/45, EPD-IZB-2013441-D	50-100	Ferdigbetong B25 M60, NEPD nr: 123N	261,0000	concrete, normal, at plant/ CH U	**228015,60**	**106628,94**
gypsum plaster board	1 kg	775	Dalsan Gypsum Industry and Trade Inc., EPD-DGI-20130062-CBD1-EN	60	Norgips Plasterboard 13, Type A (STD), NEPD no: 113E	0,354	gypsum plaster board, at plant/ CH U	**9685,09**	**17763,24**

wood fiber board	1 m3	280	Egger DFF wood fibre boards, EPD-EHW-2008611-E	no data		55,5	fibreboard soft, at plant (u=7%)/CH U	**0,00**	**1045,26**
sound impact plate	1 kg	30	Factory-made polyurethane insulatoin products, EPD-IVPU-2010112-D	depending on surrounding components, since material itself is non-rotting and resistant to most construction materials	Factory-made polyurethane insulatoin products, EPD-IVPU-2010112-D	4,31	polyurthane, rigid foam, at plant/ RER U	**0,00**	**5708,24**
								380180	**222617**

	End-of-life scenario - generic EcoInvent						
	EcoInvent					OZEB	WZEB
Material	**Functional Unit**	**density (kg/m3)**	**process**	**end-of-life - GWP (kg CO2 eq/FU)**	**Source**	**Emission (kg CO2 eq)**	**Emission (kg CO2 eq)**
structural timber	1 kg	720	incineration, no energy reclamaition	0,0136	disposal, building, waste wood, untreated, to final disposal/CH U	0,00	685,64
glulam	1 kg	720	incineration, no energy reclamaition	0,0136	approximation with structural timber	0,00	186,93
chipboard (OSB)	1 kg	720	incineration, no energy reclamaition	0,0136	approximation with structural timber	0,00	416,16
nail plate/ steel stud	1 kg	7900	to sorting plant (since it has to be taken away from the wood)	0,0614	approximation with reinfrocing steel	136,82	111,56
reinforment steel	1 kg	7900	to sorting plant (since it has to be crushed)	0,0614	disposal, building, reinforcement steel, to sorting plant/CH U	5702,06	2585,78
concrete	1 kg	2200	to sorting plant (since it has to be crushed)	0,0140	disposal, building, concrete, not reinforced, to sorting plant/CH U	26907,59	12583,03
gypsum plaster board	1 kg	1000	recycling	0,0033	disposal, building, plaster board, gypsum plaster, to recycling/CH U	90,01	213,02
wood fiber board	1 kg	740	incineration, no energy reclamaition	0,1980	disposal, building, wood fibre board, to final disposal/CH U		2759,48
sound impact plate	1 kg	30	incineration, no energy reclamaition	2,4700	disposal, building, polyurethane foam, to final disposal/CH U	0,00	3271,31
						32836	**22813**

End-of-life scenario - EcoInvent with emission substitution

	EcoInvent								OZEB	WZEB
Material	**Functional Unit**	**density (kg/m3)**	**process**	**end-of-life - GWP (kg CO2 eq/FU)**	**Source**	**Amount of energy possible to be reclaimed via wood incineration (MJ)**	**Emissions from fossil fuel producing the equal amount of energy (kgCO2eq)**	**Emission from waste incineration (kgCO2eq)**	**Emission (kg CO2 eq)**	**Net-Emission (kg CO2 eq)**
structural timber	1 kg	720	incineration, with energy reclamaition	0,0136	disposal, building, waste wood, untreated, to final disposal/CH U	138135,46	12481,92	685,64	0	-11796,28
glulam	1 kg	720	incineration, with energy reclamaition	0,0136	approximation with structural timber	37660,75	3403,03	186,93	0	-3216,10
chipboard (OSB)	1 kg	720	incineration, with energy reclamaition	0,0136	approximation with structural timber	83844,00	7576,14	416,16	0	-7159,98
nail plate/ steel stud	1 kg	7900	to sorting plant (since it has to be taken away from the wood)	0,0614	approximation with reinfrocing steel	-	-	-	136,82	111,56
reinforment steel	1 kg	7900	to sorting plant (since it has to be crushed)	0,0614	disposal, building, reinforcement steel, to sorting plant/CH U	-	-	-	5702,06	2585,78
concrete	1 kg	2200	to sorting plant (since it has to be crushed)	0,0140	disposal, building, concrete, not reinforced, to sorting plant/CH U	-	-	-	26907,59	12583,03
gypsum plaster board	1 kg	1000	recycling	0,0033	disposal, building, plaster board, gypsum plaster, to recycling/CH U	-	-	-	90,01	213,02
wood fiber board	1 kg	740	incineration, with energy reclamaition	0,1980	disposal, building, wood fibre board, to final disposal/CH U	38186,7843	3450,5578	2759,48	0,00	-691,07
sound impact plate	1 kg	30	incineration, with energy reclamaition	2,4700	disposal, building, polyurethane foam, to final disposal/CH U	9270,9225	837,7206	3271,31	0,00	2433,59
									32836	**-4936**

	End-of-life scenario - recycling contractor and emission substitution									
	EcoInvent								OZEB	WZEB
Material	**Functional Unit**	**density (kg/m3)**	**process**	**end-of-life - GWP (kg CO2 eq/FU)**	**Source**	**Amount of energy possible to be reclaimed via wood incineration (MJ)**	**Emissions from fossil fuel producing the equal amount of energy (kgCO2eq)**	**Emission from waste incineration (kgCO2eq)**	**Emission (kg CO2 eq)**	**Net-Emission (kg CO2 eq)**
structural timber	1 kg	720	incineration, with energy reclamaition	0,0136	disposal, building, waste wood, untreated, to final disposal/CH U	138135,46	13758,29	685,64	0,00	-13072,66
glulam	1 kg	720	incineration, with energy reclamaition	0,0136	approximation with structural timber	37660,75	3403,03	186,93	0,00	-3216,10
chipboard (OSB)	1 kg	720	incineration, with energy reclamaition	0,0136	approximation with structural timber	83844,00	7576,14	416,16	0,00	-7159,98
nail plate/ steel stud	1 kg	7900	to sorting plant (since it has to be taken away from the wood)	0,0614	approximation with reinfrocing steel	-	-	-	136,82	111,56
reinforment steel	1 kg	7900	to sorting plant (since it has to be crushed)	0,0614	disposal, building, reinforcement steel, to sorting plant/CH U	-	-	-	5702,06	2585,78
concrete	1 kg	2200	to sorting plant (since it has to be crushed)	0,0140	disposal, building, concrete, not reinforced, to sorting plant/CH U	-	-	-	26907,59	12583,03
gypsum plaster board	1 kg	1000	to landfill	0,0133	disposal, building, plaster board, gypsum plaster, to final disposal/CH U	-	-	-	363,87	861,13
wood fiber board	1 kg	740	incineration, with energy reclamaition	0,1980	disposal, building, wood fibre board, to final disposal/CH U	38186,7843	3450,5578	2759,48	0,00	-691,07
sound impact plate	1 kg	30	incineration, with energy reclamaition	2,4700	disposal, building, polyurethane foam, to final disposal/CH U	9270,9225	837,7206	3271,31	0,00	2433,59
									33110	**-5565**

The Research Centre on Zero emission Buildings (ZEB)

The main objective of ZEB is to develop competitive products and solutions for existing and new buildings that will lead to market penetration of buildings that have zero emissions of greenhouse gases related to their production, operation and demolition. The Centre will encompass both residential and commercial buildings, as well as public buildings.

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