Engineered Timber Construction Systems for Multi-Storey Residential Buildings with Passive House Standard

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Abstract

The work includes an evaluation of different advanced timber floor construction systems for multi-story residential buildings. Market-available state-of-the-art systems in a Nordic and Central European context are reviewed and relevant performance criteria are investigated and presented. The challenges are tested on a case study involving the building project "Ballastbrygga" located at Mandal in southern Norway. Several aspects are investigated separately for selected promising advanced timber construction systems. These are compared with a conventional concrete construction system for floor slabs to determine the impact on the energy efficiency of the building with high performance targets such as the Norwegian passive house standard NS 3700. Furthermore, an evaluation of the alternatives regarding the embodied greenhouse gas emissions in the floor structure and assembly is performed investigating the impact of additional measures resulting from the use of timber structures.

Keywords: timber construction system, passive house, operational and embodied emissions, thermal bridges

Introduction

Innovative construction systems where timber and wood-based products are used in extensive quantities in building structures are considered an energy efficient and low carbon strategy utilising favourable material properties and the possibility of substitution of less environmentally friendly materials. Such systems are here referred to as Engineered Timber Construction Systems (ETCS) as they seek to improve the performance of structural timber with engineered solutions.

The housing project "Ballastbrygga" is situated in the town of Mandal, southern Norway. It has a planned total usable treated area of more than 11000 m² and shall satisfy the Norwegian passive house standard NS 3700 [NS 3700 2010]. The two building blocks are ca. 12 m deep and 4 to 5 storeys high. Due to the rather generic dimensions "Ballastbrygga" is well suited as a case study for multi-storey apartment buildings in general.

This research is part of an R&D project "Urbant Trebyggeri" financed by "Innovasjon Norge", exploring the state-of-the-art of ETCS and their applicability in multi-storey buildings in Norway, in particular for structural elements.

Objective

The work focuses on the impact of state-of-the-art ETCS as floor structural systems on energy efficiency in the building and embodied emissions in the construction. Performance criteria are to be investigated for the selection of systems which refer to requirements for the case study project and the typology. Based on these criteria suitable structural systems are to be determined and floor assemblies are to be developed. These possible ETCS constructions are then compared with the conventional concrete constructions with respect to energy efficiency and greenhouse gas emissions.

Method

A survey of the Norwegian and Central-European markets has been performed to provide an overview of the state-of-the-art of ETCS. Performance criteria were established by reviewing the Norwegian building code TEK10 and relevant standards and professional literature. Solutions were developed either in collaboration with the manufacturers and their resources (e.g. dimensioning software, data sheets, certification and approval documents) or based on professional resources to check compliance of the ETCS with Norwegian national standards.

Energy performance for a simplified model of the case study was simulated in the dynamic simulation software SIMIEN 5.015 [Programbyggerne 2013] to examine the influence of the investigated floor constructions on heating demand and the heating load. The minimum requirements on components of NS 3700 have been used except of the normalised thermal bridge value. Instead, specific values of the thermal bridges located at the edge of the floor slabs, columns in exterior walls, and around windows were used. These were determined in Therm 6.3 [LBNL 2012] for each floor construction. The columns were assumed to be fully integrated ('flush') in the exterior wall. The edges of the slabs were modelled so that the floor slab intrudes the façade with ca. 100 mm. A light timber framing exterior wall was used in all cases. The base case A was modelled both with a load bearing beam integrated in the wall (case A1) and without (case A2), as described above (see also figure 1). Case A2 is used as base case for the study. The floor heights were altered according to the floor constructions while a clear height was kept at 2,50 m with respective consequences for façade areas, and the length of thermal bridges. Also the heat storage capacities of flooring and ceiling have been adjusted for the cases to given values in SIMIEN. For the evaluation of the heating load uses the set point temperatures of NS 3031 have been used: (21 °C from 7:00 until 23:00, and 19 °C from 23:00 until 7:00).

Greenhouse gas emissions in the form of CO2-equivalents were investigated for operation and materials. The emissions are calculated per one square meter BRA (net usable heated floor area) over the total lifetime of the building. To determine the operational emissions, a simplified energy supply system is chosen with a heat pump (system heating efficiency 2,26) covering 80 % of the heating demand. 260 g CO2-equiv./kWh as GHG emission factor for electricity has been used following the scenario of achieving zero emissions in 2100 [Selvig 2012]. The embodied emissions are calculated spreadsheet-based with emission factors from the EMPA database “Ökologische Baustoffliste” by EMPA based on EcoInvent [Althaus 2011]. Therefore the boundary condition is cradle-to-gate. The inventories comprise only the ETCS, the flooring assembly and the involved primary load bearing structure (without foundations and basement) where the estimated lifetimes of the structure is 60 years and of the replaceable flooring layers 25 years [Klimagassregnskap 2013]. The changes in wall areas due to increased floor heights are not represented. Also the involved

technical systems such as sprinkler system and heating system in relation to installed power could not be taken into account. Emissions related to transport by truck and ship are only taken into account for the load bearing floor structure from the assumed production location ("huldekker" and brettstapel-elements "Norsk Massivtre" from Norway, Cross-laminated Timber from northern Sweden, "Lignatur" from Switzerland, "Kerto Ripa" and "Lignotrend" from Germany) to Mandal. Transport of in-situ concrete is not taken into because of the possibility of local production in Mandal.

Case studies

Performance criteria

Three key parameters can be identified which determine the choice and design of applicable ETCS in floor constructions: structural capacities, fire safety, and acoustic performance.

Structural dimensioning of timber floor constructions is performed according to NS-EN 1991-1-1 and NS-EN 1995-1-1 [BKS 1997] where the crucial requirement is usually related to serviceability. In Norwegian context a "comfort criteria" is defined as a deflection less than 1.3 mm due to a 1 kN point load with a natural frequency not lower than 8 Hz [Homb 2009]. The structural system of the "Ballastbrygga" project is built up of a module of ca. 8 x 12 m as the parking deck in the basement defines the distance of load bearing columns in longitudinal direction. Therefore, three structural systems have been investigated considering the module of the architectural design: spanning over 12 m from façade to façade, spanning over 8 m in longitudinal direction, and spanning 7+5 m across the buildings depth with an intermediate support. In the last two cases additional intermediate support (columns) are required. In addition, also the dimensions of primary structural system were estimated which comprises HEB-profiles as steel beams and steel columns. A timber structure as skeleton or load-bearing walls was not investigated in this study.

Fire safety regulations in the building code rate the building as fire class 3 since it rises up to 5 floors. Therefore the primary structural systems (columns, beams) must feature a fire resistance of R 90 A2-s1,d0 and the floor slabs and secondary structure (fill-in walls) R 60 A2-s1,d0 [DIBK 2013]. The fire class also requires that the structural system must withstand an entire course of fire and be restorable afterwards. Large cavities are not acceptable and must be filled or lined with fireproof material.

Acoustic performance of floor slabs is regulated by the Norwegian building code TEK10 requiring sound insulation class C according to NS 8175 [DIBK 2013]. Consequently, the component has to satisfy an airborne sound insulation level $R_w \geq 55$ dB and an impact sound insulation level $L_{n,W} \leq 53$ dB. Parquet is planned as flooring material for the case studies. With respect to preferred building methods only 'dry' constructions were considered for the ETCS.

Selected constructions

The chosen floor constructions are presented in table 3. Prefabricated hollow-core concrete elements ("huldekker") would normally be chosen to span the buildings depth of 12 m span and constitute the base case A. It requires no additional measures with respect to fire safety. Case A is an extra-heavy element type especially developed for residential blocks and can get by with minimal flooring to satisfy acoustic demands. Alternatively, case B spans over 8 m with a reduced element height yet with a higher flooring construction.

After a pre-analysis (see table 1) of the surveyed elements only CLT, assembled elements with boxed cross sections and timber-concrete-composites were chosen for further investigation of ETCS as they show comparable heights with the base case. The acoustic requirements entail additional measures. The considered solutions are a high raised floor (case C) and a heavyweight floor construction in cases D and E. Here gypsum boards or paviours have been used as heavyweight additional load. The same thin flooring which is used for alternative B could also used in case F because of the infill with grit and in case G due to the weight of the composite construction. Regarding fire proofing wooden surfaces are generally considered as D-s2,d0 [BKS 2009] and an active fire protection concept must be developed (installation of a sprinkler system, for example).

The estimated dimensions of the primary structure are considerable due to the wide spans of the beams and the large loads per column. However, compensating measures such as load bearing walls or halving the spans were not considered because of the fixed design of the parking layout in the basement.

Energy efficiency

Table 2 gives an overview of the different input values for façade areas and thermal bridges of the cases. The base case A does not reach the required normalised thermal bridge value in neither of the cases A1 or A2. A change of structural system with smaller columns or a different solution with columns independent from the façade would be required. The ETCS show slightly higher façade areas (up to 4 %) and longer thermal bridges yet reach the required values.

Calculated heating demands and total installed heating powers are presented in figure 2. In all cases the heating demand accounts for ca. 20 % of the total net-energy demand. The exterior walls account for ca. 8..9 % of the total heat loss and the thermal bridges for ca. 5,5..7 %. The base case cannot reach the required heating demand of 15 kWh/m²a with an integrated beam in the façade (case A1). However, assuming a similar detail at the edge of the slab also for case A (case A2) all cases show a heating demand of ca. 13,5 to 14 kWh/m²h with little variations. Case B with 13,5 kWh/m²a is hereby the lowest heating with significantly smaller façade areas and the lower required heating power. The differences within the ETCS are very minimal with advantages for systems with well insulating materials. However, the significance of thermal bridges in highly insulated buildings is evident when comparing the cases D and E. The lower heating demand in case D can be attributed to the lower thermal bridge value despite a larger façade area.

In a first approach to examine the heating loads a constant set point temperature and reduced internal gains were used, showing no differences between the case studies. When using a temperature set-back during the night, the necessary installed power of the space heating system differs significantly between the cases with “huldekker” and the ETCS. The cases A and B require ca. 400 kW (35 resp. 37 W/m²) installed total power. On the other hand, the cases with ETCS have ca. 500 kW (44 W/m²) space heating load. The differences between the ETCS are small since the same value heat storage capacity was used. The installed heating power of the ventilation system is in all cases ca. 42 kW (3,3 W/m²).

CO_2 emissions

Embodied emissions

Results of the inventories are presented in figure 3. Case A with “huldekker” marks the upper end of all investigated options. The other case with concrete, case B, together with case F have the lowest emissions (ca. 40 percent less emissions than case A). The ETCS of cases C, D, E, and G have ca. 15 percent less embodied emissions than the base case. The timber–concrete-composite G accounts as ETCS with the second lowest total emissions despite the use of reinforced concrete to a large extend. It should be taken into account that case A is a concrete element especially for residences and is 25 % heavier than its typical representative.

In the base case the emissions comprise 77 % of the load bearing floor structure, 7 % of flooring and 16 % of the primary skeleton. In cases with ETCS the percentage of the load bearing slab is in the range of 27–54 %. A larger portion of emissions in ETCS are connected to the flooring construction and the primary structure. Assessing only the floor construction, the emissions from ETCS are only 34–77 % of the base case. However, in cases C and G emissions are higher than case B with the same span. It is noteworthy that case G contains more concrete than B yet also utilises timber. The measures for sufficient sound insulation are evident in the emissions of the flooring construction. The use of additional mineral-based elements like concrete and gypsum in cases D and E leads to significant emissions. The flooring construction of case C with the same performance shows lower emissions despite the construction height being almost twice as high. Case F which uses grit as fill-in in the box elements to achieve sufficient weight shows the lowest emissions of the ETCS. The primary steel structure represents between 13 and 23 % of total emissions. Emissions are noticeably higher for cases with heavy weight (case A and G) and limited span (case C). However, the differences between the other cases are neglectable due to similarly dimensioned profiles.

Taking into account the transport of the ETCS elements has influence on the results. The dependency on distance from production locations is apparent in cases C, D, E, F with transport distances between 1300 and 1600 km. On the other hand, the production of concrete elements, concrete and brettstapel and in-situ concrete in relative proximity results in relatively less emissions. The influence of transport weight leads to increased emissions of the cases A, C, F. Consequently, the case C with Swedish CLT has even higher emissions than the base case.

Regarding the technical systems, the increase of installed power of ETCS would lead to larger dimensioned heating systems and therefore also to higher embodied emissions. Furthermore, the sprinkler system which is required for all ETCS for reasons of fire safety was not included in this inventory and would increase the emissions of ETCS.

Embodied + operational emissions

The combined embodied and operational emissions are presented in figures 4 and 5 showing that the compared emissions for heating demand and floor constructions are in a similar range. However, the differences between the case studies with respect to emissions of the heating demand are minimal (the operational emissions connected to the heating demand are ca. 13,5 % in all cases). Therefore the embodied emissions of the construction become decisive for the comparison and the ranking is similar as for embodied emissions only. The case with the lowest investigated total emissions is case F which has ca. 15 % lower emissions than the base case. The other ETCS have ca. 5 % lower emissions than the base case.

Discussion

ETCS require additional measures to reach the performance criteria regarding structural, acoustic, and fire safety performance compared to the conventional concrete-based system. They show greater dimensions despite shorter span both due to lesser structural capacities and to higher flooring constructions. The lightweight timber constructions require additional measures for acoustic performance e.g. infill, loads and heavy flooring. Also for fire proofing further steps must be taken especially with respect to the demand for fireproof surfaces. Active fire safety systems such as sprinkler systems must be installed for visible wooden surfaces if covering with additional fireproof materials is not desired.

The simulations of thermal bridges have shown better results for the ETCS to achieve the advanced requirements of concepts such as the passive house standard. Here concrete constructions require careful detailing to fulfil requirements on thermal bridges while ETCS seem more robust in comparable details. Little differences are evident between the investigated studies regarding heating demand. The advantages of lower thermal bridge values are counterbalanced by the disadvantages of larger surfaces and lower heat storage capacity. The case B with a slender concrete construction showed best performance with least surface and high mass. The comparison of required heating loads shows significant differences between concrete and ETCS. The lightweight timber constructions require ca. 25 % more installed heating power.

For cradle-to-gate boundary conditions the timber construction systems show no clear advantage despite having lower embodied emissions in the load bearing structure itself. However, it should be considered that the use of low-/ zero-carbon concrete might reduce the emission of the concrete by up to 40 % [Eng Kalbakk 2011]. A larger portion of emissions in ETCS are connected to the flooring construction and the primary construction which require additional measures to compensate for the drawbacks of timber construction. This counteracts the reduced emission from the use of timber in the load bearing system. Especially materials with high emissions such as concrete, gypsum boards, and insulation increase the emissions while the use of a 'natural material' such as grit in case F shows very low emissions. Despite this special case ETCS which have otherwise similar results which might vary in other combinations of assemblies (e.g. CLT with grit as additional load). Emission from transport have a big impact especially when elements have heavy weight (A, C, F) or have to be transported over long distances (C, D, E, F). In the chosen framework of combining emissions from the floor construction with the emissions connected with heating demand the embodied emissions have proven to be more relevant for the assessment.

Conclusions

Selected floor constructions have been investigated with respect to energy demand and embodied emissions. Further work is necessary to include the specific aspects of the investigated systems to achieve a more refined and conclusive result. For the emission inventories optimised structural systems for each case study should be considered more detailed and the inventories expanded to the entire structural system (foundations, etc.). Emissions from transport are relevant for elements when transported over long distances or with heavy weight and should be investigated more carefully. Also the inclusion of technical systems into the assessment of embodied emissions is necessary for a conclusive comparison. Further investigations should also include the cooling loads in a summer situation to assess the indoor environment as an additional criteria.

Figures & tables

options	*12 m span*	*8 m span*	*7 + 5 m span*
Huldekke (HD element + avretting)	320 + 20 mm©	220 +20 mm©	220 +20 mm©
truss beams	–	550 mm©	450 mm©
CLT	–	–	259 mm©
“Kerto Ripa Kastenelement”	402 mm*	390 mm#	302 mm#
“Kerto Ripa Rippenelement”	501 mm*	470 mm#	393 mm#
“Lignatur LFE”	–	320 mm#	280 mm#
“Lignotrend Block Q3”	415 mm*	335 mm$	309 mm$
“Lignotrend Rippe Q3”	–	375 mm$	309 mm$
“HBV-System” (brettstapel C24 + concrete C20/25)	220 + 130 mm*	220 + 150 mm$	170 + 120 mm$
“SFS HBV” (brettstapel C24 + concrete C20/25)	–	240 + 140 mm#	195 + 105 mm#

* w_fin = l/200 # w_G,inst + w_Q,inst < 6 mm (DIN 1052) $ v < b, min f_1 < 8Hz (EC 5) © product data sheet

Table 1 Overview over dimensioned elements

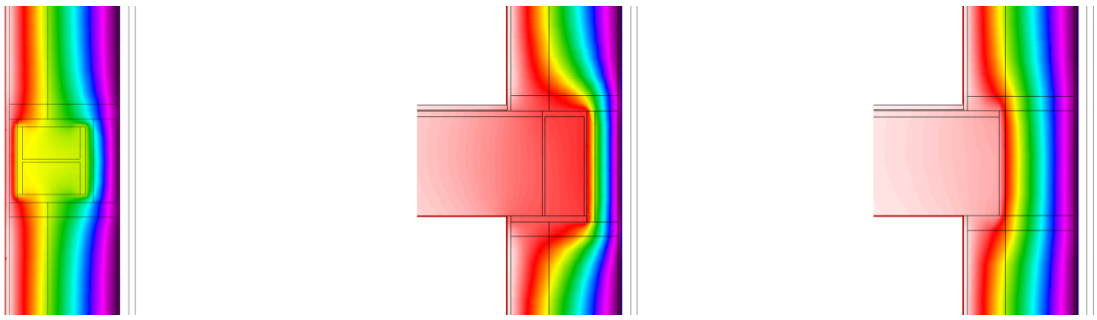


Figure 1 Thermal bridges (for case A): wall-integrated column (left) wall-integrated load-bearing beam (middle, case A1), slab spans parallel to façade without beam (right, case A2)

case study	*edge of floor slab*		*columns*		*windows*		*normalised thermal bridge value*
	length [m]	*value [W/mK]*	*length [m]*	*value [W/mK]*	*length [m]*	*value [W/mK]*	*[W/m²K]*
A1	2780.0	0.144	780.0	0.076	10000.0	0.020	0.059
A2	2780.0	0.051	780.0	0.076	10000.0	0.020	0.036
B	2780.0	0.044	766.3	0.063	10000.0	0.020	0.033
C	2780.0	0.021	799.2	0.045	10000.0	0.020	0.026
D	2780.0	0.020	809.5	0.045	10000.0	0.020	0.026
E	2780.0	0.034	793.9	0.055	10000.0	0.020	0.030
F	2780.0	0.030	787.6	0.055	10000.0	0.020	0.029
G	2780.0	0.038	795.4	0.063	10000.0	0.020	0.032

Table 2 Overview over thermal bridge values

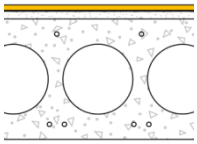
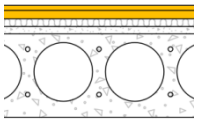
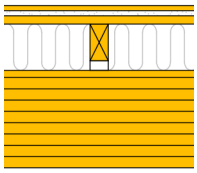
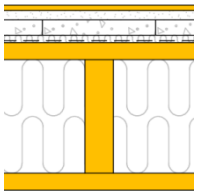
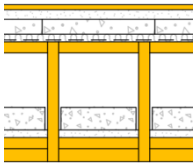
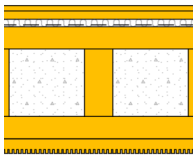
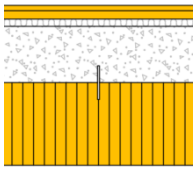
case	*name*	*drawing*	*layers*	*dim.*	*performance*	*prim. structure*
A	**Huldekke** **12 m span**		parquet 14 mm expanded PE 3 mm levelling concrete 20 mm HD 320 320 mm	height: 357 mm weight: 570 kg/m²	fire: REI 60 acoustic: $L_{n,w}$ = 52 dB R_w = 56 dB	beams: HEB 320 (8 m span) columns: HEB 220
B	**Huldekke** **8 m span**		parquet 14 mm particleboard 22 mm acoustic insulation 20 mm levelling concrete 20 mm HD 220 220 mm	height: 296 mm weight: 377 kg/m²	fire: REI 60 acoustic: $L_{n,w}$ = 52 dB R_w = 55 dB	beams: HEB 280 (7 m span) colums: HEB 200
C	**Cross-laminated timber (CLT)** **7 m span**		parquet 14 mm gypsum floorboard 13 mm particleboard 22 mm mineral wool 123 mm + batten 48x98 + green sylomer 45x40x25 CLT 259 mm	height: 431 mm weight: 173 kg/m²	fire: REI 60 + sprinkler acoustic: $L_{n,w}$ = 53 dB R_w = 60 dB	beams: HEB 260 (8 m span) columns: HEB 160
D	**Kerto Ripa** **8 m span**		parquet 14 mm 2 x gypsum 25 mm floorboard paviours 40 mm acoustic insulation 20 mm PE-foil 0,2 mm Ripa box-element 390 mm + rockwool infill	height: 489 mm weight: 193 kg/m²	fire: REI 60 + sprinkler acoustic: $L_{n,w}$ = 49 dB R_w = 68 dB	beams: HEB 260 (7 m span) columns: HEB 160
E	**Lignatur** **8 m span**		parquet 14 mm 2 x gypsum 25 mm floorboard paviours 40 mm acoustic insulation 20 mm PE-foil 0,2 mm LFE element 320 mm + "silence" inlay	height: 419 mm weight: 271 kg/m²	fire: REI 60 + sprinkler acoustic: $L_{n,w}$ = 49 dB R_w = 68 dB	beams: HEB 260 (7 m span) columns: HEB 180
F	**Lignotrend Block** **8 m span**		parquet 14 mm particleboard 22 mm acoustic insulation 20 mm PE-foil 0,2 mm Block Q3 335 BV 335 mm + blown in grit	height: 391 mm weight: 296 kg/m²	fire: REI 60 + sprinkler acoustic: $L_{n,w}$ = 49 dB R_w = (57) dB	beams: HEB 260 (7 m span) columns: HEB 180
G	**HBV-System** **8 m span**		parquet 14 mm particleboard 22 mm acoustic insulation 20 mm PE-foil 0,2 mm reinforced concrete 150 mm brettstapel 220 mm	height: 426 mm weight: 530 kg/m²	fire: REI 60 + sprinkler acoustic: $L_{n,w}$ = 46 dB R_w = 60 dB	beams: HEB 280 (7 m span) columns: HEB 200

Table 3 Investigated cases

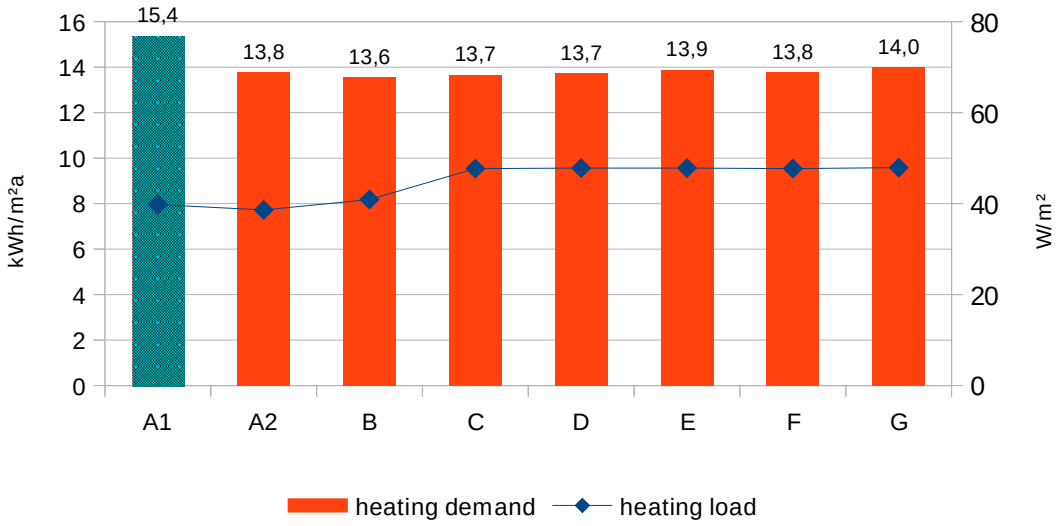


Figure 2 Heating demand and total heating power

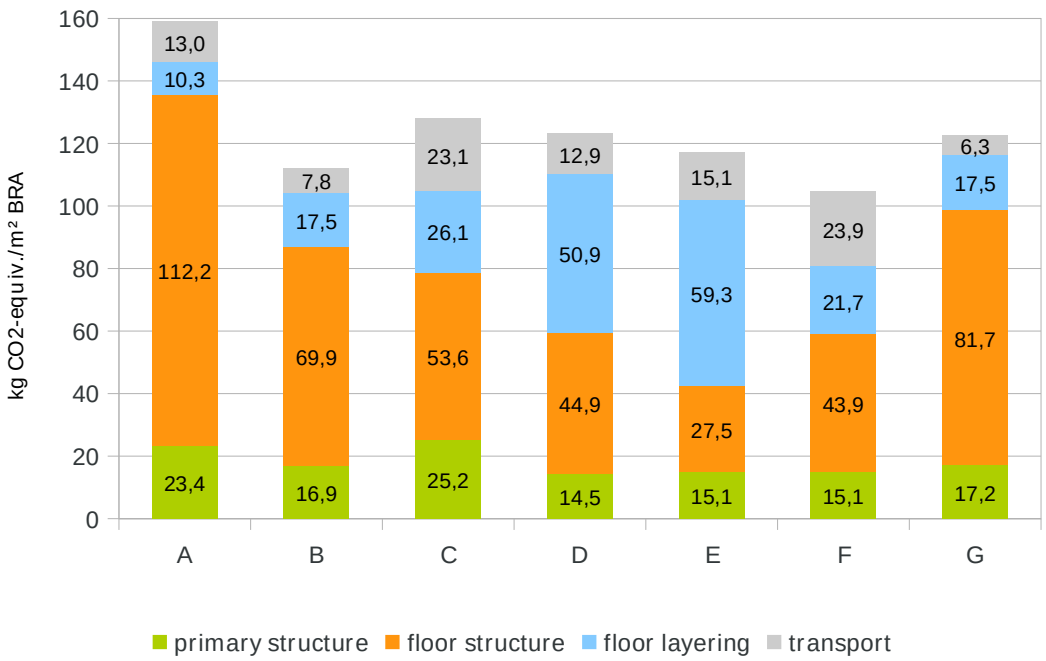


Figure 3 Embodied emissions

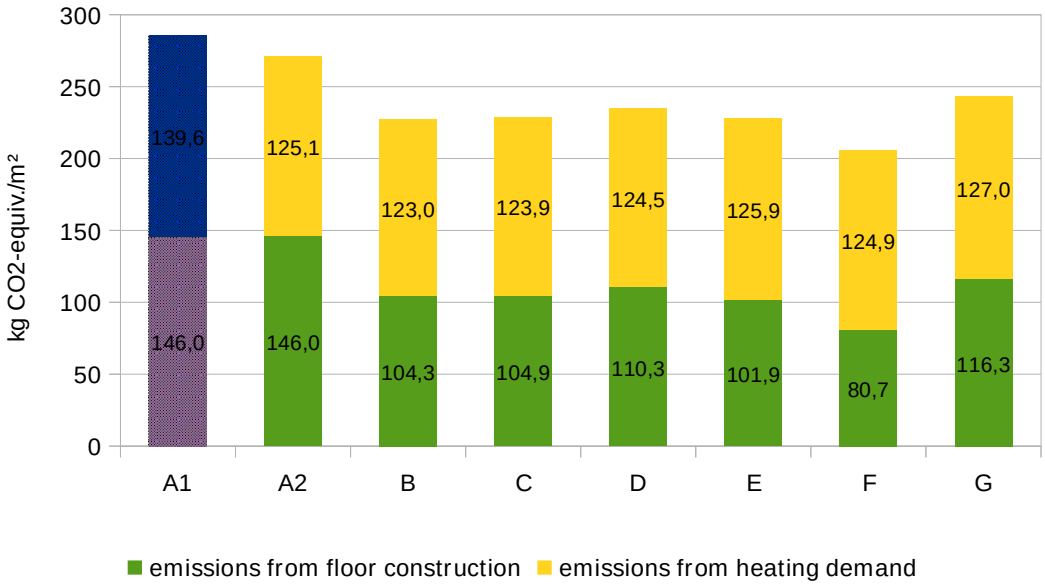


Figure 4 Embodied and operational GHG-emissions (without emissions from transport of elements)

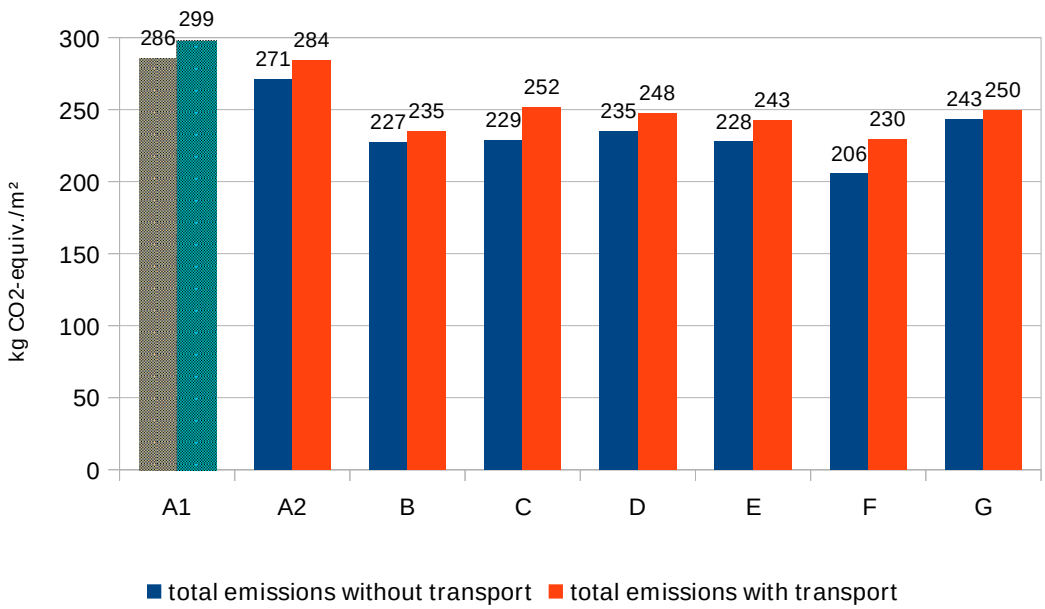


Figure 5 Total emissions without and with transport of structural floor construction

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