CZECH TECHNICAL UNIVERSITY IN PRAGUE

Faculty of Civil Engineering

Department of Building Structures

MASTER'S THESIS

ENVIRONMENTAL IMPACTS OF DESIGN ALTERNATIVES FOR A RETIREMENT HOME IN HOROMĚŘICE, CZECH REPUBLIC

Author: Bc. Vít Verner

Supervisor: Dipl.-Ing. Patricia Schneider-Marin, Architektin
Ing. Antonín Lupíšek, Ph.D.

ČESKÉ VYSOKÉ UČENÍ TECHNICKÉ V PRAZE
Fakulta stavební
Thákurova 7, 166 29 Praha 6

ZADÁNÍ DIPLOMOVÉ PRÁCE

I. OSOBNÍ A STUDIJNÍ ÚDAJE

Příjmení: Verner Jméno: Vít Osobní číslo: 424624

Zadávající katedra: K124 - Katedra konstrukcí pozemních staveb

Studijní program: Budovy a prostředí

Studijní obor: Budovy a prostředí

II. ÚDAJE K DIPLOMOVÉ PRÁCI

Název diplomové práce: Environmentální dopady variant návrhu domova pro seniory v Horoměřicích

Název diplomové práce anglicky: Environmental Impacts of Design Alternatives for a Retirement home in Horoměřice, Czech Republic

Pokyny pro vypracování:
Rámcový obsah práce:
- Popis metodiky LCA
- Rešerše srovnávacích LCA studií
- Popis základní varinaty dle návrhu architekta
- Vyhodnocení základní varinaty
- Návrh alternativních varinat provedení a jejich vyhodnocení
- Porovnání variant a výběr optimálního řešení z hlediska environmentálních dopadů
- Vybrané části projektové dokumentace: půdorys jednoho podlaží, jeden svislý řez, komplexní řez jednou fasádou nebo vybrané kritické detaily

Seznam doporučené literatury:

Jméno vedoucího diplomové práce: Ing. Antonín Lupíšek, Ph.D.

Datum zadání diplomové práce: 24.9.2019 Termín odevzdání diplomové práce: 5.1.2020 (KOS)
Údaj uveďte v souladu s datem v časovém plánu příslušného ak. roku

Podpis vedoucího práce Podpis vedoucího katedry

III. PŘEVZETÍ ZADÁNÍ

Beru na vědomí, že jsem povinen vypracovat diplomovou práci samostatně, bez cizí pomoci, s výjimkou poskytnutých konzultací. Seznam použité literatury, jiných pramenů a jmen konzultantů je nutné uvést v diplomové práci a při citování postupovat v souladu s metodickou příručkou ČVUT „Jak psát vysokoškolské závěrečné práce“ a metodickým pokynem ČVUT „O dodržování etických principů při přípravě vysokoškolských závěrečných prací“.

Datum převzetí zadání Podpis studenta(ky)

I, the undersigned, declare that this thesis is my original work created under supervision of Dipl.-Ing. Patricia Schneider-Marin, Architektin and Ing. Antonín Lupíšek, Ph.D. I declare that all used sources are listed below in accordance with ethical codes of the Czech Technical University in Prague.

In Prague, 5. 1. 2020

……………………………………
Vít Verner

I would like to acknowledge the valuable expertise, inputs and guidance from Dipl.-Ing. Patricia Schneider-Marin, Architektin (Technical University of Munich) and Ing. Antonín Lupíšek, Ph.D. (Czech Technical University in Prague).

ABSTRACT

The master’s thesis deals with the environmental impacts of design alternatives for the Retirement Home in Horoměřice, Czech Republic using the life cycle assessment.

State of the art of the LCA and multiple case studies were reviewed. Methodology of the LCA used in this study was specified. Three design alternatives of the retirement home were analyzed—the original architectural study with a reinforced concrete frame structural system, a modified design with a reinforced concrete and sand-lime wall system, and a new design with a reinforced concrete and cross-laminated timber wall system.

A “cradle-to-gate” (A1 - A3) LCA was carried out based on two input data sources and weighting was applied. Although the results of the analysis vary depending on the source, the overall weighted ranking of all alternatives remains the same. The timber alternative performs significantly better than both the sand-lime modification and the original design.

KEY WORDS

life cycle assessment, environmental impacts, reinforced concrete, sand-lime masonry, cross-laminated timber

TABLE OF CONTENTS

1. LIST OF ABBREVIATIONS AND DEFINITIONS

ADPF	Abiotic Resource Depletion Potential of Fossil Fuels
AP	Acidification Potential
CF	Characterization Factor
CLT	Cross-laminated Timber
EP	Eutrophication Potential
EPD	Environmental Product Declaration
GHG	Greenhouse gasses
GLT	Glue-laminated Timber
GWP	Global Warming Potential
LCA	Life Cycle Assessment / Analysis
LCIA	Life Cycle Impact Assessment / Analysis
ODP	Ozone Layer Depletion Potential
PEI_n	Non-renewable Primary Energy Demand
PEI_{TOTAL}	Total Primary Energy Demand
POCP	Photochemical Ozone Creation Potential
RC	Reinforced Concrete
USCS	Unified Soil Classification System

2. INTRODUCTION

2.1. CONSTRUCTION AND ENVIRONMENT

Discussions about impacts of human actions on the environment have intensified worldwide throughout past decades. The levels of greenhouse gasses (GHG) emissions, most notably carbon dioxide, nitrous oxide and methane, have skyrocketed in the last 70 years (Figure 2.1) forcing the climate to change [1]. To confine this change in sustainable bounds the production of GHG has to be substantially reduced.

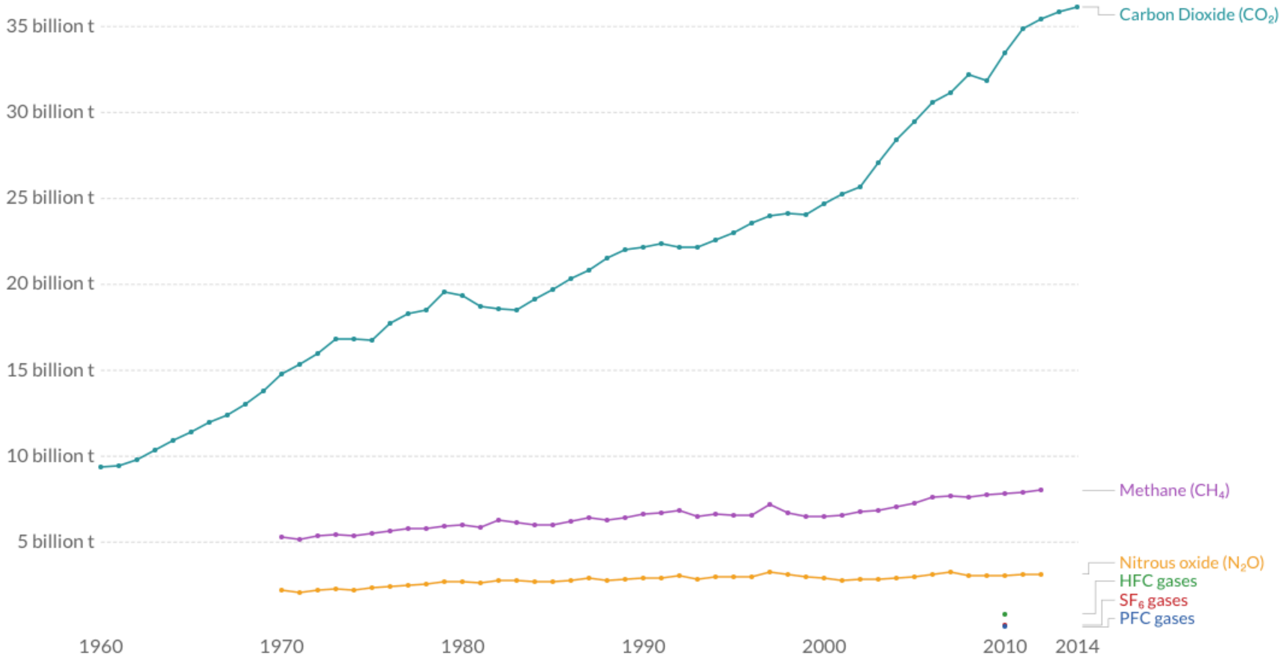


Figure 2.1. World greenhouse gas emissions by gas. [2]

Construction industry alone makes up a significant part of GHG production (Figure 2.2) and it is therefore crucial to implement environmentally friendly design strategies into practice.

As seen in Figure 2.2, CO_2 emissions produced in order to ensure operation of buildings are more than twice the size of the embodied emissions of the structures and construction processes. This ratio (especially in developed countries) has been increasing slowly [8], as ever more modern buildings require less energy to operate among others due to greater thermal insulation usage and technological improvements such as increased efficiency of building systems. Figure 2.3 shows how a correlated ratio of energy consumption in construction has evolved in the Czech Republic, specifically.

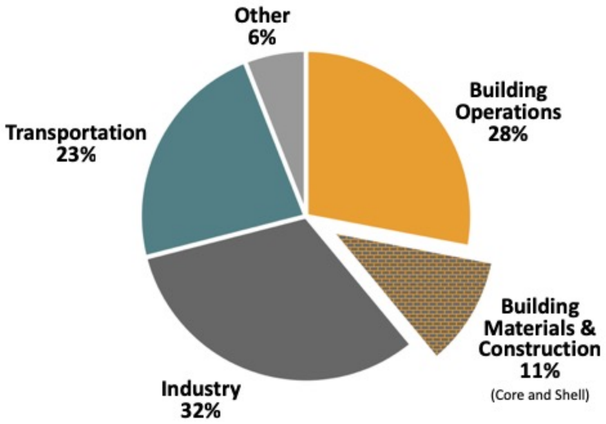
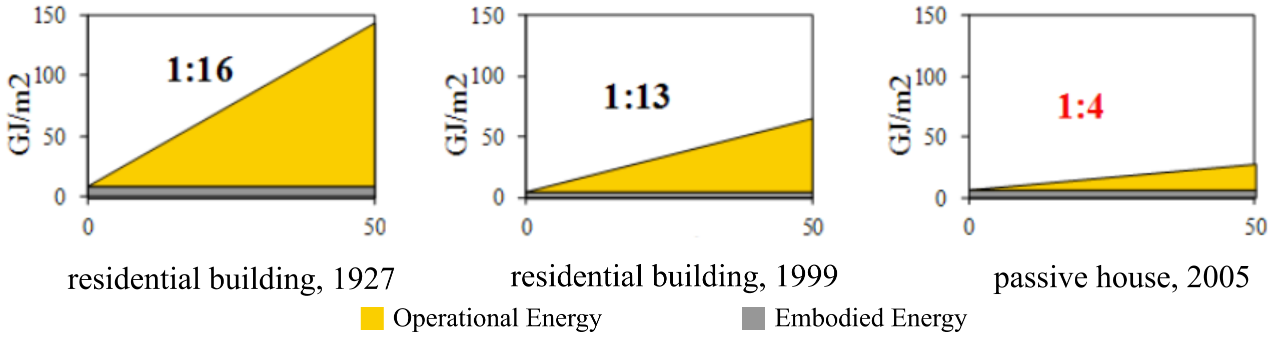


Figure 2.2. Global CO_2 emissions by sector, 2018. [3]



residential building, 1927

residential building, 1999

passive house, 2005

🟨 Operational Energy ⬛ Embodied Energy

Figure 2.3. Energy consumption for building construction and operation in the Czech Republic. [4]

The recent reduction in operational energy is evident. This fact brings the embodied energy (and embodied environmental indicators) in the spotlight as it now represents a significant percentage of energy usage in the construction sector.

2.2. GOAL OF THE THESIS

This thesis is a contribution to the research on optimum life cycle assessment (LCA) design of a building in terms of its environmental impacts. It deals with a case study of the Retirement Home in Horoměřice, Czech Republic.

The original study [5] by Barbora Šádková was created in 2017 with emphasis on architectural design. It was later modified in *Bearing Structure of Retirement Home in Horoměřice* [6] with respect to operational aspects (flat units vs. facilities), selected indoor-environment-comfort criteria and environmental criteria. In both mentioned cases, compromises were made, some of which at the cost of increasing the environmental footprint of the design.

The goal of this thesis is to evaluate and compare the original, modified and other design alternatives of the retirement home using the LCA focusing on embodied environmental indicators only.

3. LCA: STATE OF THE ART

The Life Cycle Assessment represents a method to evaluate the environmental impacts of any process carried out by mankind—creation and usage of construction materials included. It is an important tool used to quantify environmental impacts of (existing or proposed) structures and thus to support decision-making for sustainable building designs.

The process of LCA consists of four components [16]:

- goal and scope definition,
- life cycle inventory analysis,
- life cycle impact assessment,
- assessment results interpretation.

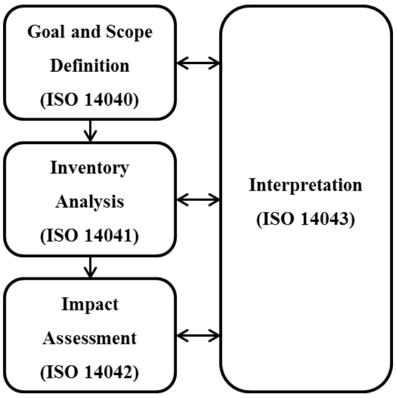


Figure 3.1. LCA components. [22]

3.1. GOAL AND SCOPE DEFINITION

3.1.1. GOAL DEFINITION

The definition of **LCA goals** is the very first and important part of the analysis. It determines and guides the choices made in later phases. According to EN ISO 14040 [17], the goal of the study should define:

- the intended application and the reason for carrying out the study,
- the intended audience,
- whether the result is intended to be used in comparative assertions disclosed to the public.

Based on these points the scope of the life cycle assessment will then be determined.

3.1.2. SCOPE DEFINITION

The definition of the LCA scope describes the detail and depth of the analysis. It should also show, that the goal set earlier may be met with the chosen scope. The most important aspects when defining the scope are as follows [18]: functional unit, system boundaries, allocation methods, assumptions and limitations, data quality requirements and impact categories.

Functional unit defines what is being studied and facilitates the possibility of comparison of different products. When analyzing building materials, for example, commonly used functional units are 1 kg or 1 m^3 of given material or in case of complete buildings 1 m^2 of living area.

System boundaries define which processes and activities are included in the assessment. The selection of these depends on the goal of the study. As production processes are often connected, a clear definition of included and excluded activities is required. Exclusion of certain processes (“cut-offs”) are possible based on the goal of the analysis:

“*For example, in an LCA of a product the construction of the production site and capital equipment is often excluded due to the fact that this is assumed to have a small impact on the overall result.” [18]*

Another example of this sort might be the consideration of depreciation of machines that are designed for the extraction and transport of primary raw materials [15].

Figure 3.2 shows all stages and modules of any product’s life: product stage, construction process stage, use stage, end-of-life stage and product reuse/recycling stage. Based on the selected scope the assessment may consider the whole life cycle of the product (modules A1 - D) or only a part of it.

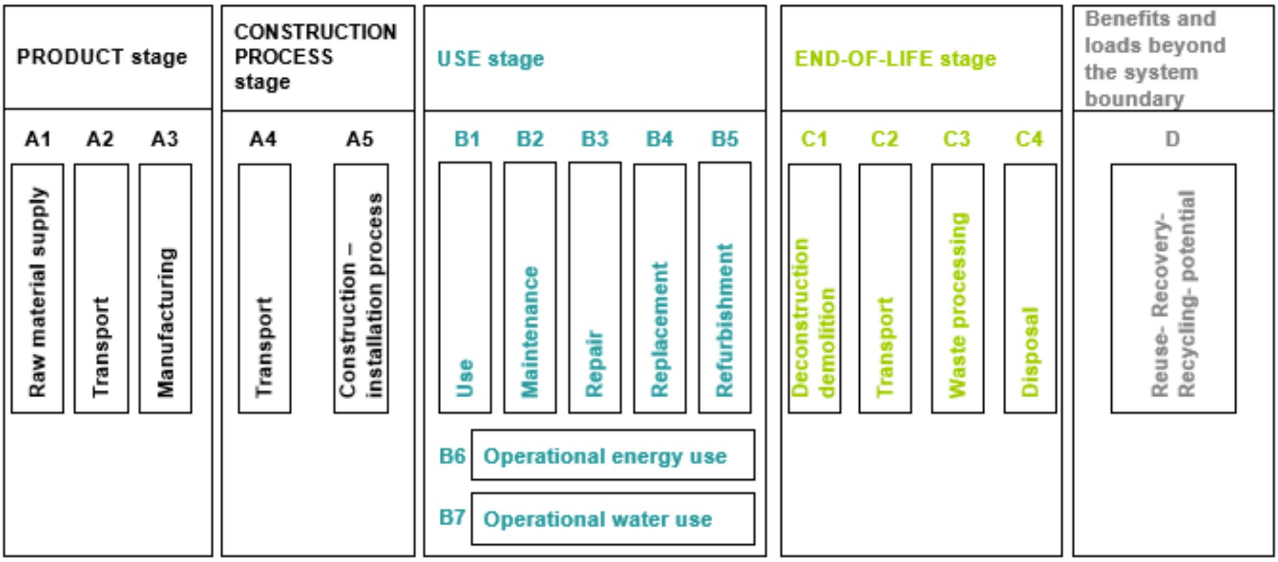


Figure 3.2. Life cycle assessment stages. [7]

Typical examples of LCA systems are as follows:

- A1 - A3: “Cradle-to-Gate” only product stage is considered,
- A1 - A4: “Cradle-to-Site” product stage and transportation to building site are

considered,

- A1 - A5: ”Cradle-to-Installation” product and construction process stages are considered,
- A1 - D: “Cradle-to-Grave” all stages are considered.

Allocation refers to the partition of environmental loads of a process used to create multiple products. Allocation method needs to be specified in a manner ensuring that only an appropriate portion of the environmental load is considered in analysis of each product.

Due to complexity of the assessment, various **assumptions** often have to be made. The nature of these assumptions and choices such as system boundary setting, selection of data sources and impact categories may be subjective [17]. Therefore it is essential that they are transparent and, most importantly, the same for all compared alternatives of the analyzed product.

Data quality requirements address among others [17]:

- time-related coverage,
- geographical coverage,
- technology coverage,
- precision, completeness and representativeness of the data,
- sources of the data,
- uncertainty of information.

Environmental **Impact categories** are selected, again, based on the goal of the analysis. They may be divided into groups with respect to the type of impact they contribute to. Figure 3.3 presents these categories and their environmental impacts.

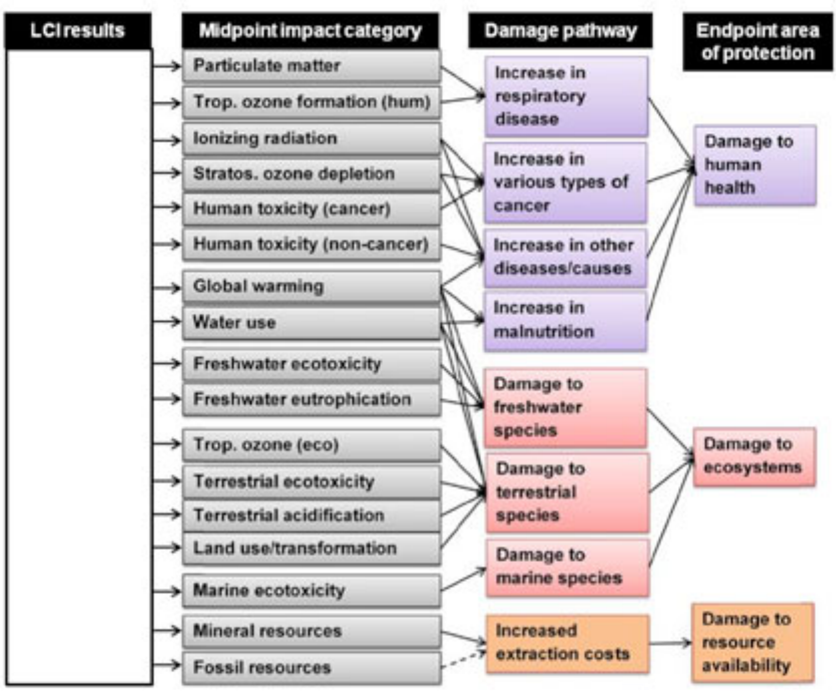


Figure 3.3. Environmental impact categories. [21]

3.2. LIFE CYCLE INVENTORY ANALYSIS

Life cycle inventory analysis is a process of compiling and quantifying all material and energy flows in the assessed system. It involves data collection and calculation procedures to quantify relevant inputs and outputs [17]. These procedures may differ with regards to the goal and scope of the LCA. Figure 3.4 shows a simple flowchart of a product system that may be developed for better understanding of the product system while defining system boundaries, and also during the phase of inventory analysis.

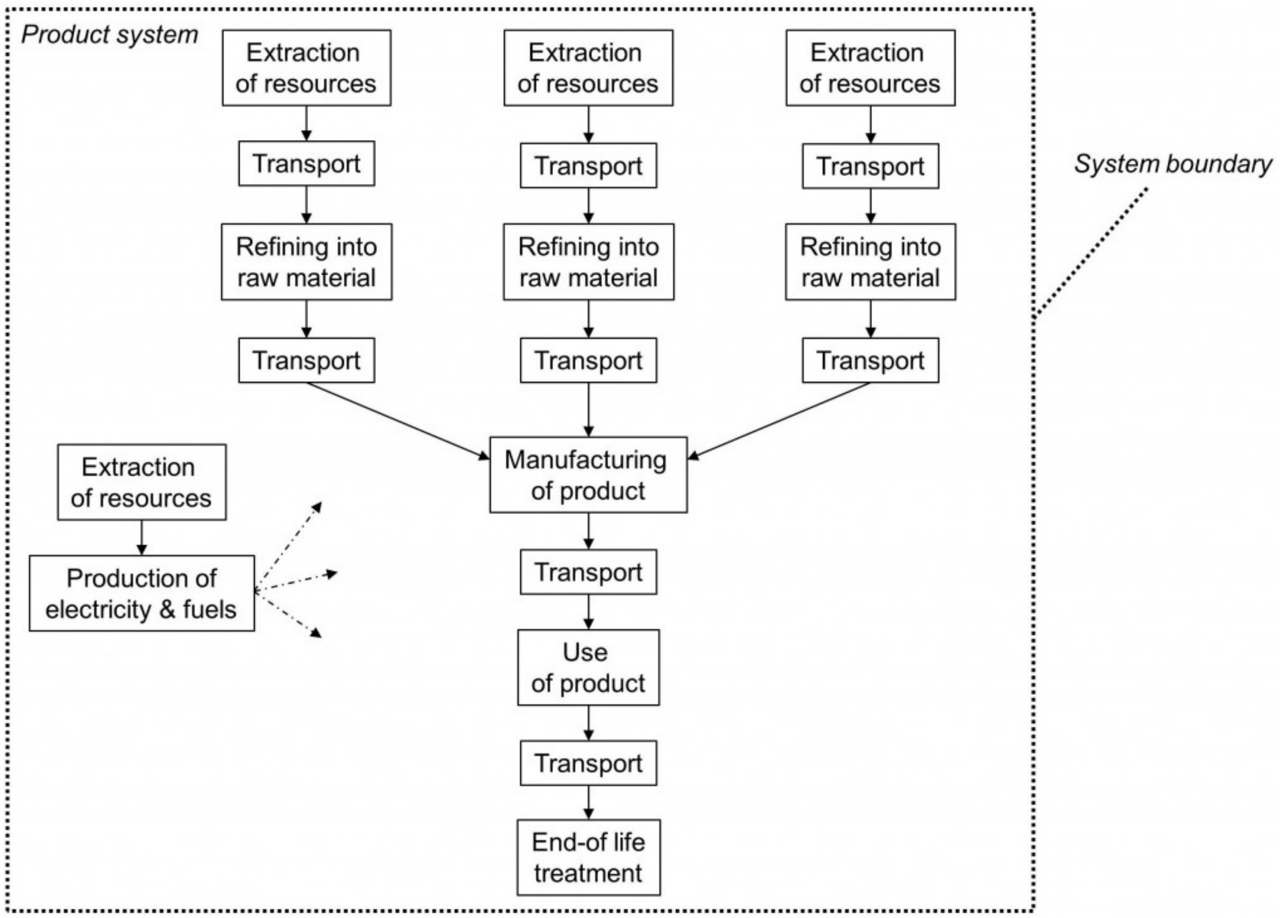
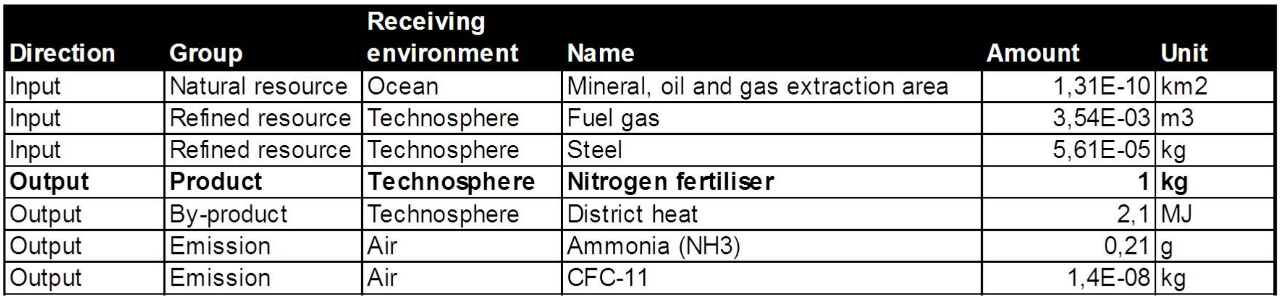


Figure 3.4. Product system flowchart. [19]

Apart from the allocation methods described above, the calculation of energy flow shall be considered while taking into account the different fuels and electricity sources used, the efficiency of conversion and distribution of energy flow as well as the inputs and outputs associated with the generation and use of that energy flow [17].

Figure 3.5 presents a small segment of a completed life cycle inventory analysis of a nitrogen fertilizer.



Direction	Group	Receiving environment	Name	Amount	Unit
Input	Natural resource	Ocean	Mineral, oil and gas extraction area	1,31E-10	km2
Input	Refined resource	Technosphere	Fuel gas	3,54E-03	m3
Input	Refined resource	Technosphere	Steel	5,61E-05	kg
Output	**Product**	**Technosphere**	**Nitrogen fertiliser**	**1**	**kg**
Output	By-product	Technosphere	District heat	2,1	MJ
Output	Emission	Air	Ammonia (NH3)	0,21	g
Output	Emission	Air	CFC-11	1,4E-08	kg

Figure 3.5. Life cycle inventory analysis example. [23]

3.3. LIFE CYCLE IMPACT ASSESSMENT

The process of LCIA involves assigning of the inventory data to specific environmental impacts. According to EN ISO 14040 [17] it consists of several mandatory and optional stages [15, 24, 25]:

Mandatory stages:

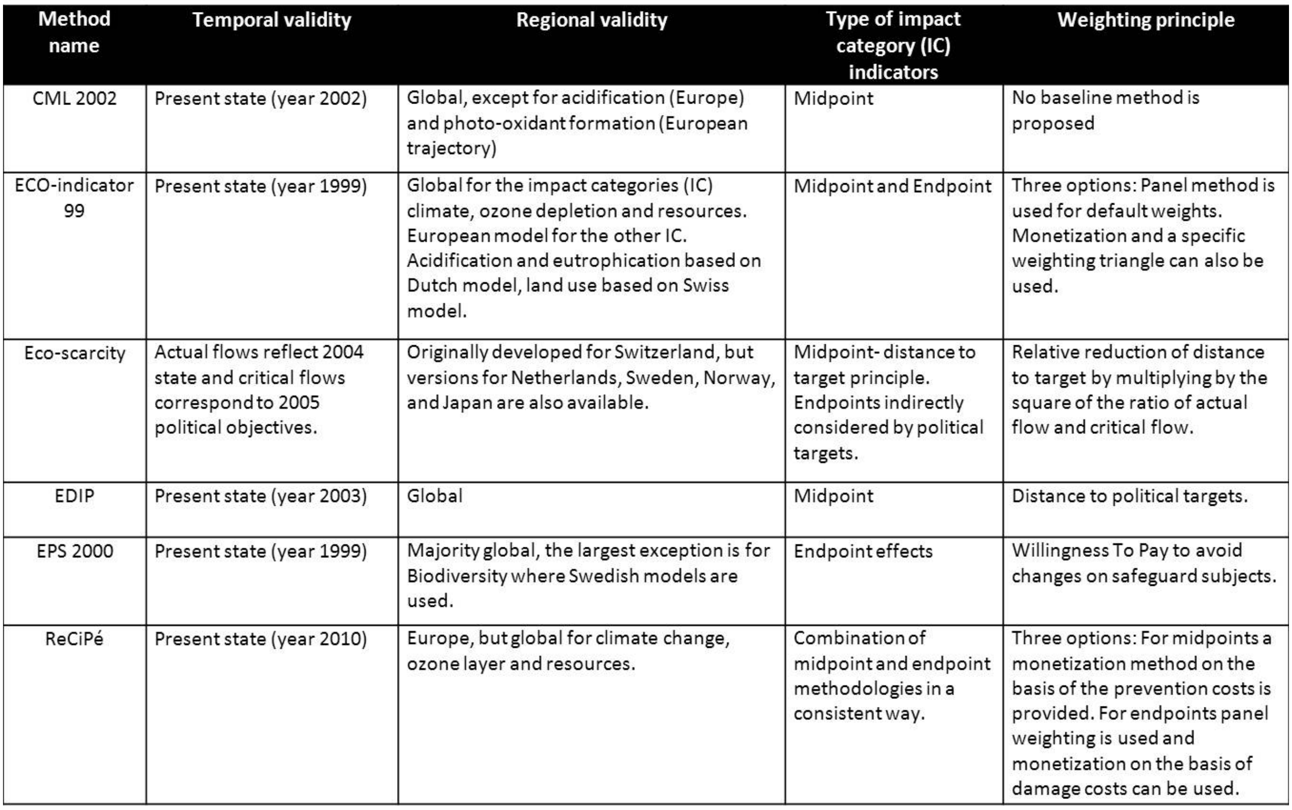
- **Selection of impact categories, category indicators and characterization models**. Environmental impact categories and midpoint indicators are selected with respect to the goal and scope of the analysis (3.1.2). An iterative process of reviewing the goal and scope may be required if the assessment infers they cannot be met.
- **Classification**. Inventory parameters are sorted and associated with specific environmental impacts.
- **Characterization**. Inventory results are converted to common equivalence units using appropriate characterization factors (CFs). CFs indicate the relative contribution of evaluated substances to each impact category. For many impact categories, however, these factors are not directly available. They are often extracted from models, either existing or self-constructed [16] (see also impact assessment methods below).

Optional stages:

- **Normalization**. The quantified impact results are compared to a certain reference value. For example new product to old product or to regional average.
- **Grouping**. For the purpose of result interpretation, the environmental impacts are sorted and grouped with regards to e. g. geographic relevance.
- **Weighting**. The results for each impact category are assigned an importance value—weight. Specific categories may then be considered more significant than others. Applying weights also facilitates an overall performance comparison based on multiple impact categories. This,

however, may also lead to substantially different results of the assessment depending on the considered weighting set. It is recommended that the selection of the weighting set shall be described in the scope definition and shall not be changed at any later stage of the study [26].

Figure 3.6 lists several examples of existing impact assessment methods. These are often used in practice, as most of the choices in the assessment are already implied (selection of impact categories, category indicators, etc.) and models for characterization and weighting are described.



Method name	Temporal validity	Regional validity	Type of impact category (IC) indicators	Weighting principle
CML 2002	Present state (year 2002)	Global, except for acidification (Europe) and photo-oxidant formation (European trajectory)	Midpoint	No baseline method is proposed
ECO-indicator 99	Present state (year 1999)	Global for the impact categories (IC) climate, ozone depletion and resources. European model for the other IC. Acidification and eutrophication based on Dutch model, land use based on Swiss model.	Midpoint and Endpoint	Three options: Panel method is used for default weights. Monetization and a specific weighting triangle can also be used.
Eco-scarcity	Actual flows reflect 2004 state and critical flows correspond to 2005 political objectives.	Originally developed for Switzerland, but versions for Netherlands, Sweden, Norway, and Japan are also available.	Midpoint- distance to target principle. Endpoints indirectly considered by political targets.	Relative reduction of distance to target by multiplying by the square of the ratio of actual flow and critical flow.
EDIP	Present state (year 2003)	Global	Midpoint	Distance to political targets.
EPS 2000	Present state (year 1999)	Majority global, the largest exception is for Biodiversity where Swedish models are used.	Endpoint effects	Willingness To Pay to avoid changes on safeguard subjects.
ReCiPé	Present state (year 2010)	Europe, but global for climate change, ozone layer and resources.	Combination of midpoint and endpoint methodologies in a consistent way.	Three options: For midpoints a monetization method on the basis of the prevention costs is provided. For endpoints panel weighting is used and monetization on the basis of damage costs can be used.

Figure 3.6. Examples of existing impact assessment methods. [25]

To perform an LCIA of a building design, existing software or databases are used. These contain ready to use LCIA (and in some cases also inventory analysis) results for building materials and products. Some of the databases are listed below:

- Ecoinvent (Switzerland),
- Envimat (Czech Republic),
- Ökobaudat (Germany),
- IBO Baustoffdatenbank (Austria),
- INIES (France),
- ICE (United Kingdom).

Datasets from these databases may, however, differ drastically depending on LCA methodology used—as described above. These differences may be caused by the definition of the LCA scope—common problematic questions deal with, among others [10]:

- which production processes will be included in the assessment,
- if and how to include the transportation of analyzed products,
- how to include maintenance, refurbishment or replacement of used products,
- how to include the recycling of used products with regards to future recycling technologies.

Data from these databases vary also with regards to location, as individual countries or areas differ in distinctive production technologies, accounted transportation distances, sources of energy production and the recency of the data [4].

Figure 3.7 illustrates the differences mentioned above on a specific example—a comparison of LCIA results of wood fibre insulation board based on the Ecoinvent [11] and Ökobaudat [29] databases. The values are harmonized on the basis of Ecoinvent results. While some indicators remain fairly similar, substantial differences occur in the PEIn and GWP impact categories. Global warming potential indicator, especially, points out the distinction of LCA scopes used, suggesting unlike system boundaries.

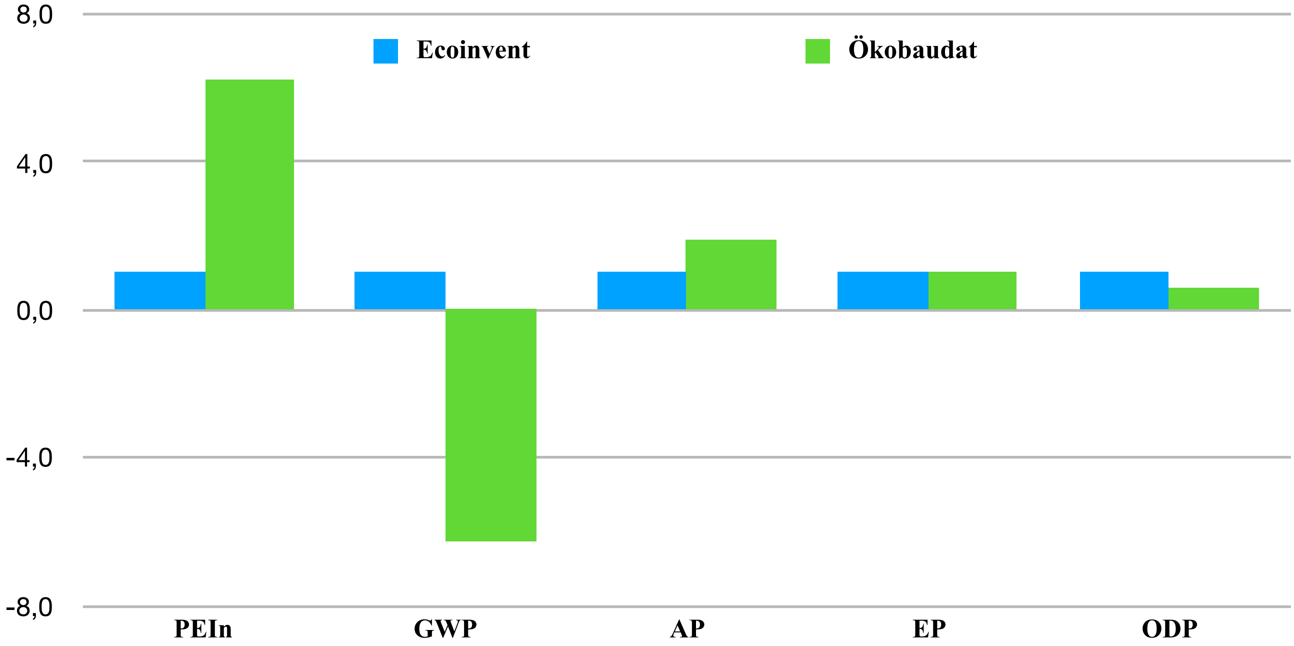


Figure 3.7. Comparison of LCIA results of wood fibre insulation board based on different LCIA datasets. Values are harmonized to Ecoinvent dataset.

When assessing the environmental impacts it is therefore crucial to use only data from sources that are based on identical LCA methodology as well as location.

3.4. ASSESSMENT RESULTS INTERPRETATION

The goal of the interpretation phase of LCA is to reach valid conclusions and recommendations based on the combined results of life cycle inventory analysis and life cycle assessment. These should be in accordance with the goal and scope of the study which was set (and possibly modified) in the earlier stages. Interpretation of results should be well documented and transparent.

The interpretation phase consists of three main elements [27]:

- **Identification of significant issues**. Most impactful items of both inventory analysis and impact assessment are pointed out.
- **Evaluation of results**. Completeness and consistency check and sensitivity analysis are carried out. In order to obtain valid LCA results, it is crucial not to omit any substantial processes when defining the system boundaries (3.1.2). Especially in case of comparative studies, it is of upmost importance for all studies to be consistent, following the same methodology. Sensitivity analysis is conducted to determine which items of the inventory or impact assessment notably influence the results. The scope of the LCA may then be modified again if required—for example, if the high-impact data considered in the inventory analysis stage were not accurate enough and now present significant uncertainties.
- **Conclusions and recommendations** are made based on the evaluated results.

4. CASE STUDIES RESEARCH

Multiple LCA studies from various geographical areas have been reviewed in order to create viable design alternatives of the retirement home that are to be evaluated.

4.1. COMPARATIVE LCA OF STRUCTURAL SYSTEM ALTERNATIVES

This study [12] examines the potential of reducing greenhouse gas emissions by substituting multi-story steel and concrete buildings with timber structures. LCA was applied to compare the global warming potential of a reinforced concrete structure with a corresponding timber structure for building heights of 3, 7, 12 and 21 storeys.

Existing reinforced concrete structures were chosen. Timber alternatives to those structures were then dimensioned to meet the same loading conditions. The structures were also designed with the same footprint areas and building heights. Figure 4.1 shows the specifications of considered buildings.

	3	7	12	21
Location	USA	USA	USA	Trondheim, Norway
Design wind speed	67 m/s	67 m/s	67 m/s	26 m/s
Live load	2.4 kN/m2	2.4 kN/m2	2.4 kN/m2	2-3 kN/m2
Storey height	3.66 m	3.66 m	3.66 m	3.4 m
Building height	12 m	26.5 m	44.8 m	76 m
Gross floor area	2613 m2	6097 m2	10542 m2	11823 m2

Material	RC structures				Timber structures			
	3	7	12	21	3	7	12	21
Concrete C25/30 (m^3)	925	2031	3436	0	23	174	261	718
Concrete C35/45 (m^3)	0	0	0	7186	0	0	0	0
Rebar steel (t)	51	105	186	955	2	24	36	93
Glulam (m^3)	0	0	0	0	78	125	206	234
CLT (m^3)	0	0	0	0	513	1410	2792	4639

Figure 4.1. Specifications of analyzed buildings. [12]

Three scenarios were considered varying on the amount of fly ash and scrap rebar steel used in the concrete elements. These are explained in Figure 4.2.

	PA Reference scenario	PB Worst-case scenario	PC Best-case scenario
Concrete	5 % fly ash	no fly ash	30 % fly ash
Rebar steel	80 % scrap content	16 % scrap content	100 % scrap content

Figure 4.2. Production technology scenarios for steel and concrete. [12]

The LCA was conducted in the "Cradle-to-Gate" scope using the Ecoinvent material database. The results as shown in Figure 4.3 prove a significant improvement of the GWP indicator of the timber structures.

		CC/GFA (kg CO_2-eq/m^2)								
	Storeys	Reference scenario			Worst-case scenario			Best-case scenario		
		RC	T	Saving	RC	T	Saving	RC	T	Saving
App. 1	3	120.5	26.3	-78 %	179.1	27.9	-84 %	82.8	25.3	-69 %
	7	112.3	37.8	-66 %	165.8	45.7	-72 %	77.3	33.8	-56 %
	12	111.6	40.0	-64 %	165.3	46.8	-72 %	76.7	36.4	-52 %
	21	270.1	67.3	-75 %	441.8	83.2	-81 %	177.7	59.0	-67 %

Figure 4.3. GWP per m2 for all structures in reinforced concrete (RC) and timber (T) and relative saving of GHG. [12]

4.2. LCA OF TWO RESIDENTIAL TOWERS AT THE UNIVERSITY OF BRITISH COLUMBIA

This study [13] compares the environmental impact of two similar existing buildings (Figure 4.4) in Vancouver, Canada. The Tallwood House (completed 2017) is an 18-storey building with a hybrid structure - the foundations, first floor, second floor slab and stair/elevator cores are

Figure 4.4. Studied buildings: Tallwood House (a) and Cedar House (b). [13]

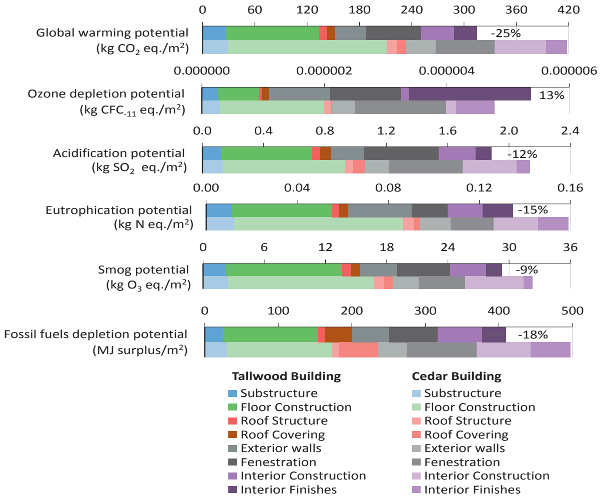


Figure 4.5. Comparison of environmental impacts of building materials per m^2. [13]

made of reinforced concrete while the rest of the building is composed of CLT boards and GLT columns. The Cedar House (2015) is also an 18-storey building with a structure made entirely of reinforced concrete.

A “Cradle-to-Gate” LCA was applied to assess the environmental performance of both buildings. LCA material data were taken over from the North American database Athena. The results (Figure 4.5) show that the building materials life cycle impacts are significantly smaller in all but one (ODP) studied categories.

4.3. LCA OF BUILDINGS COMPARING STRUCTURAL STEELWORK WITH OTHER CONSTRUCTION TECHNIQUES

This study [14] shows the results of a life cycle assessment of three office building with load bearing systems made of reinforced concrete, steel and timber.

System boundaries of the LCA were set to include all load bearing structures. Cladding, interior fittings and building services were neglected. Exactly as in the case of the retirement home, the energy demands of the three office buildings are estimated to be the same. The scope of the LCA was set as “Cradle-to-Gate”.

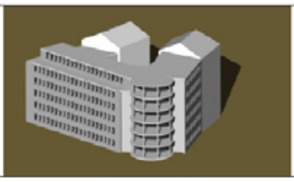
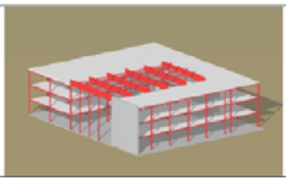
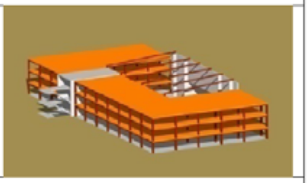
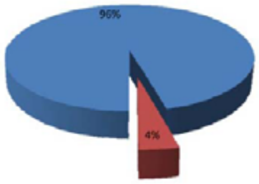
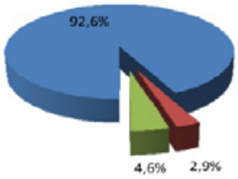
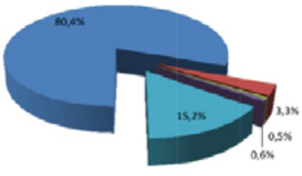
	reinforced concrete construction		steel skeleton construction		timber skeleton construction	
						
■ concrete ■ reinforcement ■ structural steel, connecting plates ■ sawn timber ■ timber GLT						
concrete	1.090 kg/m² net area	96,0 %	650 kg/m² net area	92,6 %	492 kg/m² net area	80,4 %
reinforcement	45 kg/m² net area	4,0 %	20 kg/m² net area	2,9 %	20 kg/m² net area	3,3 %
structural steel, connecting plates	0 kg/m² net area	0 %	32 kg/m² net area	4,6 %	3 kg/m² net area	0,5 %
sawn timber	0 kg/m² net area	0 %	0 kg/m² net area	0 %	4 kg/m² net area	0,6 %
timber GLT	0 kg/m² net area	0 %	0 kg/m² net area	0 %	93 kg/m² net area	15,2 %
total	1.135 kg/m² net area	100 %	702 kg/m² net area	100 %	612 kg/m² net area	100 %

Figure 4.6. Analyzed office buildings, comparison of mass fraction per m^2 net area arranged by construction materials. [12]

The functional unit was defined as square meter net area. The influence of the building size may, therefore, be disregarded. Environmental impact data were taken over from the Ecoinvent v1.3 database. Figure 4.6 presents the analyzed buildings and the weight of materials used.

Figure 4.7 illustrates the environmental performance of analyzed structures harmonized on the basis of the reinforced concrete construction.

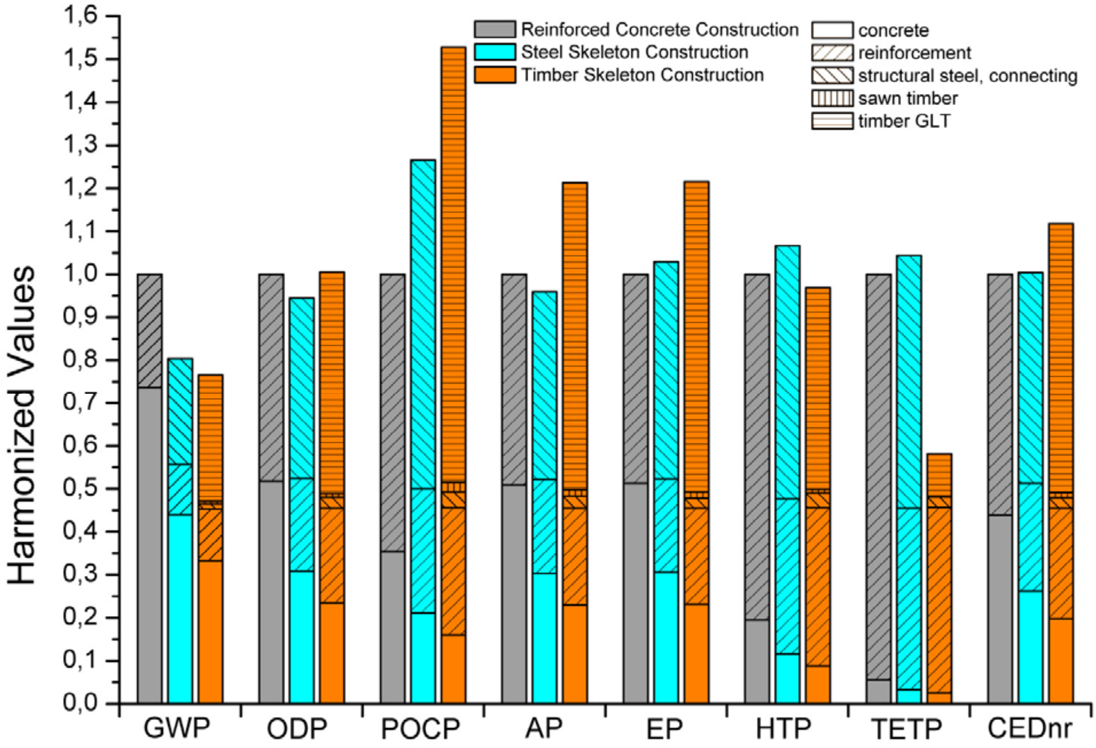


Figure 4.7. Comparison of construction techniques with their environmental performance. [12]

According to these results, all assessed techniques prove to be very similar and no construction technique is preferable as their ranking differs in considered environmental categories.

To provide an overall comparison, environmental performances of each technique will be benchmarked using the weighted environmental indicators as proposed in the next chapter. Harmonized values have been estimated from Figure 4.7.

Table 4.1 - Benchmarking of analyzed construction techniques

construction technique	performance	environmental categories						weighted score
		PEI_n	GWP	AP	EP	ODP	POCP	
reinforced concrete	harmonized	**1,000**	**1,000**	**1,000**	**1,000**	**1,000**	**1,000**	**92,4 %**
	weighted	0,404	0,221	0,111	0,038	0,073	0,077	
steel	harmonized	**1,005**	**0,805**	**0,960**	**1,035**	**0,950**	**1,270**	**96,6 %**
	weighted	0,402	0,274	0,115	0,037	0,077	0,061	
timber	harmonized	**1,125**	**0,765**	**1,215**	**1,220**	**1,005**	**1,535**	**89,3 %**
	weighted	0,359	0,288	0,091	0,032	0,073	0,050	

The weighted results (Table 4.1) surprisingly favor the steel construction while the timber structure benchmarked last of the three. Even after applying weights to environmental indicators, however, the results are still rather close, varying in 7,3 percentage points at most.

4.4. COMPARATIVE LCA OF A CONCRETE APARTMENT BUILDING AND TIMBER APARTMENT BUILDING

This study [28] presents the results of an LCA of two similar apartment buildings in Trondheim, Norway. The goal of the study was to compare greenhouse gas emissions from both buildings. The assessment considered modules A1 - A3 (product stage), A4 (transportation to the building site) and B6 (operational energy use). Due to different number of floors, the functional unit was set as $kgCO_{2,eqv}/m^2$.

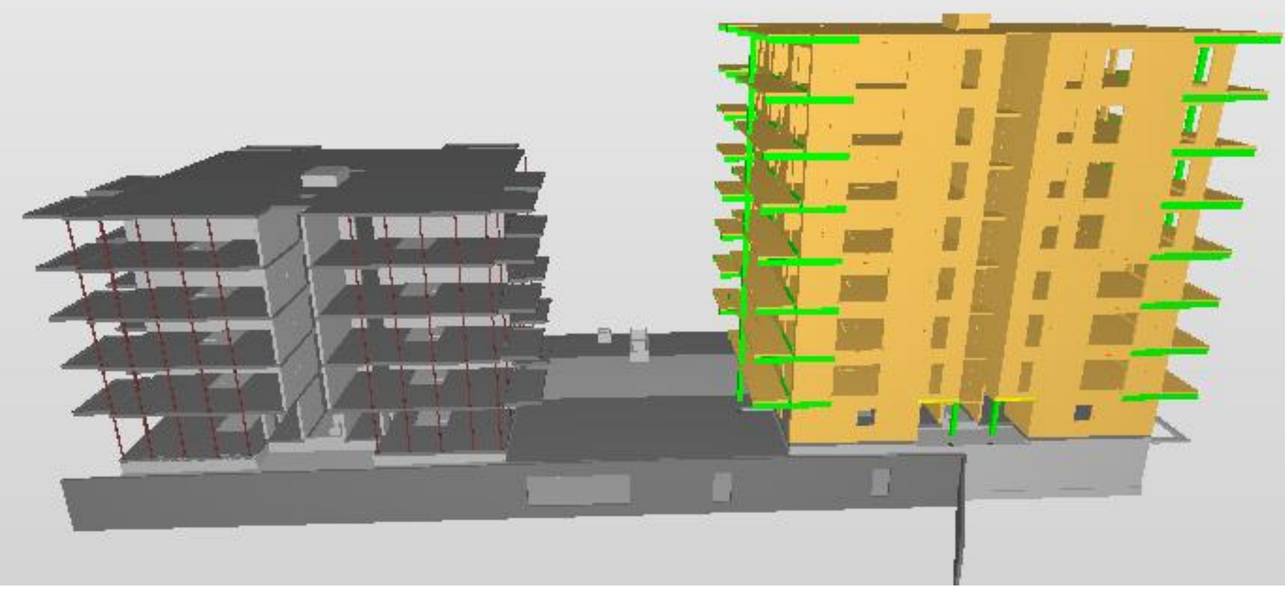


Figure 4.8. Case buildings: Maskinparken 2 (left) and Maskinparken TRE. [28]

Case buildings are shown in Figure 4.8. Building on the left—Maskinparken 2—is a 5-floor concrete and steel building. Maskinparken TRE is an 8-floor wooden apartment building. The walls, slabs, main staircase and the elevator cores are made of CLT elements. This building is designed to meet the Norwegian passive house standards, while the concrete building is designed to meet less strict standards. The two buildings are connected by an underground car park made of reinforced concrete. Construction was finished in 2018.

	Maskinparken 2	Maskinparken TRE
Gross internal area	2376,1 m^2	3784,8 m^2
Number of stories	5	8
Number of apartments	31	47
Construction system	Reinforced concrete and steel	CLT
Foundation	Concrete underground car park	Concrete underground car park
Façade	Aired plaster	Wood panelling
Balconies	Prefabricated concrete	CLT
Outer walls	Insulated stud work	Lined CLT walls

Figure 4.9. Case buildings: basic information summary. [28]

Material quantities for each building are presented in Figure 4.10. Looking at the data of the CLT building, it is apparent that the reinforced concrete structure of the underground garage makes up a significant portion of used concrete in both buildings.

	Maskinparken 2 [ton]	[%]	Maskinparken TRE [ton]	[%]
Cast-in-place concrete	3874	82,8	3185	65,6
Prefabricated concrete	227	4,9	66	1,4
Steel	20	0,4	23	0,5
Screed	196	4,2	417	8,6
Reinforcement	151	3,2	125	2,6
Cross laminated timber	4	0,1	540	11,1
Wood	34	0,7	51	1,1
EPS	2	0,1	0	0,0
Bathroom cabins	62	1,3	102	2,1
Façade panel and plaster	13	0,3	0	0,0
Gypsum board	51	1,1	207	4,3
Stone wool insulation	8	0,2	71	1,5
Windows and balcony doors	16	0,3	25	0,5
Doors	11	0,2	16	0,3
Glass railing	0	0,0	17	0,3
Other materials	10	0,2	10	0,2

Figure 4.10. Case buildings: material quantities. [28]

LCA results are depicted in Figure 4.11. The GHG emissions for the product stage (A1 - A3) of the CLT building are about 25% lower compared to the concrete building. The impact of concrete and reinforcement used in the underground garage proves to be significant in both cases (Figures 4.11 and 4.12)

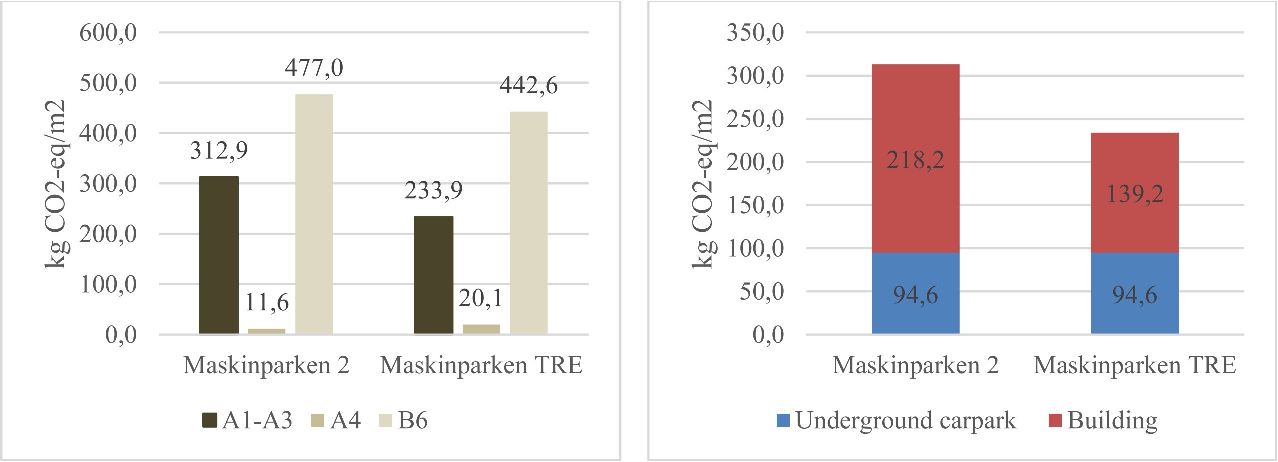


Figure 4.11. GHG emissions from all evaluated LCA stages (left) and product stage only. [28]

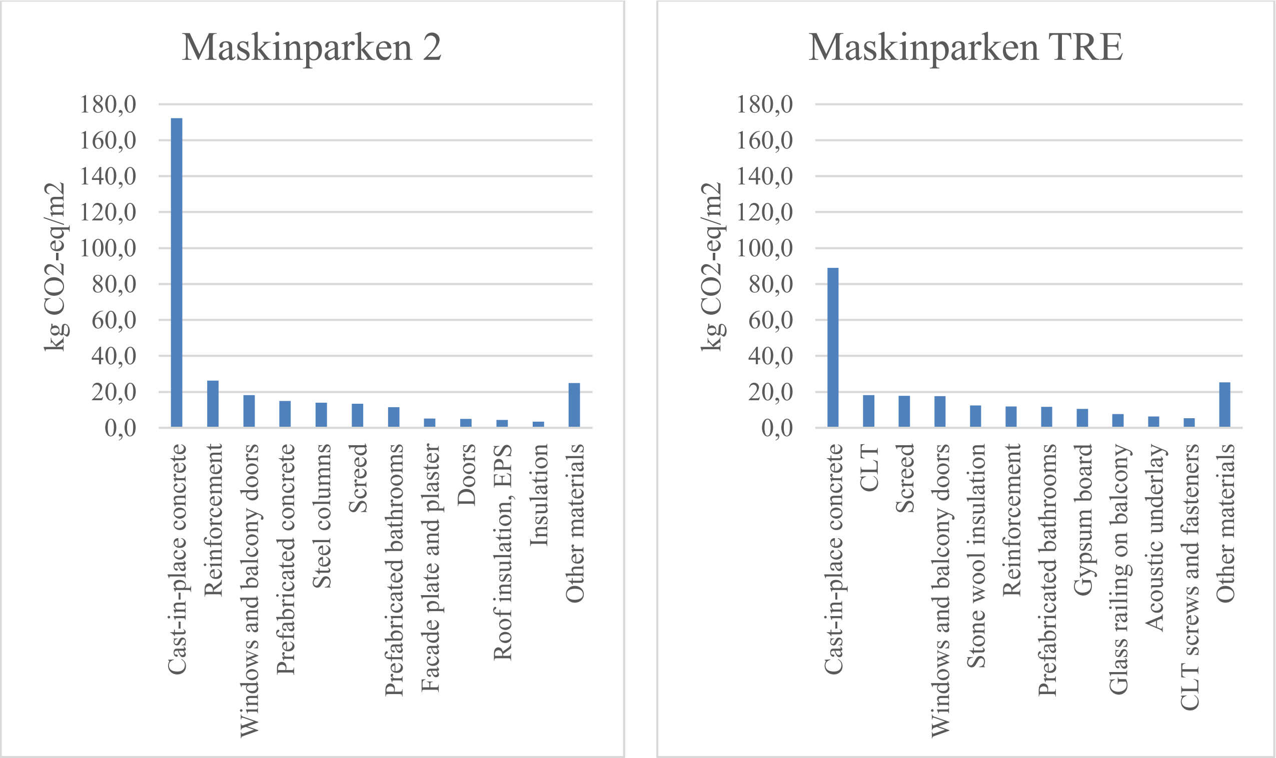


Figure 4.12. GHG emissions from used materials (product stage only). [28]

4.5. FINDINGS

All the reviewed studies have shown that timber structures perform significantly better in the global warming potential category. The study of LCA of two residential towers in Canada (4.2) even indicates better environmental performance of timber structures in all but one indicator.

On the other hand the study of three different structural systems (4.3) has presented inconclusive results as each system performed better in different categories. Furthermore, after applying weights to those categories, concrete and steel structures were evaluated as more favorable than timber structures.

The studies show both positive and negative overall results of timber structures. An alternative design of the Retirement Home with a timber structure will be created, evaluated and compared to the case studies presented in this chapter.

5. METHODS

The goal of this thesis is to minimize the environmental impacts of construction of the Retirement Home in Horoměřice. In order to do so, the original study will be evaluated using life cycle assessment. Alternative designs of the building will be presented, analyzed and compared.

First of all, the original design [5] will be assessed. The LCA methodology used is described below.

In *Bearing Structure of Retirement Home in Horoměřice* [6], a modified design was introduced. This alternative proposes changes to the structural system based on, among others, selected environmental impact indicators. Through the comparison of LCA results it will be determined whether this modification will indeed prove as environmentally favorable.

Multiple case studies have been reviewed. These studies and also present trends in the local construction industry suggest that implementation of timber structural systems may serve as a mitigation of environmental impacts of construction. These claims will be put to the test as a third alternative of the retirement home using the CLT shear wall system will be assessed and compared.

5.1. LCA METHODOLOGY

5.1.1. GOAL DEFINITION

The life cycle assessment will be applied to and serves as a benchmarking tool of the building of Retirement Home in Horoměřice, specifically. The LCA will be conducted for academic purposes only and its scope will be defined accordingly.

5.1.2. SCOPE DEFINITION

In this study, embodied environmental impacts of load bearing structures, infill walls and thermal insulation elements will be examined (see assumptions below). These impacts are represented mainly in the LCA modules A, C and D (Figure 3.2). Figures 5.1 - 5.3 show, however, that the significance of product stage modules (A1 - A3) of common building materials is far greater than the significance of construction process stage (A4 - A5), end-of-life stage (C) and reuse / recycling stage (D).

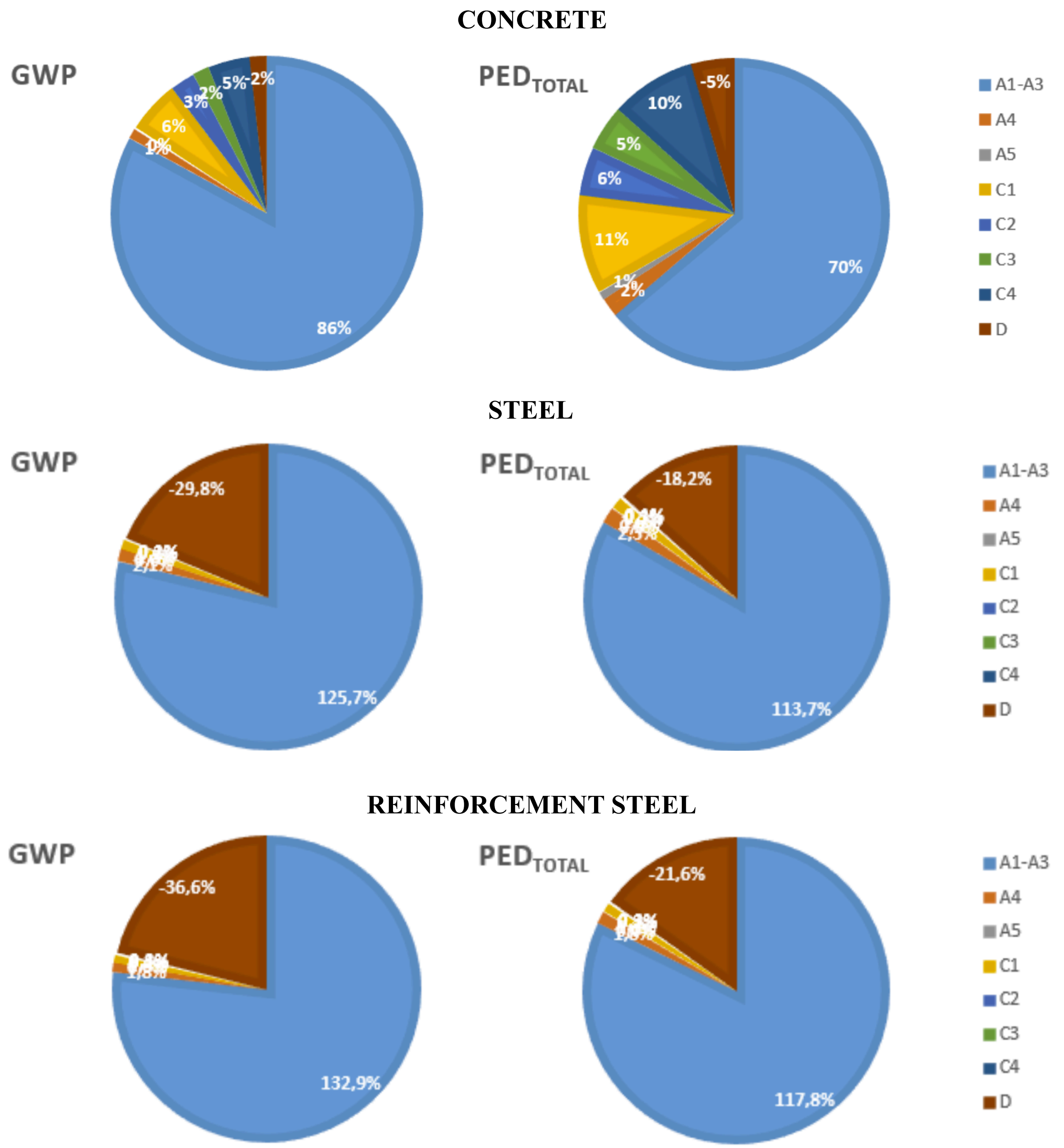


Figure 5.1. Importance of individual modules in LCA of concrete, steel and reinforcement steel. [7]

Moreover, the data required to consider the latter stages are not easily accessible as it has proven to be difficult to accurately determine the environmental impacts these stages of the product reaching 50 years or more to the future.

It is for these reasons that the **system boundaries** will be limited by modules A1 - A3.

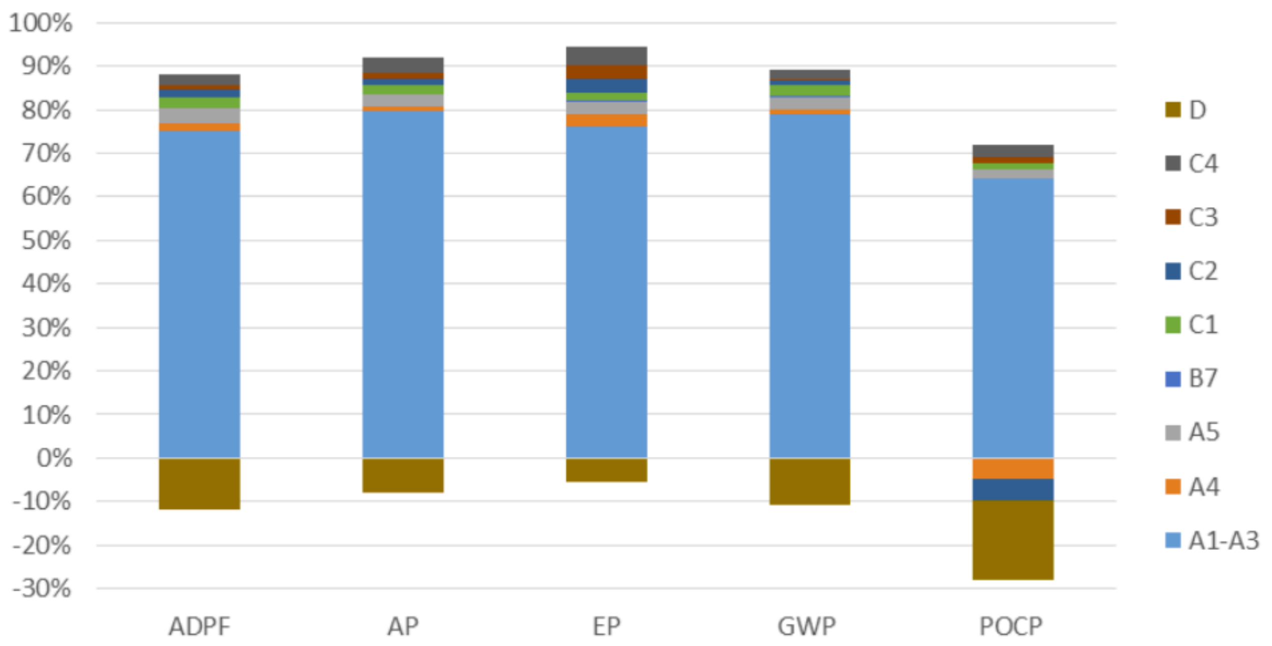


Figure 5.2. Importance of modules in LCA in selected environmental categories of a studied concrete structure. [7]

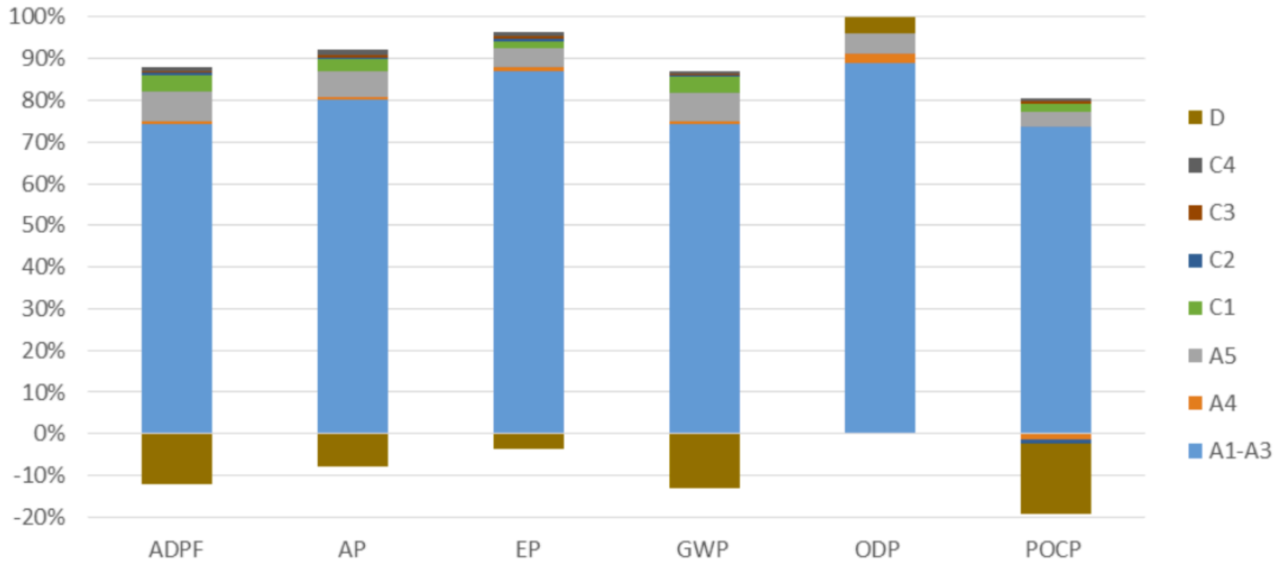


Figure 5.3. Importance of modules in LCA in selected environmental categories of a studied composite (steel and concrete) structure. [7]

In order to enable the limitation of the LCA scope, **assumptions** had to be made.

In the case of Retirement Home in Horoměřice, it is assumed that all assessed design alternatives will demand nearly identical amount of energy for operation.

This study acknowledges that even though all considered alternatives will be designed with identical U-values and without any layout changes, this assumption may introduce uncertainties into the analysis. Due to differences in another, unaccounted for, factors such as thermal capacity of designed systems (and e. g. cooling energy demand differences resulting from this factor) the operation stage (B1-B7) impacts may vary with each alternative. These factors could be eliminated by implementing appropriate environmentally friendly design strategies (shading options, thermal storage adobe walls, etc.) which is not, however, the goal of this thesis.

Floors, interior and exterior finishings will not be included in the analysis as it is assumed these could be designed in a similar fashion in all evaluated alternatives. Furthermore, it is assumed that environmental impacts of the carcass are much greater than the completing constructions.

As defined in the system boundaries, this assessment will evaluate the environmental impacts of used materials. In the life cycle inventory analysis and life cycle impact assessment stages, these impacts are calculated with regards to the **functional unit** of 1 kg of given material. With regards to the goal of this LCA (as all analyzed alternatives represent the very same building) no universally comparable unit (such as 1 m^2 of living area) is necessary—the alternatives will be compared based on absolute values.

Data quality requirements will be defined to meet the goal of the LCA. Only time-, location- and technology-appropriate data will be used (see also 5.1.4).

Environmental impact categories have been chosen as follows:

-	PEIn	Non-renewable primary energy demand,
-	GWP	global warming potential,
-	AP	acidification potential,
-	EP	eutrophication potential,
-	ODP	ozone layer depletion potential,
-	POCP	photochemical ozone creation potential.

These indicators have been chosen in accordance with the National Tool for Building Quality Certification for the Czech Republic - SBToolCZ [9].

5.1.3. LIFE CYCLE INVENTORY ANALYSIS

It is not within the reach of this thesis to evaluate the impacts of production processes for each material. Instead, publicly available LCIA databases will be used.

5.1.4. LIFE CYCLE IMPACT ASSESSMENT

The LCIA will be based on BIM models of the design alternatives. These models have been created by modification of structural elements and by addition of non-load-bearing elements to the 3D structural model presented in [6]. Volumes of used materials will be extracted from the BIM model [S6] and organized [S5].

LCIA databases will be used to obtain already **classified** and **characterized** life cycle impact data for every building material used. As mentioned in 3.3, datasets provided by these databases may differ significantly. Two different databases will be used to evaluate every analyzed alternative. The results will then be compared to each other and used as a sensitivity study of sorts. Databases chosen for this study are Ecoinvent v3.6 (Switzerland, [11]) and Ökobaudat 2019-III (Germany, [29]). Datasets taken over from these databases will at no point of the study be combined.

The Ecoinvent database, in most cases, provides environmental impact data specified for these locations: Switzerland, Europe without Switzerland, and rest of the world. Europe without Switzerland dataset will be considered, as it is most likely to correspond with the current situation of construction industry in the Czech Republic.

Normalization will be performed in terms of comparison of all analyzed alternatives. **Grouping** will not be part of this assessment.

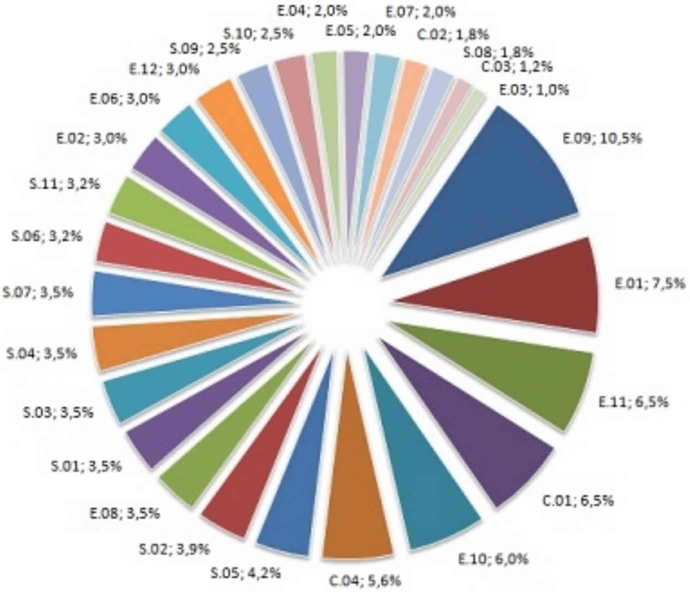


Figure 5.4. Weights of sustainable building criteria according to SBToolCZ for residential buildings. [9]

Individual impact indicators will be assigned **weights**. The importance of each indicator will be determined based on the SBToolCZ methodology [9]. SBToolCZ considers not only environmental but also social and economical criteria (Figure 5.4). Since only selected criteria will be analyzed in this scenario, the weight of each category will be rescaled with respect to its original relevance.

Table 5.1 - Considered environmental categories and their weights

SBToolCZ ID	SBToolCZ weight	abbreviation	description	rescaled weight
E.09	10,5 %	**PEIn**	Non-renewable Primary Energy Demand	**40,38 %**
E.01	7,5 %	**GWP**	Global Warming Potential	**28,85 %**
E.02	3,0 %	**AP**	Acidification Potential	**11,54 %**
E.03	1,0 %	**EP**	Eutrophication Potential	**3,85 %**
E.04	2,0 %	**ODP**	Ozone Layer Depletion Potential	**7,69 %**
E.05	2,0 %	**POCP**	Photochemical Ozone Creation Potential	**7,69 %**
			∑	100,00 %

5.1.5. INTERPRETATION

The outcome will be interpreted in the Results chapter. Significant contributors to each impact category will be pointed out for every alternative. A simplified sensitivity analysis will be performed by comparing the results of the two used LCIA databases.

After the assessment of all alternatives an overall score will be determined by applying of the weighting set.

5.2. RETIREMENT HOME - ORIGINAL STUDY

This section introduces the original study of the Retirement Home in Horoměřice [5] as designed by Bc. Barbora Šádková in 2017.

5.2.1. BASIC INFORMATION

Name of the building:	Retirement Home in Horoměřice
Purpose of the building:	retirement home
Number of floors:	4 above-ground floors, 1 basement floor
Location:	K Rybníku, Horoměřice, Czech Republic k. ú. Horoměřice, plot nr. 80/1, 70/4, 601/2

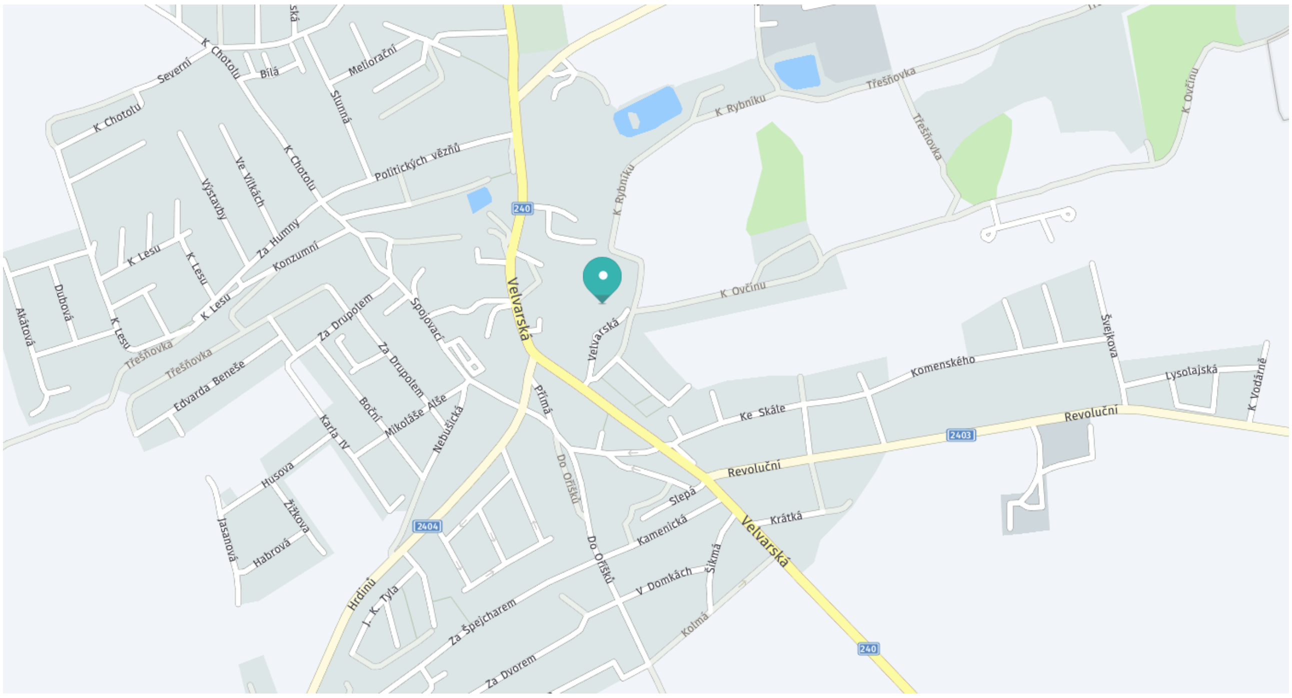


Figure 5.5. Building location. [30]

5.2.2. LOCATION

The master's thesis of Barbora Šádková consists of the urban design of the town centre (Figure 5.6) and the architectural design of the retirement home. The building is located next to the old Horoměřice castle and a small public park in the K Rybníku street.

Figure 5.6. Urban design of Horoměřice town center. The retirement home building is marked. [5]

5.2.3. ARCHITECTURAL AND STRUCTURAL DESIGN

The U-shaped floor plan of the building is a result of the urban design concept. Maximum lengths of the west, south and east facades are approximately 22 m, 40 m and 42 m, respectively.

The building consists of one basement floor and four above-ground floors. The first floor copies the floor plan dimensions of the basement floor. Its facade is finished by dark brown plaster. In the east section of the building, upper floors deviate from the floor plans of lower floors and create short repetitive cantilever structures. The facade of these floors is ventilated with the finish made of timber cladding. The contrast of the facades separates the entrance floor with common spaces from the typical upper floors with living units.

The structural system is a cast-in-place reinforced concrete frame. The columns were designed with dimensions of 300 x 300 mm. The point-supported reinforced concrete slabs were dimensioned as 300 mm thick. The infill walls are made of hollow fired bricks 100 mm or 300 mm thick. The roof structure is created by timber roof trusses. The load-bearing structures of the frame system are illustrated in Figure 5.7.

The above-ground floors are thermally insulated by mineral wool (220 mm). The basement is insulated by XPS (100 mm).

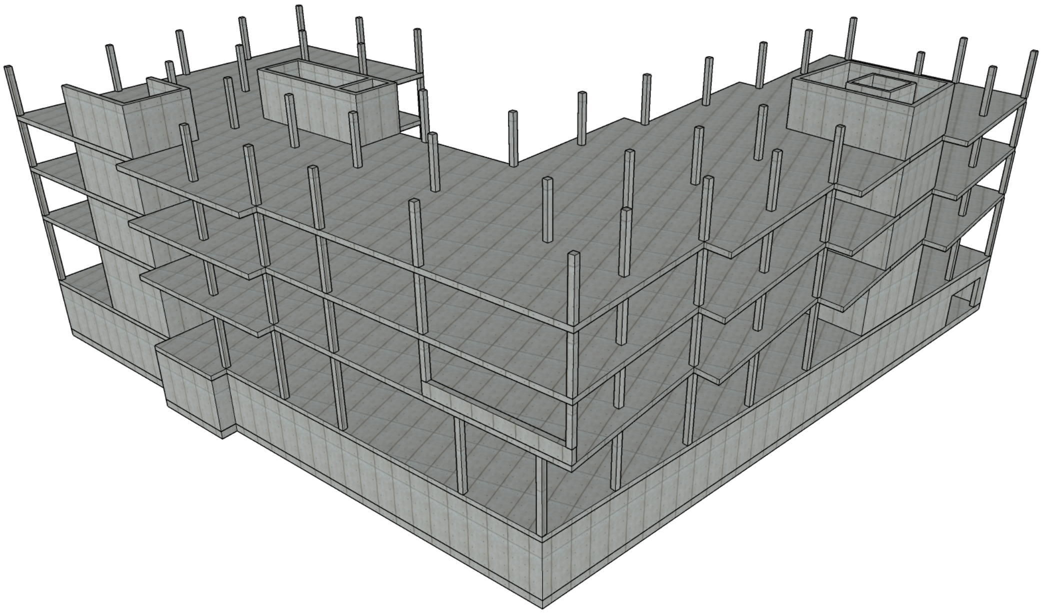


Figure 5.7. Schematic 3D model of the original structural system. [6]

5.2.4. LAYOUT DESIGN

The main entrance is located on the south side of the building. A side entrance connects the entrance hall to the garden and the park on the north side. Access to the underground car park is enabled by a ramp in the north-east corner.

The basement consists of a large underground garage, a kitchen, a technical room and facilities. Supply of the kitchen is enabled through an elevator next to the main entrance. To deliver food from the kitchen to the dining area upstairs a set of food elevators is used.

On the first floor there are an entrance hall, a dining room, common areas and administrative spaces. In the east wing there are medical rooms and five living units.

All upper floors are nearly identical. On each floor there are 3 single rooms, 15 double rooms, a common room, specially equipped bathroom and a storage room.

In total, 59 living units were designed accommodating up to 106 residents.

5.2.5. DRAWINGS

All drawings presented below were taken over from the original architectural study [5].

BLOCK PLAN

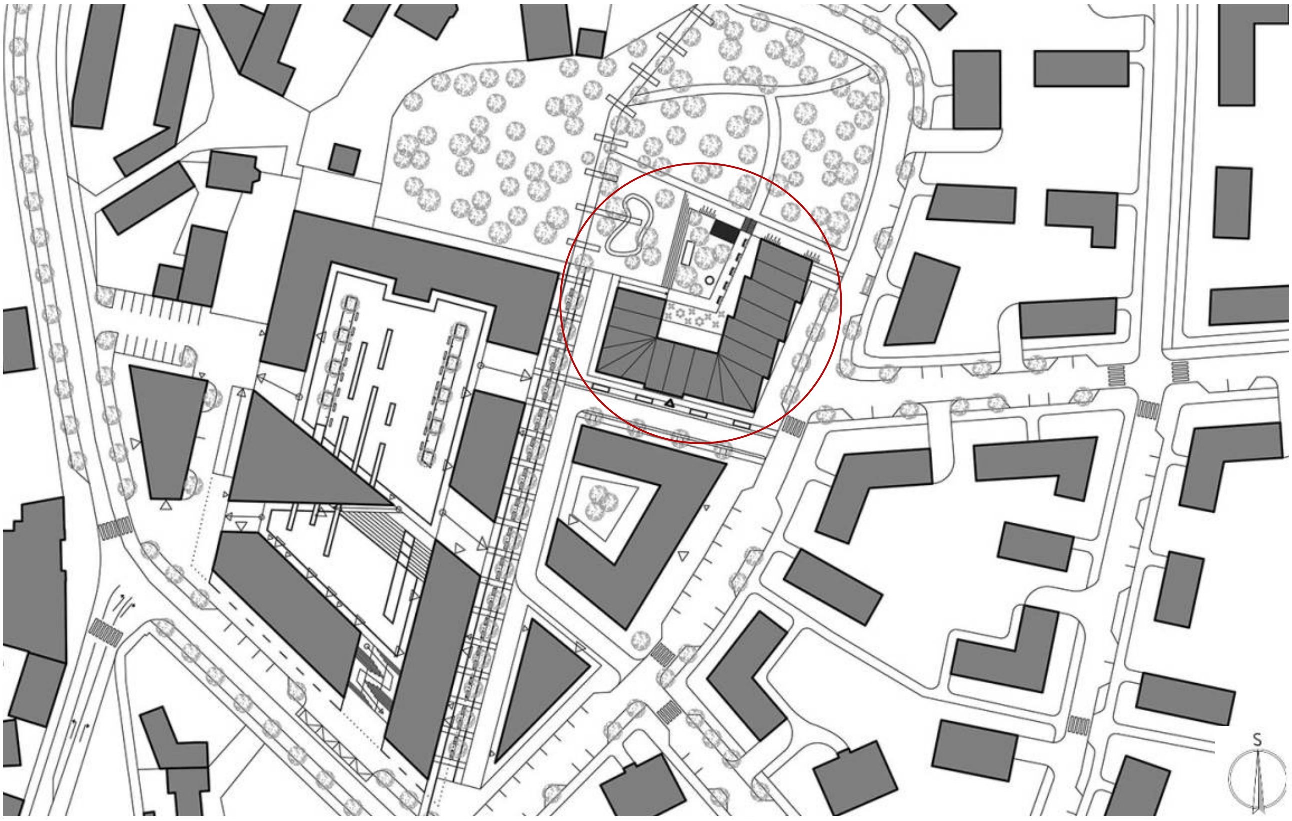


Figure 5.8. Urban design block plan. [5]

BASEMENT FLOOR

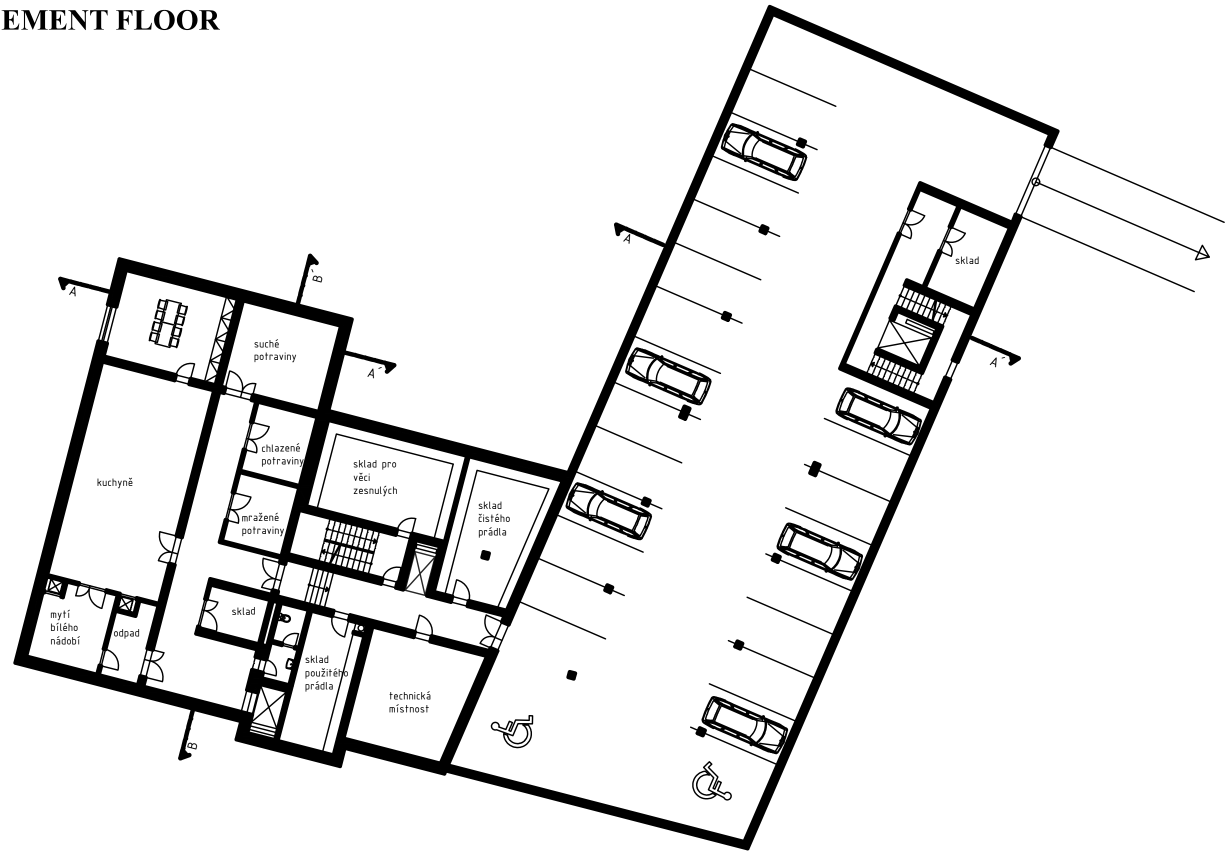


Figure 5.9. Floor plan - basement. [5]

1ST FLOOR

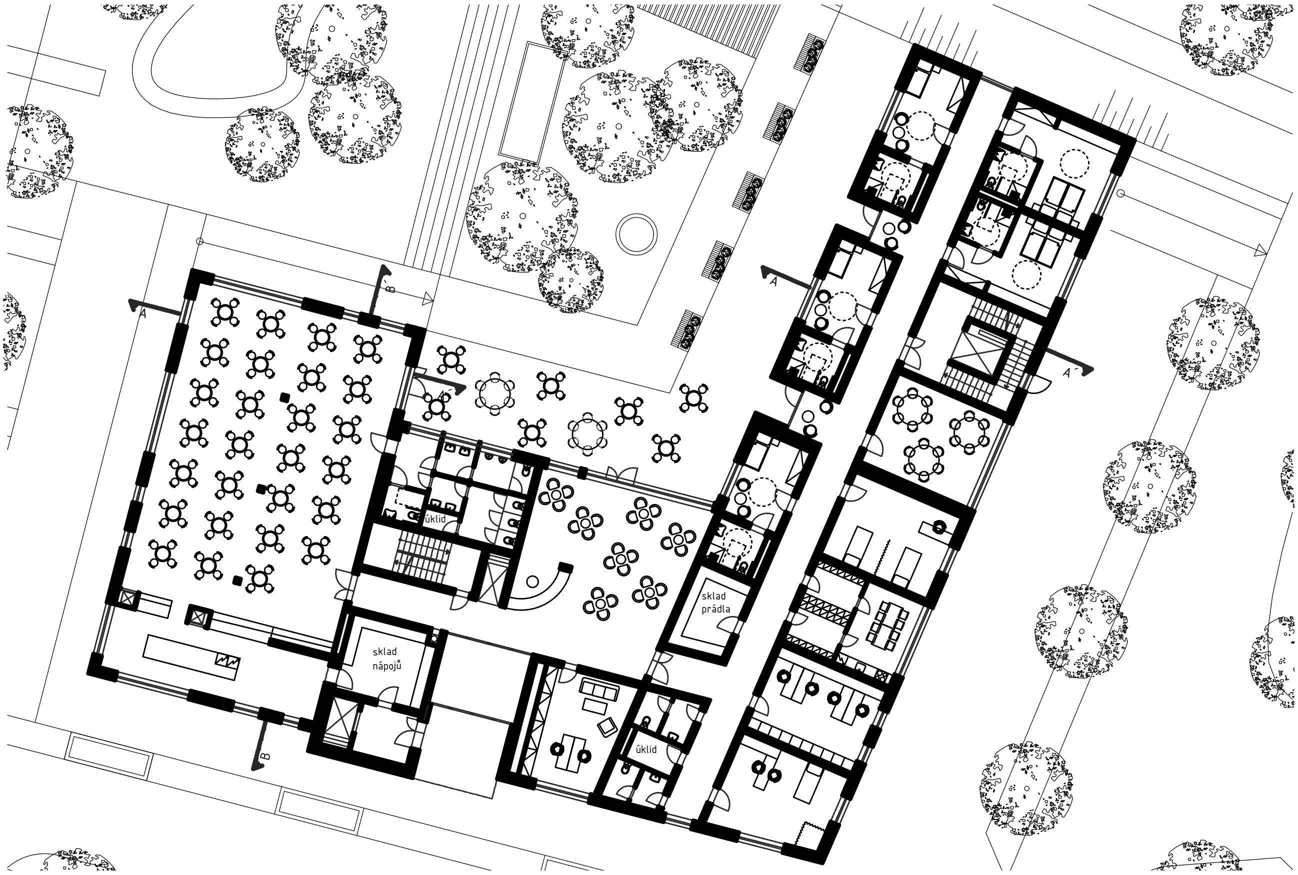


Figure 5.10. Floor plan - first floor. [5]

2ND FLOOR

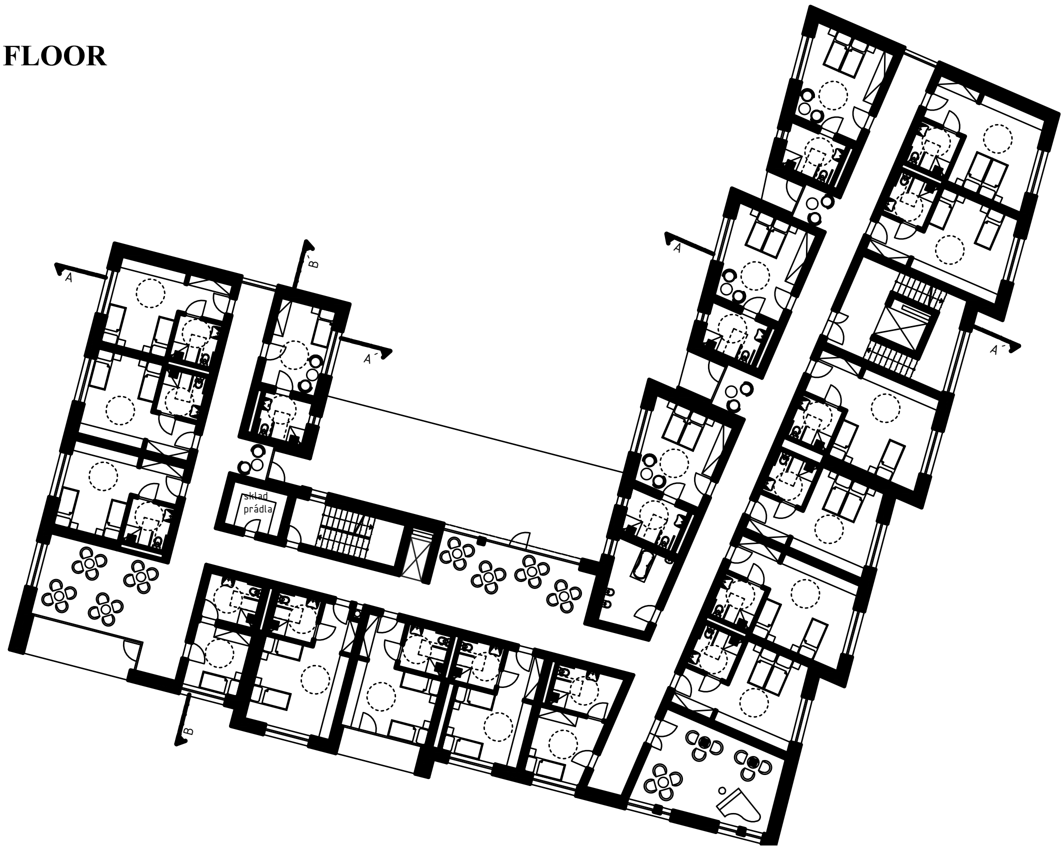


Figure 5.11. Floor plan - second floor. [5]

3RD FLOOR

Figure 5.12. Floor plan - third floor. [5]

4TH FLOOR

Figure 5.13. Floor plan - fourth floor. [5]

SECTION A

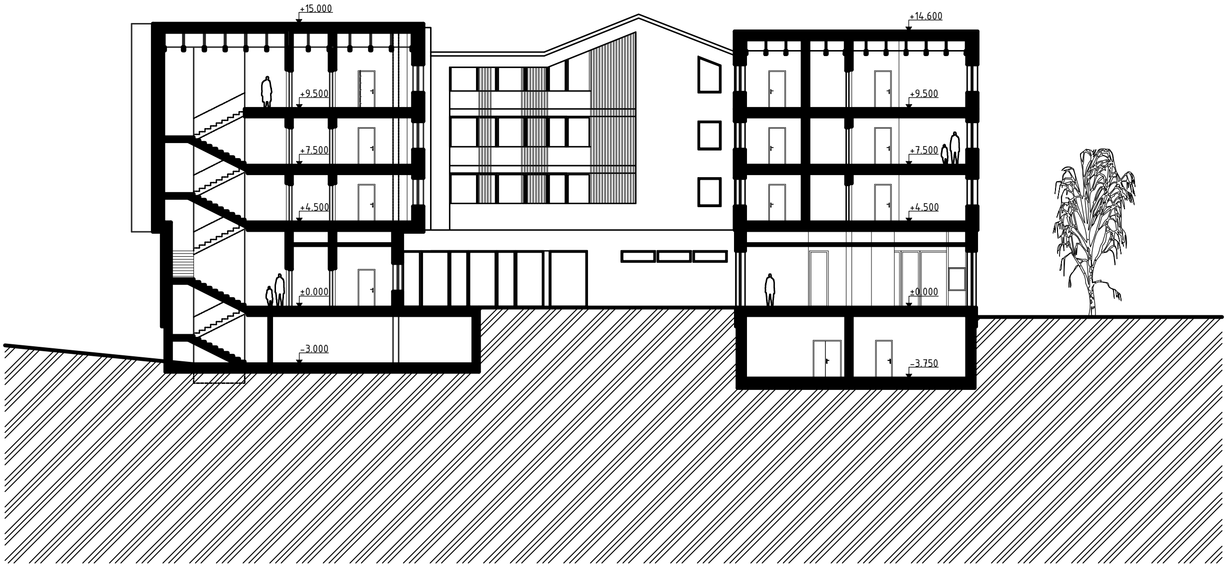


Figure 5.14. Section A. [5]

SECTION B

Figure 5.15. Section B. [5]

ELEVATION - NORTH

Figure 5.16. North elevation. [5]

ELEVATION - SOUTH

Figure 5.17. South elevation. [5]

ELEVATION - EAST

Figure 5.18. East elevation. [5]

ELEVATION WEST

Figure 5.19. West elevation. [5]

VISUALIZATION 1

Figure 5.20 - Visualization 1 (south-east view). [5]

VISUALIZATION 2

Figure 5.21. Visualization 2 (south-east view). [5]

VISUALIZATION 3

Figure 5.22. Visualization 3 (north view). [5]

5.2.6. BIM-MODEL

The evaluated BIM-model was created based on a 3D structural model. The load-bearing structures were modified according to the original design. Non-load bearing structures made of hollow fired bricks were added.

In *Bearing Structure of Retirement Home in Horoměřice* [6], a preliminary design of foundation piles was made. The piles were dimensioned as 8,0 m long and 1,3 m thick in diameter. They support the reinforced concrete columns of the basement floor. These piles were added to the BIM-model as well.

The foundation strips supporting the basement walls were not designed in [6]. Two alternatives (plain concrete and reinforced concrete) will be created and assessed based on the LCA methodology described above. The better performing alternative will be added to the 3D model.

5.2.6.1. DESIGN OF FOUNDATION STRIPS

Preliminary design of the foundation strips was created with respect to the design load values from [6] (Figure 5.23) and load-bearing capacity of subsoil values taken over from [31] (Table 5.2).

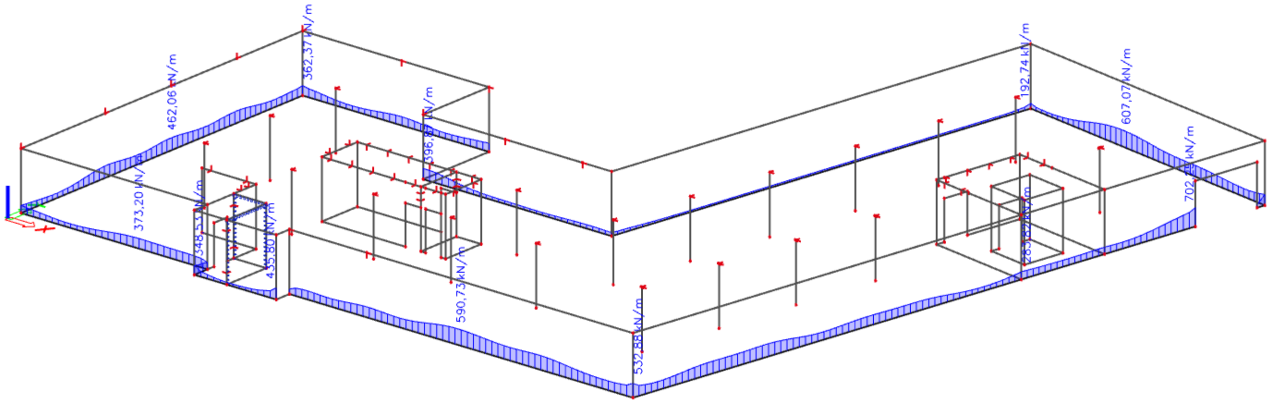


Figure 5.23. Maximum design loads of the foundation strips.

Table 5.2 - Load-bearing capacity of subsoil - sand (excerpt) [31]

soil class	USCS symbol	load-bearing capacity of subsoil [kPa]			
		foundation strip width - b [m]			
		0,5	**1,0**	**3,0**	**6,0**
S1	**SW**	300	500	800	600
S2	**SP**	250	350	600	500

Input information:

maximum design load:	$f_d = 610{,}0$ kN/m
strip width estimate:	$b' = 1{,}0$ m
load-bearing capacity of subsoil:	$R_{dt} = 500$ kPa
basement wall thickness	$t_w = 200$ mm

Minimal strip width:

$f_d \,.\, l \leq R_{dt} \,.\, b \,.\, l$; l = 1,0 m (length of the foundation strip)

$b \geq (f_d \,.\, l) / (R_{dt} \,.\, l)$

$b \geq (610{,}0 \,.\, 1{,}0) / (500{,}0 \,.\, 1{,}0)$

$b \geq 1{,}22$ m

Preliminary design: **b = 1,3 m**

Load distribution angle:

plain concrete:	$\alpha_{PC} = 60$ °
reinforced concrete:	$\alpha_{RC} = 45$ °

Minimal strip height:

$h \geq (b - t_w) / 2 \,.\, \mathrm{tg}\alpha$

$h_{PC} \geq (1{,}3 - 0{,}2) / 2 \,.\, \mathrm{tg}60 = 953$ mm

$h_{RC} \geq (1{,}3 - 0{,}2) / 2 \,.\, \mathrm{tg}45 = 550$ mm

Preliminary design: **$h_{PC} = 960$ mm**

$h_{RC} = 550$ mm

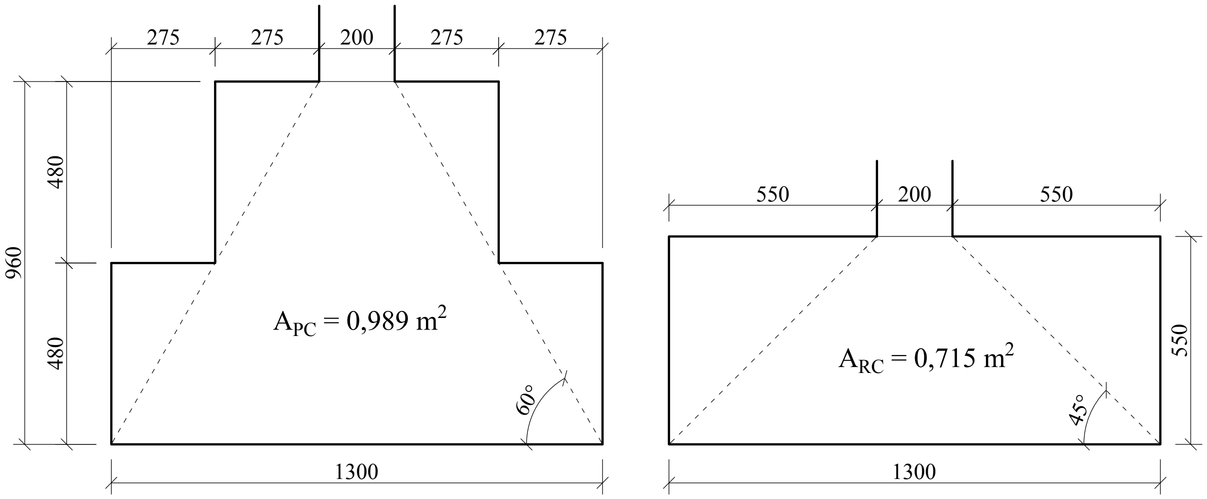


Figure 5.24. Dimensions of strip foundation alternatives - plain concrete (left) and reinforced concrete.

The two schematic design alternatives and their cross section areas are presented in Figure 5.24. Both alternatives were using the Ecoinvent material database (Annex I):

Table 5.3 - Foundation strips design alternatives - LCIA

material	**A** cross-section area [m²]	**ρ** bulk density [kg/m³]	**m'** mass per 1m [kg/m]	**environmental indicator values per 1m of foundation strip**						**total weighted score [%]**
				PEI [MJ]	**GWP** [kg_{CO2}]	**AP** [g_{SO2}]	**EP** [$g_{PO4^{3-},eqv}$]	**ODP** [$g_{CFC2,eqv}$]	**POCP** [$g_{C2H4,eqv}$]	
plain concrete	0,989	2300,0	2274,7	**1,3E+03**	**2,5E+02**	**4,2E+02**	**1,0E+02**	**8,4E-03**	**1,5E+01**	**96,1 %**
	relative score			100,0 %	88,7 %	100,0 %	100,0 %	92,0 %	100,0 %	
	weighted score			0,404	0,256	0,115	0,038	0,071	0,077	
reinforced concrete (0,5 %)	0,715	2330,0	1665,95	**1,6E+03**	**2,2E+02**	**4,5E+02**	**1,6E+02**	**7,8E-03**	**3,4E+01**	**86,9 %**
	relative score			83,1 %	100,0 %	94,3 %	64,1 %	100,0 %	45,5 %	
	weighted score			0,336	0,289	0,108	0,024	0,077	0,035	

Even though the cross-section area of the RC foundation strip is smaller and the reinforcement percentage is rather low, this alternative performs worse than the plain concrete strip. Therefore, plain concrete foundation strips as illustrated in Figure 5.24 will be designed and added to the BIM-model.

The evaluated 3D model is depicted in Figure 5.25.

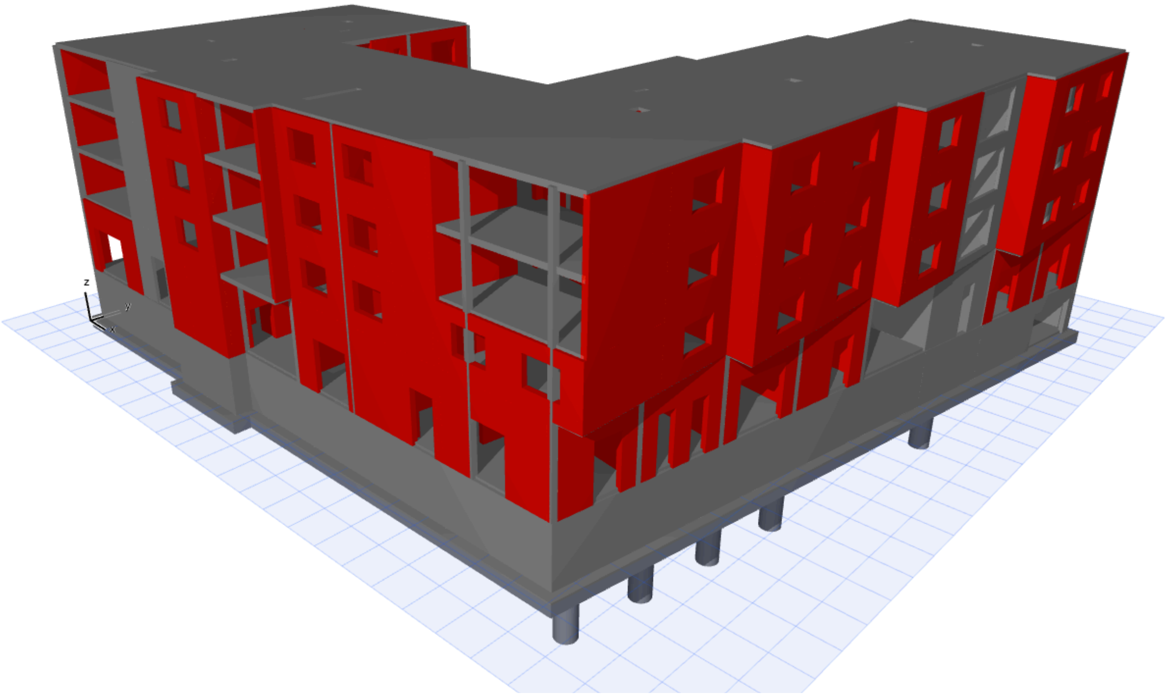


Figure 5.25. BIM-model of the original design.

The volumes of used materials extracted from the model are presented in the following table:

Table 5.4 - Total volume and mass of materials - original design

Material	Total Volume [m³]	bulk density [kg/m³]	Total Mass [t]
Plain Concrete	231,8	2300,0	533,1
Reinforced Concrete (0,25%)	199,2	2310,0	460,1
Reinforced Concrete (0,5 %)	2047,9	2330,0	4771,5
Reinforced Concrete (2,0 %)	56,9	2410,0	137,1
Hollow Fired Brick	1386,1	825,0	1143,5
Polystyren, Extruded	54,8	25,0	1,4
Mineral Wool	748,4	115,0	86,1
$\sum$	**4724,9**		**7132,7**

The estimation of reinforcement percentages (for all alternatives) is described in Annex I.

5.3. RETIREMENT HOME - ALTERNATIVE 1

5.3.1. DESIGN MODIFICATIONS

This alternative was created as a modification of the original study based on the analysis of the structural system of the building [6]. The original frame system provided variability of the building layout but it was assumed it could not reach the level of indoor comfort of the shear wall system—infill walls were designed as light structures with rather low sound reduction index and the concept of non-load-bearing infill walls itself brings up the issue of acoustic bridges in-between the living units of the retirement home.

A hybrid structural system was proposed. In the spaces of the basement floor and part of the first floor, where the underground garage, facilities and common area are located, the frame system shall be preserved. For the rest of the building, where no layout changes are expected, the structural system will be changed to shear wall system.

Based on this modification a masonry structures optimization was conducted in order to select best performing material of the walls in terms of the following criteria:

- thickness
- weight
- thermal capacity (of innermost 100 mm)
- sound reduction index
- primary energy demand
- global warming potential
- acidification potential

For the purpose of this optimization these masonry units and thermal insulation elements (external walls) were considered:

- hollow fired bricks (Porotherm Profi)
- hollow fired bricks with MW filling (Porotherm T Profi)
- hollow fired bricks with EPS filling (Heluz Family 2in1)
- aerated concrete blocks (Ytong P3-450)
- sand-lime blocks (Vapis QUADRO)

- expanded polystyrene (EPS)
- mineral wool (MW)
- wood fibre boards

Combinations of every masonry unit with each insulation type were created, all with the same U-value of 0,15 $Wm^{-2}K^{-1}$. Weights were assigned to the evaluated criteria as shown in Table 5.5.

Table 5.5 - Weights of evaluated criteria [6]

t	m’	C_{100}	R_w’	PEI’	GWP’	AP’	∑
0,10	0,10	0,25	0,25	0,10	0,10	0,10	1,00

The results of the optimization are shown in Figure 5.26. Based on these results, the best performing combination was determined. It consisted of sand-lime blocks and wood fibre board insulation in case of external walls. Where necessary, due to fire safety issues, the wood fibre insulation was, however replaced by mineral wool [6]. Thermal insulation of the roof was also changed from mineral wool to cellulose fibre.

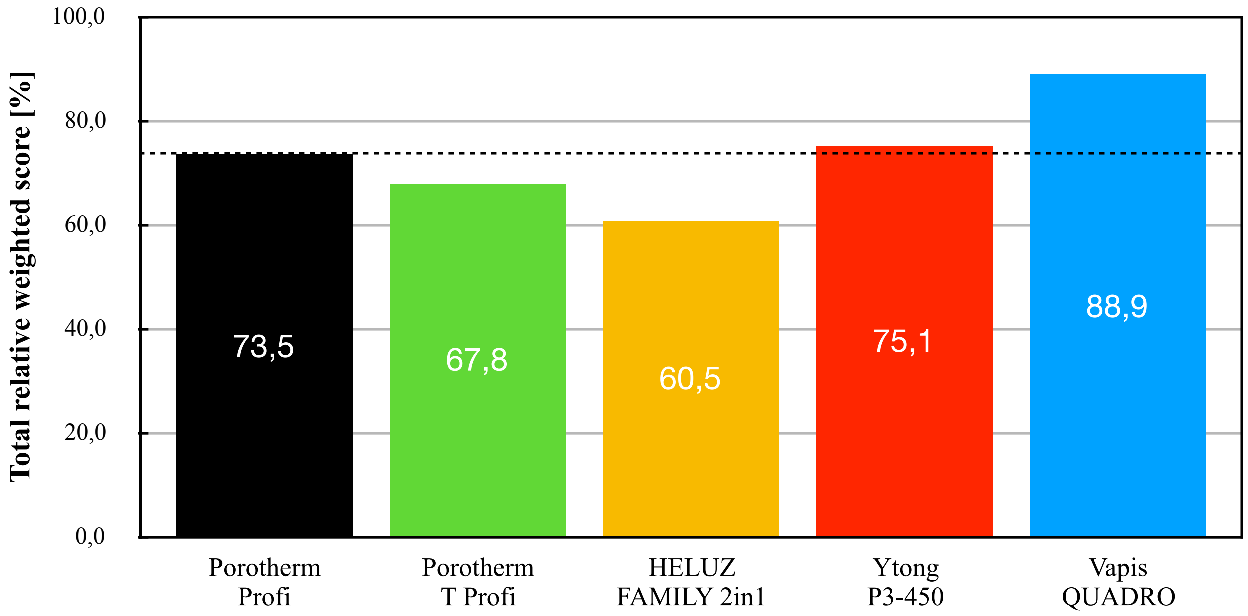


Figure 5.26. Masonry structures optimization results. [6]

Finally, the structural system of Alternative 1 may be summarized as follows: RC columns of dimensions 400 x 400 mm and 250 x 850 mm were designed in the basement floor and partly in the first floor. Shear walls made of primarily sand-lime blocks (thickness of 200 mm) or RC (thickness of also 200 mm) create the structural system of upper (typical) floors. RC slabs were dimensioned as 240 mm thick. The load-bearing structures are illustrated in Figures 5.27 - 5.29.

Figure 5.27. Schematic drawing of load-bearing structures - 1st floor. [6]

Figure 5.28. Schematic drawing of load-bearing structures - typical floor. [6]

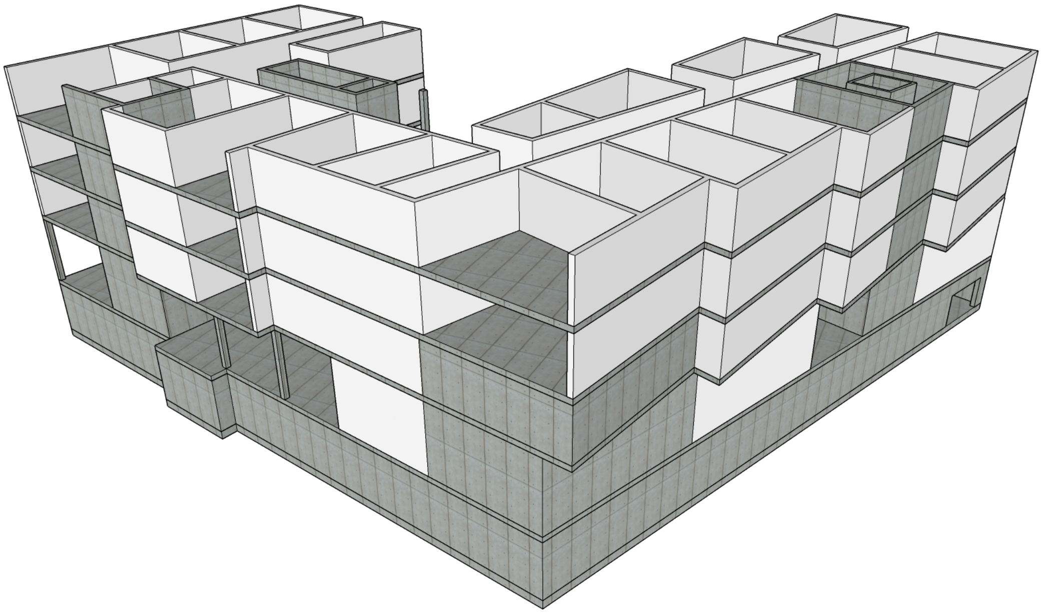


Figure 5.29. Schematic 3D model of the structural system of Alternative 1. [6]

5.3.2. BIM-MODEL

The BIM-model was created in accordance with 5.2.6, including the design of the foundation strips. It is depicted in Figure 5.28.

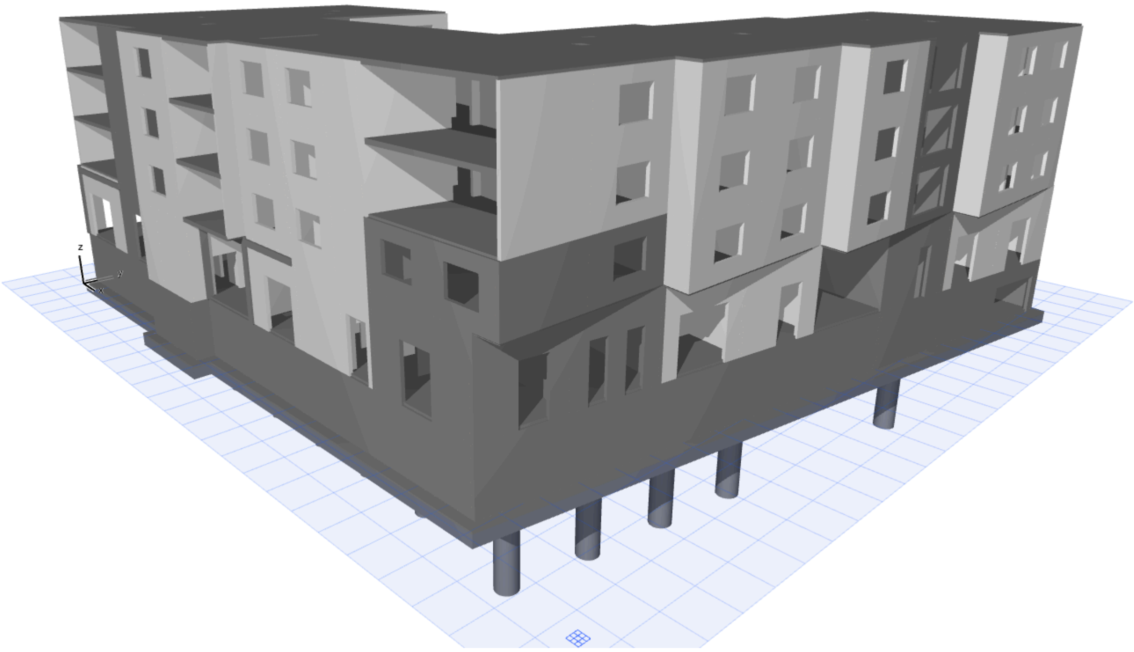


Figure 5.28. BIM-model of Alternative 1.

The volumes of used materials extracted from the model are presented in table 5.6:

Table 5.6 - Total volume and mass of materials - alternative 1

Material	Total Volume [m³]	bulk density [kg/m³]	Total Mass [t]
Plain Concrete	231,8	2300,0	533,1
Reinforced Concrete (0,25%)	350,0	2310,0	808,5
Reinforced Concrete (0,5 %)	1694,5	2330,0	3948,1
Reinforced Concrete (2,0 %)	27,9	2410,0	67,3
Reinforced Concrete (6,0 %)	73,8	2630,0	194,1
Sand-lime Blocks	850,3	2000,0	1700,6
Polystyren, Extruded	54,8	25,0	1,4
Mineral Wool	162,2	115,0	18,7
Wood Fibre	384,4	160,0	61,5
Cellulose Fibre	337,6	50,0	16,9
$\sum$	**4167,3**		**7350,1**

5.4. RETIREMENT HOME - ALTERNATIVE 2

5.4.1. DESIGN MODIFICATIONS

This alternative was created based on the reviewed case studies (4) and the LCIA results of the original design and Alternative 1. The goal of this design was to minimize the use of concrete and reinforcement as all studied cases prove significant environmental impacts of these materials. Instead timber structure made of CLT boards will be created in terms of a preliminary design.

Even in this alternative the use of concrete cannot be avoided, however. The structural system will remain unchanged (compared to Alternative 1) in the basement and partly in the first and second floors due to durability and structural design requirements.

This alternative assumes the maximum design loads as in Alternative 1 [6]. Dead and live design loads of the floors are listed in the following tables.

Tabulka 5.7 - Design dead loads of floors [6]

layer	t [m]	γ [kN/m^3]	g_k [kN/m^2]	γ_G [-]	g_d [kN/m^2]
ceramic tiles	0,010	20,0	0,20	1,35	0,27
adhesive	0,005	15,0	0,08		0,10
cement screed*	0,067	22,0	1,47		1,99
EPS system board*	0,028	0,4	0,01		0,01
CLT board	-	-	-		-
gypsum plaster	0,010	13,0	0,13		0,18
		celkem	**1,89**		**2,55**

*Equivalent thickness was determined with respect to the irregular shape.

The non-load bearing CLT walls (bathroom partitions) will be considered as a uniformly distributed dead load $f_{p,d}$. Its value is calculated for the typical floors based on the partition wall thickness (t_p), length (l_p), height (h_p) and self weight (γ_p), and the area of a typical living unit (A_{lu}).

Table 5.8 - Design dead loads - partition walls

floor	partitions				A_{lu} [m^2]	$f_{p,k}$ [kN/m^2]	γ_f [-]	$f_{p,d}$ [kN/m^2]
	t_p [m]	l_p [m]	h_p [m]	γ_p [kN/m^3]				
2nd - 4th	0,080	5,700	2,860	5,0	34,0	**0,24**	1,5	**0,36**

Table 5.9 - Design live loads [6]

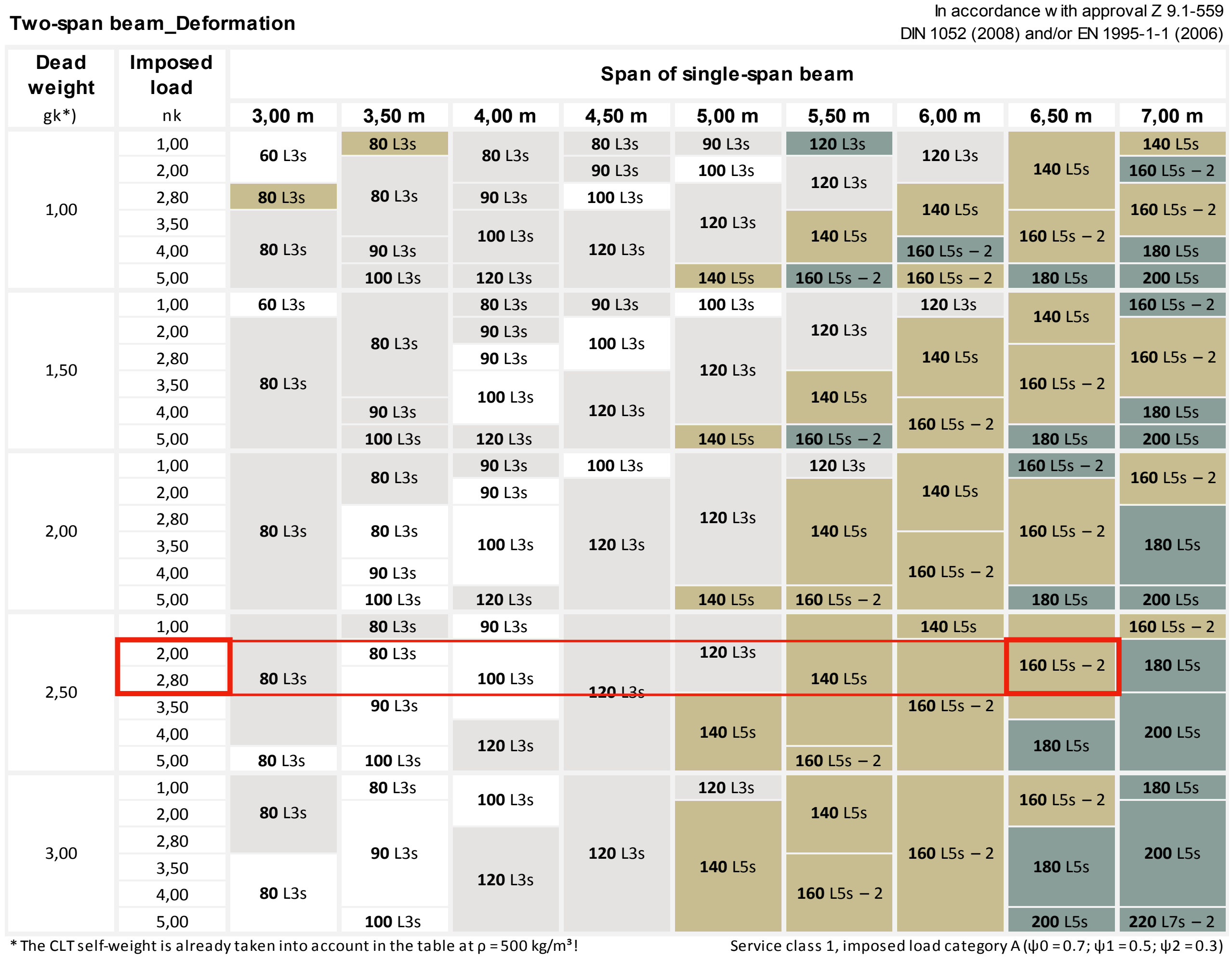
category	q_k [kN/m²]	γ_q [-]	q_d [kN/m²]
floor slabs	2,00	1,5	3,00
staircases	2,00		3,00
balconies, loggias	2,50		3,75

Total characteristic dead and live loads $f_{s,g,k}$ and $f_{s,q,k}$ considered in the preliminary design of CLT slabs:

$$\mathbf{f_{s,g,k}} = g_k = 2{,}55 = \mathbf{2{,}55\ kN/m^2}$$

$$\mathbf{f_{s,q,k}} = f_{p,k} + q_k = 0{,}24 + 2{,}0 = \mathbf{2{,}24\ kN/m^2}$$

The preliminary dimensions of CLT slabs will be determined according to preliminary design tables (for continuous beams) presented in Figure 5.29 for the maximum slab span of 6,5 m [6]:



Two-span beam_Deformation

In accordance w ith approval Z 9.1-559
DIN 1052 (2008) and/or EN 1995-1-1 (2006)

Dead weight gk*)	Imposed load nk	Span of single-span beam								
		3,00 m	**3,50 m**	**4,00 m**	**4,50 m**	**5,00 m**	**5,50 m**	**6,00 m**	**6,50 m**	**7,00 m**
1,00	1,00	**60** L3s	**80** L3s	**80** L3s	**80** L3s	**90** L3s	**120** L3s	**120** L3s	**140** L5s	**140** L5s
	2,00		**80** L3s		**90** L3s	**100** L3s	**120** L3s			**160** L5s – 2
	2,80	**80** L3s		**90** L3s	**100** L3s	**120** L3s		**140** L5s		**160** L5s – 2
	3,50	**80** L3s		**100** L3s	**120** L3s		**140** L5s		**160** L5s – 2	
	4,00		**90** L3s					**160** L5s – 2		**180** L5s
	5,00		**100** L3s	**120** L3s		**140** L5s	**160** L5s – 2	**160** L5s – 2	**180** L5s	**200** L5s
1,50	1,00	**60** L3s	**80** L3s	**80** L3s	**90** L3s	**100** L3s	**120** L3s	**120** L3s	**140** L5s	**160** L5s – 2
	2,00	**80** L3s		**90** L3s	**100** L3s	**120** L3s		**140** L5s		**160** L5s – 2
	2,80			**90** L3s					**160** L5s – 2	
	3,50			**100** L3s	**120** L3s		**140** L5s			
	4,00		**90** L3s					**160** L5s – 2		**180** L5s
	5,00		**100** L3s	**120** L3s		**140** L5s	**160** L5s – 2		**180** L5s	**200** L5s
2,00	1,00	**80** L3s	**80** L3s	**90** L3s	**100** L3s	**120** L3s	**120** L3s	**140** L5s	**160** L5s – 2	**160** L5s – 2
	2,00			**90** L3s	**120** L3s		**140** L5s		**160** L5s – 2	
	2,80		**80** L3s	**100** L3s						**180** L5s
	3,50							**160** L5s – 2		
	4,00		**90** L3s							
	5,00		**100** L3s	**120** L3s		**140** L5s	**160** L5s – 2		**180** L5s	**200** L5s
2,50	1,00	**80** L3s	**80** L3s	**90** L3s	**120** L3s	**120** L3s	**140** L5s	**140** L5s	**160** L5s – 2	**160** L5s – 2
	2,00		**80** L3s	**100** L3s				**160** L5s – 2		**180** L5s
	2,80		**90** L3s							
	3,50					**140** L5s				**200** L5s
	4,00			**120** L3s					**180** L5s	
	5,00	**80** L3s	**100** L3s				**160** L5s – 2			
3,00	1,00	**80** L3s	**80** L3s	**100** L3s	**120** L3s	**120** L3s	**140** L5s	**160** L5s – 2	**160** L5s – 2	**180** L5s
	2,00		**90** L3s			**140** L5s				**200** L5s
	2,80			**120** L3s					**180** L5s	
	3,50	**80** L3s					**160** L5s – 2			
	4,00									
	5,00		**100** L3s						**200** L5s	**220** L7s – 2

* The CLT self-weight is already taken into account in the table at ρ = 500 kg/m³!

Service class 1, imposed load category A (ψ0 = 0.7; ψ1 = 0.5; ψ2 = 0.3)

Figure 5.29. Preliminary design table for continuous beam CLT boards. [32]

Ceiling slab preliminary design: **t_s = 160 mm**

Design loads of vertical CLT elements will be determined using the preliminary design method used in [6] for dimensioning of load-bearing sand-lime walls. This calculation is based on the dead and live loads of the floors and approximate load area of the walls.

Table 5.10 - Approximate most unfavorable line load of CLT walls

structure	**notes**	**f_k [kN/m²]**	**γ_f [-]**	**load width [m]**	**amount n [-]**	**$f_{w,k,i}$ [kN/m]**
roofing	self weight	1,20	1,35	10,40	1	12,48
	snow load	0,70	1,50			7,28
	live load	0,75	1,50			7,80
roof slab	self weight 0,16 . 5,0	0,80	1,35	5,20	1	4,16
ceiling slabs	self weight 0,16 . 5,0	0,80	1,35	5,20	2	8,32
	floor	1,89	1,35			19,66
	live load	2,00	1,50			20,80
	partitions	0,24	1,50			2,50

Table 5.11 - Approximate self weight of CLT walls of upper floors

structure	**notes**	**f_k [kN/m]**	**γ_f [-]**	**h [m]**	**$f_{k,total,sw}$ [kN/m]**
CLT	0,14 . 5,0	0,70	1,35	6,20	4,34

Total characteristic dead and live loads $f_{f,g,k}$ and $f_{f,q,k}$ considered in the preliminary design of CLT walls:

$$\mathbf{f_{w,g,k}} = \sum f_{w,g,k,i} = 12{,}48 + 4{,}16 + 8{,}32 + 19{,}66 + 4{,}34 = \mathbf{48{,}96\ kN/m^2}$$

$$\mathbf{f_{w,q,k}} = \sum f_{w,q,k,i} = 7{,}28 + 7{,}80 + 20{,}80 + 2{,}50 = \mathbf{38{,}38\ kN/m^2}$$

Structural height of the typical floors: h_w = 3,1 m.

The preliminary dimensions of CLT walls will be determined according to preliminary design tables (for external walls) presented in Figure 5.30:

External walls (w = 1.00 kN/m²)

In accordance with approval Z 9.1-559
DIN 1052 (2008) and/or EN 1995-1-1 (2006)

Dead weight gk*)	**Imposed load** nk	**Height (buckling length)**											
		2,50 m				**3,00 m**				**4,00 m**			
		R 0	**R 30**	**R 60**	**R 90**	**R 0**	**R 30**	**R 60**	**R 90**	**R 0**	**R 30**	**R 60**	**R 90**
10,00	10,00	60 C3s	80 C3s	80 C3s	120 C3s	60 C3s	80 C3s	100 C5s	120 C3s	60 C3s	80 C3s	100 C5s	120 C3s
	20,00			100 C5s						80 C3s			140 C5s
	30,00										90 C3s	120 C5s	
	40,00					80 C3s			140 C5s		100 C3s		
	50,00												
	60,00	80 C3s					90 C3s			90 C3s	100 C5s		
20,00	10,00	60 C3s	80 C3s	80 C3s	120 C3s	60 C3s	80 C3s	100 C5s	120 C3s	80 C3s	80 C3s	100 C5s	140 C5s
	20,00			100 C5s							90 C3s	120 C5s	
	30,00					80 C3s			140 C5s		100 C3s		
	40,00												
	50,00	80 C3s					90 C3s			90 C3s	100 C5s		
	60,00				140 C5s			120 C5s					
30,00	10,00	60 C3s	80 C3s	100 C5s	120 C3s	60 C3s	80 C3s	100 C5s	120 C3s	80 C3s	90 C3s	120 C5s	140 C5s
	20,00					80 C3s					100 C3s		
	30,00								140 C5s				
	40,00						90 C3s			90 C3s	100 C5s		
	50,00	80 C3s			140 C5s			120 C5s					
	60,00												
40,00	10,00	60 C3s	80 C3s	100 C5s	120 C3s	60 C3s	80 C3s	100 C5s	120 C3s	80 C3s	90 C3s	120 C5s	140 C5s
	20,00					80 C3s			140 C5s		100 C3s		
	30,00						90 C3s			90 C3s	100 C5s		
	40,00	80 C3s			140 C5s			120 C5s					
	50,00												
	60,00		90 C3s				100 C3s			100 C3s	120 C3s		
50,00	10,00	60 C3s	80 C3s	100 C5s	120 C3s	80 C3s	80 C3s	100 C5s	140 C5s	80 C3s	100 C3s	120 C5s	140 C5s
	20,00						90 C3s			90 C3s			
	30,00	80 C3s			140 C5s			120 C5s			100 C5s		
	40,00												
	50,00		90 C3s				100 C3s			100 C3s	120 C3s		
	60,00			120 C5s									
60,00	10,00	60 C3s	80 C3s	100 C5s	120 C3s	80 C3s	90 C3s	100 C5s	140 C5s	90 C3s	100 C3s	120 C5s	140 C5s
	20,00	80 C3s			140 C5s			120 C5s			100 C5s		
	30,00												
	40,00		90 C3s				100 C3s			100 C3s	120 C3s		
	50,00			120 C5s									
	60,00												160 C5s

* The CLT self-weight is already taken into account in the table at ρ = 500 kg/m³!

Service class 1, imposed load category A ($\psi_0 = 0.7$; $\psi_1 = 0.5$; $\psi_2 = 0.3$)

Figure 5.30. Preliminary design table for external walls made of CLT boards. [33]

Load-bearing wall preliminary design: **t_w = 120 mm**

Partition wall preliminary design: **$t_{w,p}$ = 80 mm**

The CLT structure will be designed as a platform framing system. The anchoring as illustrated in Figure 5.31 will approximately be accounted for in the LCA of the design, also. The amount of steel needed for anchoring is estimated below.

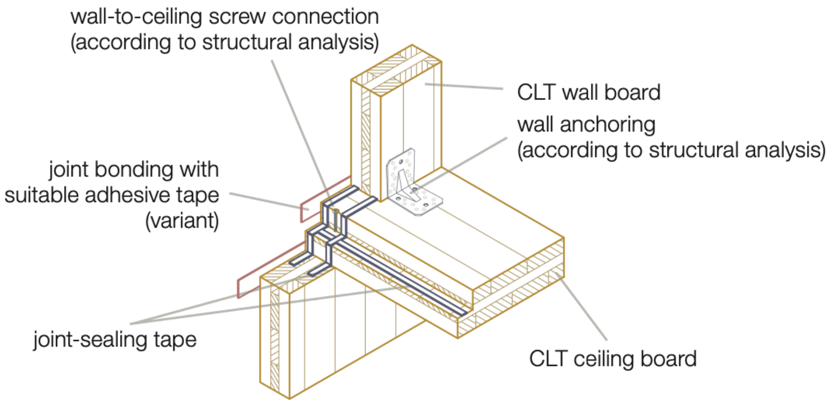


Figure 5.31. Platform framing CLT system. [34]

In this preliminary design, it will be assumed that the steel angles used for anchoring are placed 500 mm apart. The volume of a single steel angle will be estimated as 2,528 . 10^{-5} m^3, which represents an equal leg angle with dimensions of 80 x 80 mm and 2 mm thickness.

The quantity of angles required will be estimated based on the area and wall length of a typical living unit of the retirement home. The unit is 6,4 x 5,0 m, length of partition walls inside each unit is 5,7 m. Total volume of steel will be added to the material quantities extracted from the BIM-model.

Total unit wall length: $l = 5{,}0 + 6{,}4 + 5{,}0 + 5{,}7 = 22{,}1$ m
(one sided anchoring)
Quantity of angles per unit: $n_{unit} = l / 0{,}5 = 22{,}1 / 0{,}5 = 44{,}2$ pcs/unit
Livin unit area: $A_{unit} = 6{,}4 \,.\, 5{,}0 = 32{,}0$ m^2
Quantity of angles per m^2: $n_{m2} = n_{unit} / A_{unit} = 44{,}2 / 32{,}0 = 1{,}38$ pcs/m^2
Total floor area: $A = 2934$ m^2
Quantity of angles in total: $n = n_{m2} \,.\, A = 1{,}38 \,.\, 2934 \doteq 4050$ pcs
Total volume: $V = n \,.\, V_{angle} = 4050 \,.\, 2{,}528 \,.\, 10^{-5} = 0{,}1023$ m^3

The structural system of Alternative 2 remains the similar as of Alternative 1 in terms of the basement and the first floor with the only difference being lower reinforcement percentage of RC beam grid supporting the load-bearing walls (due to significantly lower self weight of CLT boards). In the upper floors, sand-lime blocks are replaced with CLT wall boards with thickness of 120 mm

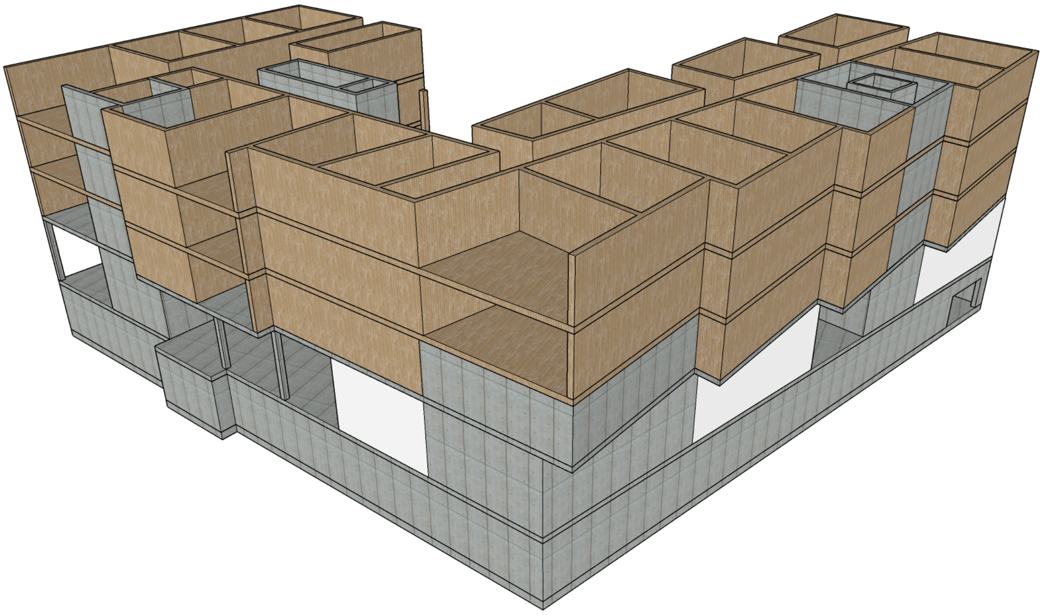


Figure 5.32. Schematic 3D model of the structural system of Alternative 2.

(load-bearing structures) or 80 mm (partition walls). The third floor, fourth floor and roof slabs are made of CLT floor boards with thickness of 160 mm.

The load-bearing structures are illustrated in Figure 5.32.

5.4.2. BIM-MODEL

Again, the BIM-model was created in accordance with 5.2.6, including the design of the foundation strips. It is presented in Figure 5.33.

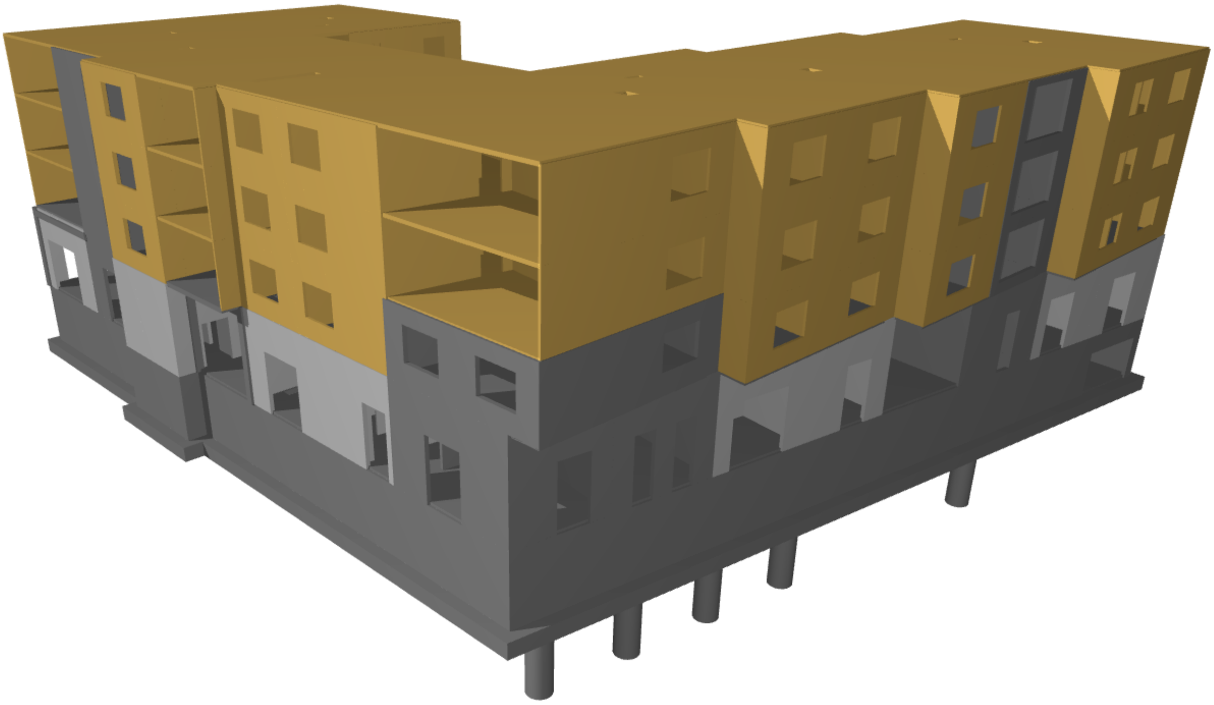


Figure 5.33. BIM-model of Alternative 2.

The volumes of used materials extracted from the model are listed in table 5.12:

Table 5.12 - Total volume and mass of materials - Alternative 2

Material	Total Volume [m³]	bulk density [kg/m³]	Total Mass [t]
Plain Concrete	231,8	2300,0	533,1
Reinforced Concrete (0,25 %)	353,2	2310,0	815,9
Reinforced Concrete (0,5 %)	1150,6	2330,0	2680,8
Reinforced Concrete (2,0 %)	27,9	2410,0	67,3
Reinforced Concrete (3,0 %)	73,8	2470,0	182,3
Sand-lime Blocks	249,7	2000,0	499,4
CLT	852,9	500,0	426,5
steel	0,1	7850,0	0,8
Polystyren, Extruded	54,8	25,0	1,4
Mineral Wool	147,5	115,0	17,0
Wood Fibre	352,3	160,0	56,4
Cellulose Fibre	337,6	50,0	16,9
∑	**3832,2**		**5297,7**

6. RESULTS

First of all, the results of Ecoinvent based assessment will be presented for all alternatives. The results of Ökobaudat based analysis will be described afterwards. Finally, a comparison of the two will be shown.

6.1. ECOINVENT

6.1.1. ORIGINAL DESIGN

The LCIA results of the original design are presented in Table 6.1 and Figure 6.1.

Table 6.1 - LCIA results - Ecoinvent - Original Design

Material	Total Mass [t]	PEIn [GJ]	GWP [t_{CO2}]	AP [kg_{SO2}]	EP [$kg_{PO4^{3-},eqv}$]	ODP [$g_{CFC2,eqv}$]	POCP [$kg_{C2H4,eqv}$]
Plain Concrete	533,1	306,5	58,6	98,6	24,5	2,0	3,6
Reinforced Concrete (0,25%)	460,1	350,2	55,9	104,2	33,2	1,9	6,3
Reinforced Concrete (0,5 %)	4771,5	4509,5	634,7	1277,3	467,9	22,2	97,1
Reinforced Concrete (2,0 %)	137,1	274,7	27,3	69,2	33,9	1,0	8,1
Hollow Fired Brick	1143,5	2943,0	272,9	623,9	196,7	20,4	45,4
Polystyren, Extruded	1,4	132,1	5,2	18,3	4,1	0,1	2,1
Mineral Wool	86,1	1737,9	97,5	719,4	157,5	4,8	38,3
∑	**7132,7**	**10254,0**	**1152,2**	**2910,8**	**917,8**	**52,4**	**200,9**

Relative Contribution	0 - 5 %	5 - 10 %	10 - 20 %	20 - 30 %	30 - 40 %	40 - 50 %	50+ %

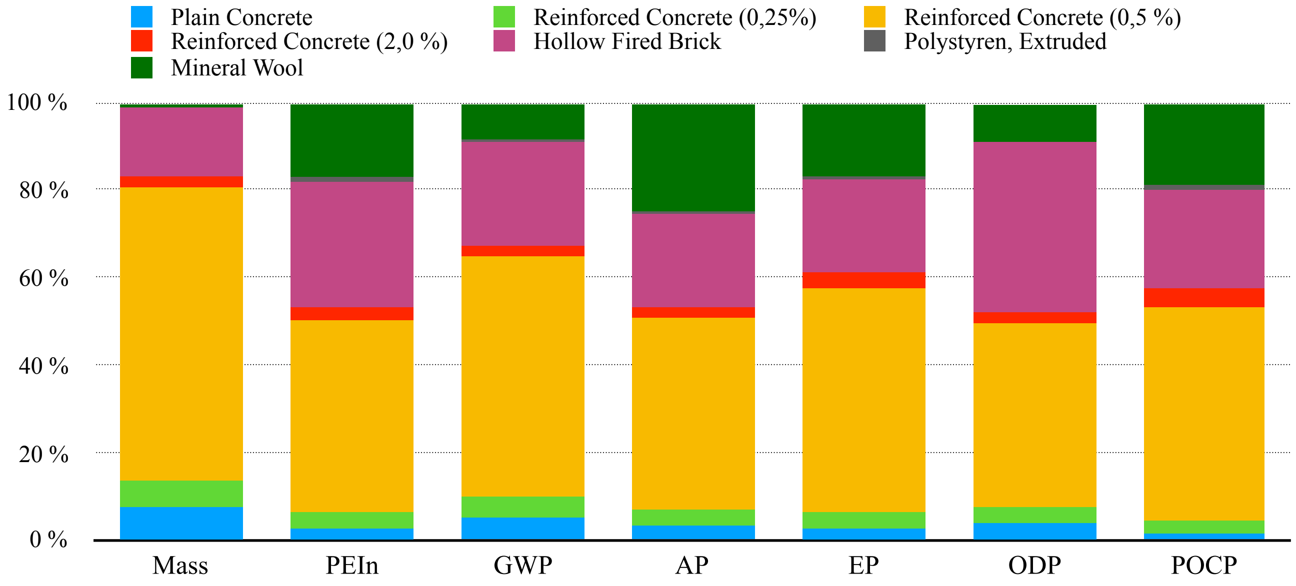


Figure 6.1. Relative contributions of materials to individual categories - Original Design.

6.1.2. ALTERNATIVE 1

The LCIA results of Alternative 1 are presented in Table 6.2 and Figure 6.2.

Table 6.2 - LCIA results - Ecoinvent - Alternative 1

Material	Total Mass [t]	PEIn [GJ]	GWP [t_{CO2}]	AP [kg_{SO2}]	EP [$kg_{PO4^{3-},eqv}$]	ODP [$g_{CFC2,eqv}$]	POCP [$kg_{C2H4,eqv}$]
Plain Concrete	533,1	306,5	58,6	98,6	24,5	2,0	3,6
Reinforced Concrete (0,25%)	808,5	615,4	98,3	183,2	58,4	3,4	11,0
Reinforced Concrete (0,5 %)	3948,1	3731,3	525,2	1056,9	387,1	18,4	80,3
Reinforced Concrete (2,0 %)	67,3	134,9	13,4	34,0	16,6	0,5	4,0
Reinforced Concrete (6,0 %)	194,1	873,7	69,0	206,3	116,1	2,7	29,3
Sand-lime Blocks	1700,6	2175,3	221,7	362,0	96,9	20,0	37,8
Polystyren, Extruded	1,4	132,1	5,2	18,3	4,1	0,1	2,1
Mineral Wool	18,7	376,7	21,1	155,9	34,1	1,0	8,3
Wood Fibre	61,5	114,9	10,8	63,3	26,1	0,5	1,9
Cellulose Fibre	16,9	120,6	6,2	49,0	10,8	0,7	2,1
∑	**7350,1**	**8581,4**	**1029,5**	**2227,4**	**774,8**	**49,2**	**180,3**

Relative Contribution	0 - 5 %	5 - 10 %	10 - 20 %	20 - 30 %	30 - 40 %	40 - 50 %	50+ %

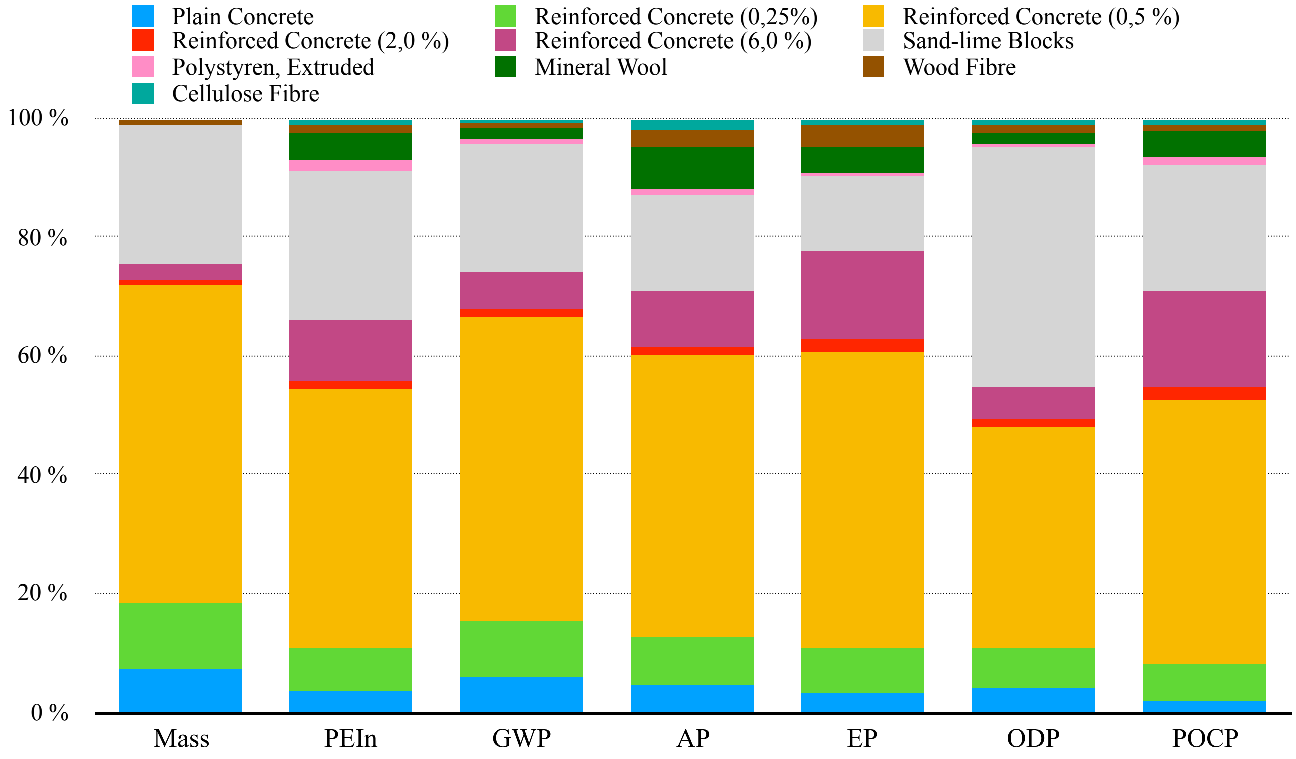


Figure 6.2. Relative contributions of materials to individual categories - Alternative 1.

6.1.3. ALTERNATIVE 2

The LCIA results of Alternative 2 are presented in Table 6.3 and Figure 6.3.

Table 6.3 - LCIA results - Ecoinvent - Alternative 2

Material	Total Mass [t]	PEIn [GJ]	GWP [t_{CO2}]	AP [kg_{SO2}]	EP [$kg_{PO4^{3-},eqv}$]	ODP [$g_{CFC2,eqv}$]	POCP [$kg_{C2H4,eqv}$]
Plain Concrete	533,1	306,5	58,6	98,6	24,5	2,0	3,6
Reinforced Concrete (0,25%)	815,9	621,0	99,2	184,8	58,9	3,4	11,1
Reinforced Concrete (0,5 %)	2680,8	2533,6	356,6	717,6	262,9	12,5	54,6
Reinforced Concrete (2,0 %)	67,3	134,9	13,4	34,0	16,6	0,5	4,0
Reinforced Concrete (3,0 %)	182,3	486,8	43,9	119,1	62,1	1,7	15,2
Sand-lime Blocks	499,4	638,8	65,1	106,3	28,5	5,9	11,1
CLT	426,5	2286,0	119,2	663,5	317,3	10,1	52,7
steel	0,8	23,4	2	6,6	3,8	0,0	1,0
Polystyren, Extruded	1,4	132,1	5,2	18,3	4,1	0,1	2,1
Mineral Wool	17,0	342,5	19,2	141,8	31,0	0,9	7,6
Wood Fibre	56,4	105,3	9,9	58,0	23,9	0,5	1,7
Cellulose Fibre	16,9	120,6	6,2	49,0	10,8	0,7	2,1

∑	**5297,7**	**7731,6**	**798,2**	**2197,7**	**844,4**	**38,3**	**166,6**

Relative Contribution	0 - 5 %	5 - 10 %	10 - 20 %	20 - 30 %	30 - 40 %	40 - 50 %	50+ %

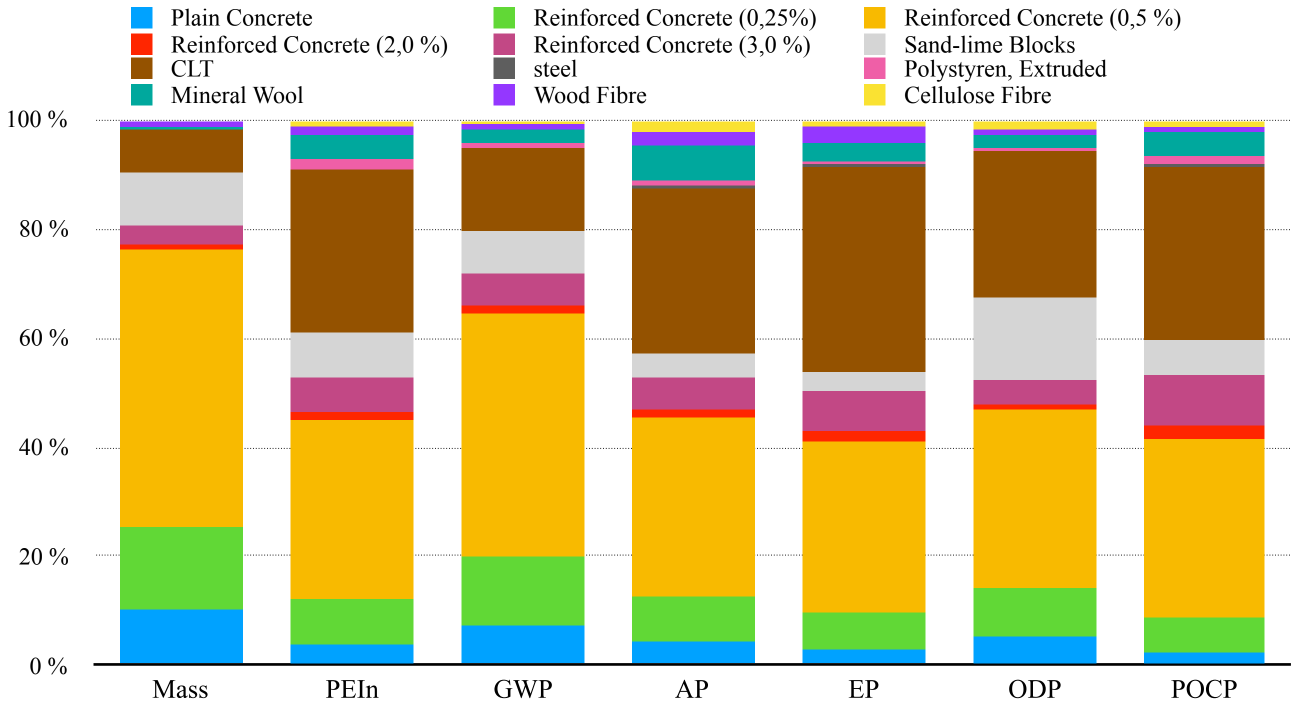


Figure 6.3. Relative contributions of materials to individual categories - Alternative 2.

6.1.4. ECOINVENT RESULTS COMPARISON

Following Tables and Figures present a comparison of weighted results based on the Ecoinvent database.

Table 6.4 - LCIA results - Ecoinvent - Comparison

Design Alternative	PEIn [GJ]	GWP [t_{CO2}]	AP [kg_{SO2}]	EP [$kg_{PO4^{3-},eqv}$]	ODP [$g_{CFC2,eqv}$]	POCP [$kg_{C2H4,eqv}$]	Total Weighted Score [%]
Original Design	**10254,0**	**1152,2**	**2910,8**	**917,8**	**52,4**	**200,9**	**74,4 %**
relative score	75,4 %	69,3 %	75,5 %	84,4 %	73,1 %	82,9 %	
weighted score	0,305	0,200	0,087	0,032	0,056	0,064	
Alternative 1	**8581,4**	**1029,5**	**2227,4**	**774,8**	**49,2**	**180,3**	**87,1 %**
relative score	90,1 %	77,5 %	98,7 %	100,0 %	77,8 %	92,4 %	
weighted score	0,364	0,224	0,113	0,038	0,060	0,071	
Alternative 2	**7731,6**	**798,2**	**2197,7**	**844,4**	**38,3**	**166,6**	**99,7 %**
relative score	100,0 %	100,0 %	100,0 %	91,8 %	100,0 %	100,0 %	
weighted score	0,404	0,289	0,115	0,035	0,077	0,077	

Alt. 1 Difference	-1672,5	-122,7	-683,4	-143,0	-3,2	-20,6	**12,7 %**
Alt. 2 Difference	-2522,4	-353,9	-713,1	-73,3	-14,1	-34,3	**25,3 %**

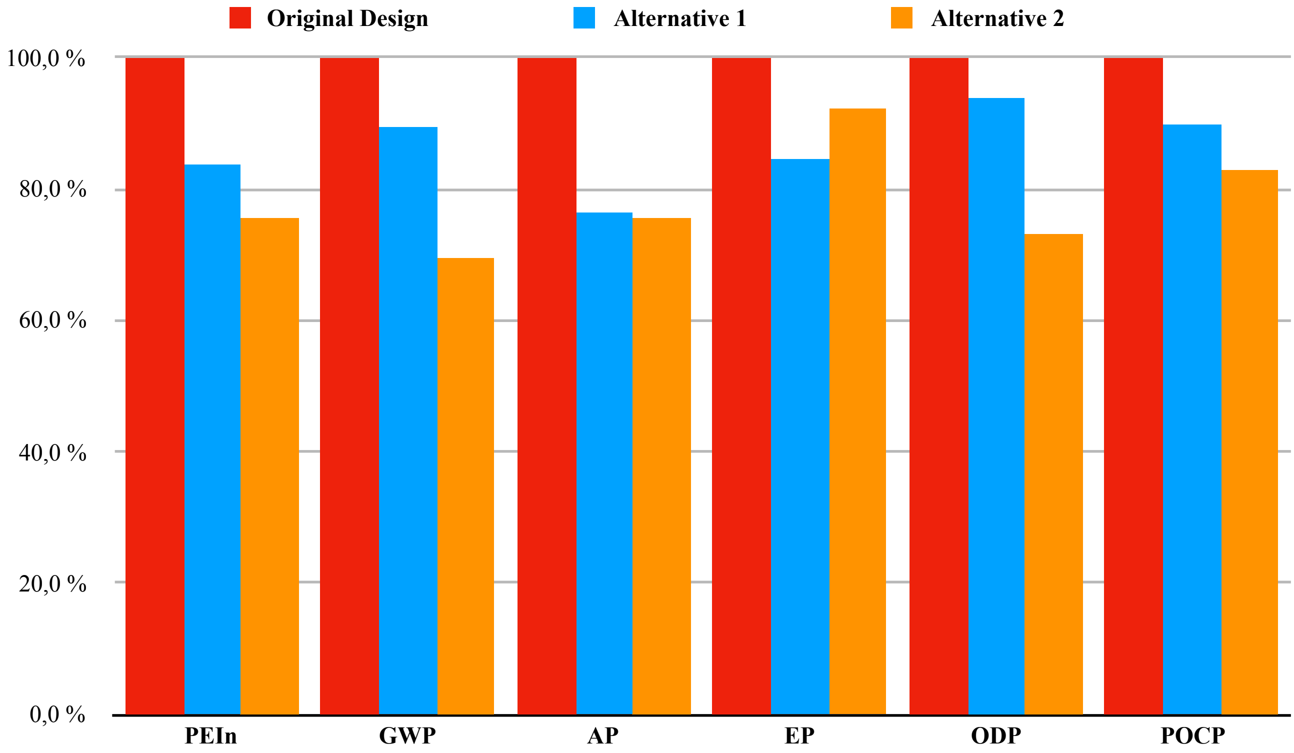


Figure 6.4. Relative comparison of each category for all alternatives (Ecoinvent).

6.2. ÖKOBAUDAT

6.2.1. ORIGINAL DESIGN

The Ökobaudat-based LCIA results of the original design are presented in Table 6.5 and Figure 6.5.

Table 6.5 - LCIA results - Ökobaudat - Original Design

Material	Total Mass [t]	PEIn [GJ]	GWP [t_{CO2}]	AP [kg_{SO2}]	EP [$kg_{PO4^{3-},eqv}$]	ODP [$g_{CFC2,eqv}$]	POCP [$kg_{C2H4,eqv}$]
Plain Concrete	533,1	244,3	48,6	70,4	13,1	1,3E-02	5,7
Reinforced Concrete (0,25%)	460,1	243,7	44,3	66,0	11,9	1,1E-02	6,0
Reinforced Concrete (0,5 %)	4771,5	2864,8	483,6	737,6	130,2	1,2E-01	72,4
Reinforced Concrete (2,0 %)	137,1	138,0	17,9	30,0	4,8	3,2E-03	3,8
Hollow Fired Brick	1143,5	2575,4	275,0	391,2	42,2	2,9E-03	26,2
Polystyren, Extruded	1,4	121,3	4,0	6,3	0,8	4,1E-08	2,0
Mineral Wool	86,1	1019,5	109,2	524,5	58,5	1,4E-04	25,9

∑	**7132,7**	**7207,0**	**982,6**	**1826,0**	**261,5**	**1,5E-01**	**142,0**

Relative Contribution	0 - 5 %	5 - 10 %	10 - 20 %	20 - 30 %	30 - 40 %	40 - 50 %	50+ %

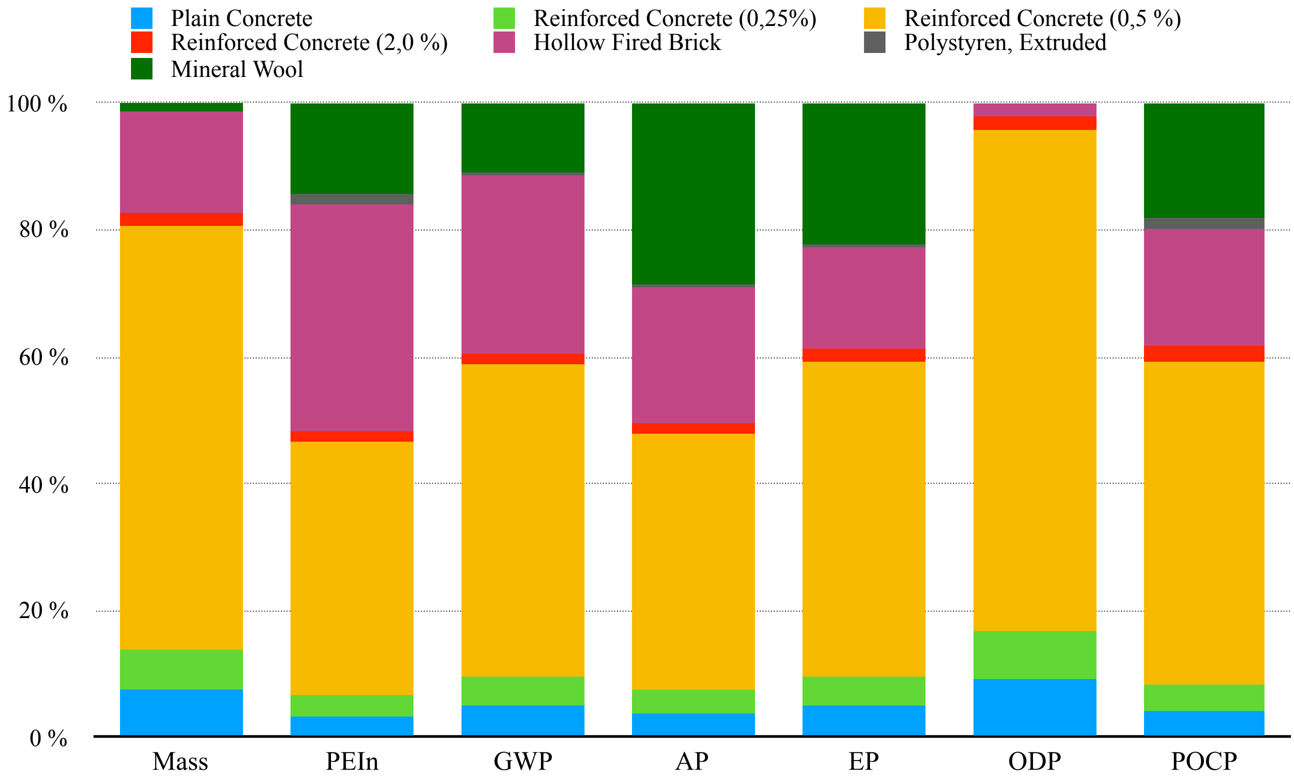


Figure 6.5. Relative contributions of materials to individual categories - Original Design.

6.2.2. ALTERNATIVE 1

The LCIA results of Alternative 1 are presented in Table 6.6 and Figure 6.6.

Table 6.6 - LCIA results - Ökobaudat - Alternative 1

Material	Total Mass [t]	PEIn [GJ]	GWP [t$_{CO2}$]	AP [kg$_{SO2}$]	EP [kg$_{PO_4^{3-},eqv}$]	ODP [g$_{CFC2,eqv}$]	POCP [kg$_{C2H4,eqv}$]
Plain Concrete	533,1	244,3	48,6	70,4	13,1	0,0	5,7
Reinforced Concrete (0,003%)	808,5	428,4	77,9	115,9	21,0	0,0	10,5
Reinforced Concrete (0,5 %)	3948,1	2370,4	400,1	610,3	107,8	0,1	59,9
Reinforced Concrete (2,0 %)	67,3	67,8	8,8	14,7	2,4	0,0	1,9
Reinforced Concrete (6,0 %)	194,1	381,4	38,5	72,0	10,3	0,0	11,2
Sand-lime Blocks	1700,6	1723,4	258,0	187,4	46,3	0,0	-12,2
Polystyren, Extruded	1,4	121,3	4,0	6,3	0,8	0,0	2,0
Mineral Wool	18,7	221,0	23,7	113,7	12,7	0,0	5,6
Wood Fibre	61,5	711,5	-67,5	119,1	27,2	0,3	26,4
Cellulose Fibre	16,9	33,9	-21,6	16,9	3,0	0,1	1,4

∑	**7350,1**	**6303,3**	**770,5**	**1326,8**	**244,5**	**0,5**	**112,4**

Relative Contribution	0 - 5 %	5 - 10 %	10 - 20 %	20 - 30 %	30 - 40 %	40 - 50 %	50+ %

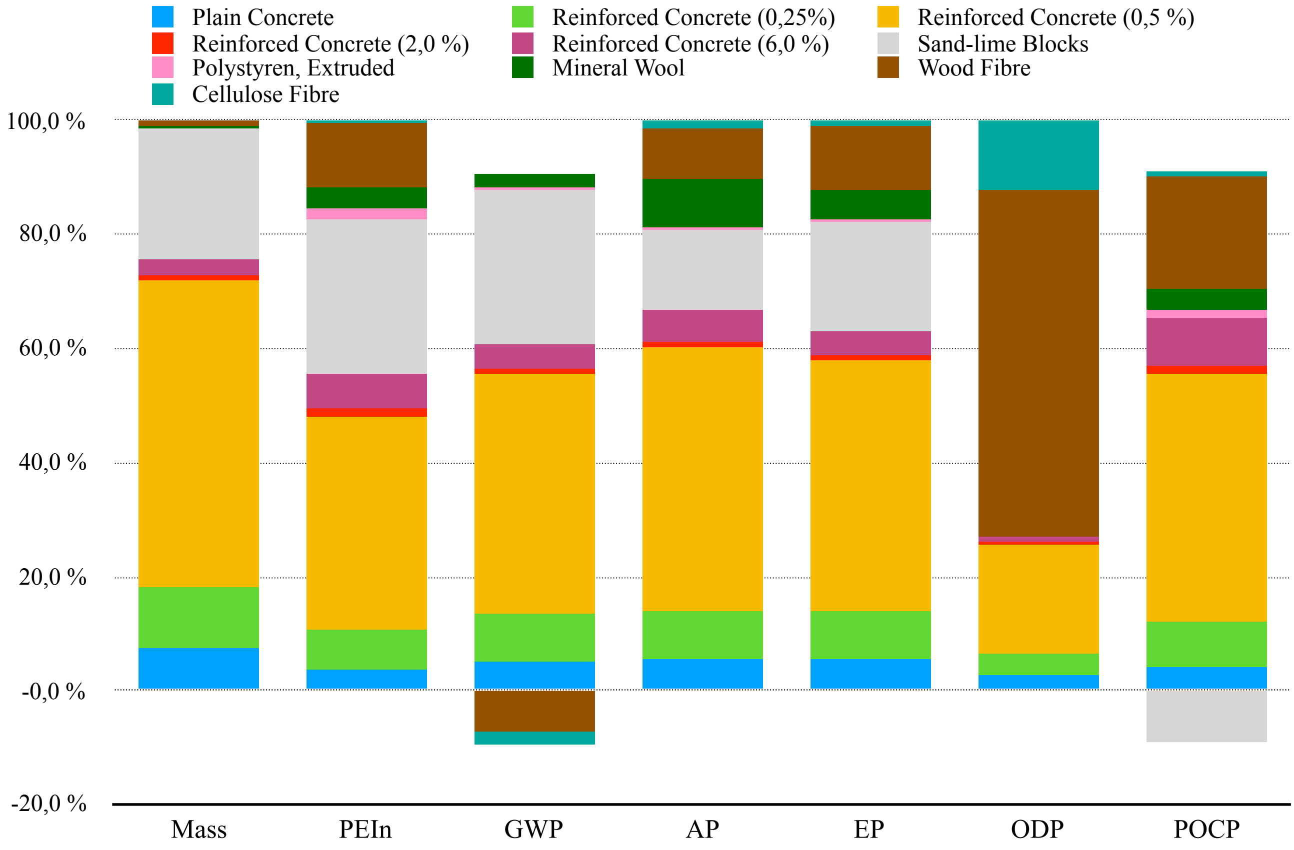


Figure 6.6. Relative contributions of materials to individual categories - Alternative 1.

6.2.3. ALTERNATIVE 2

The LCIA results of Alternative 2 are presented in Table 6.7 and Figure 6.7.

Table 6.7 - LCIA results - Ökobaudat - Alternative 2

Material	Total Mass [t]	PEIn [GJ]	GWP [t_{CO2}]	AP [kg_{SO2}]	EP [$kg_{PO_4^{3-},eqv}$]	ODP [$g_{CFC2,eqv}$]	POCP [$kg_{C2H4,eqv}$]
Plain Concrete	533,1	244,3	48,6	70,4	13,1	0,0	5,7
Reinforced Concrete (0,25%)	815,9	432,3	78,6	117,0	21,2	0,0	10,6
Reinforced Concrete (0,5 %)	2680,8	1609,5	271,7	414,4	73,2	0,1	40,7
Reinforced Concrete (2,0 %)	67,3	67,8	8,8	14,7	2,4	0,0	1,9
Reinforced Concrete (3,0 %)	182,3	230,1	27,1	47,3	7,2	0,0	6,5
Sand-lime Blocks	499,4	506,1	75,8	55,0	13,6	0,0	-3,6
CLT	426,5	1975,2	-556,6	593,6	138,6	0,8	112,2
steel	0,8	14,3	1	2,8	0,3	0,0	0,6
Polystyren, Extruded	1,4	121,3	4,0	6,3	0,8	0,0	2,0
Mineral Wool	17,0	200,9	21,5	103,4	11,5	0,0	5,1
Wood Fibre	56,4	652,2	-61,9	109,2	25,0	0,3	24,2
Cellulose Fibre	16,9	33,9	-21,6	16,9	3,0	0,1	1,4

∑	**5297,7**	**6088,0**	**-102,7**	**1551,1**	**309,9**	**1,2**	**207,3**

Relative Contribution	0 - 5 %	5 - 10 %	10 - 20 %	20 - 30 %	30 - 40 %	40 - 50 %	50+ %

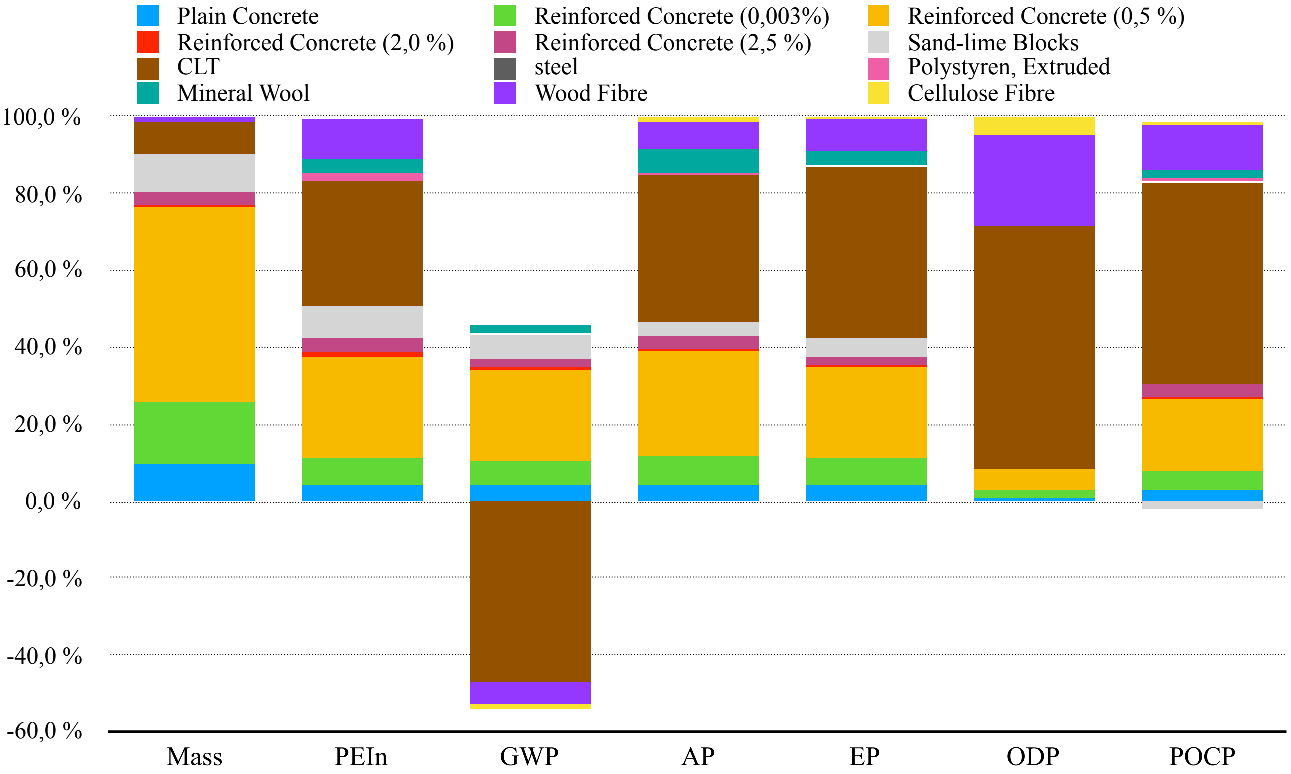


Figure 6.7. Relative contributions of materials to individual categories - Alternative 2.

6.2.4. ÖKOBAUDAT RESULTS COMPARISON

Following Tables and Figures present a comparison of weighted results based on the Ökobaudat database.

Table 6.8 - LCIA results - Ökobaudat - Comparison

Design Alternative	PEIn [GJ]	GWP [t_{CO2}]	AP [kg_{SO2}]	EP [$kg_{PO4^{3-},eqv}$]	ODP [$g_{CFC2,eqv}$]	POCP [$kg_{C2H4,eqv}$]	Total Weighted Score [%]
Original Design	**7207,0**	**982,6**	**1826,0**	**261,5**	**0,1**	**142,0**	**62,6 %**
relative score	84,5 %	9,5 %	72,7 %	93,5 %	100,0 %	79,2 %	
weighted score	0,341	0,027	0,084	0,036	0,077	0,061	
Alternative 1	**6303,3**	**770,5**	**1326,8**	**244,5**	**0,5**	**112,4**	**67,7 %**
relative score	96,6 %	11,8 %	100,0 %	100,0 %	29,2 %	100,0 %	
weighted score	0,390	0,034	0,115	0,038	0,023	0,077	
Alternative 2	**6088,0**	**-102,7**	**1551,1**	**309,9**	**1,2**	**207,3**	**87,3 %**
relative score	100,0 %	100,0 %	85,5 %	78,9 %	12,3 %	54,2 %	
weighted score	0,404	0,289	0,098	0,030	0,009	0,042	

Alt. 1 Difference	-903,7	-212,1	-499,3	-17,0	0,4	-29,6	**5,1 %**
Alt. 2 Difference	-1119,0	-1085,3	-274,9	48,3	1,1	65,3	**24,7 %**

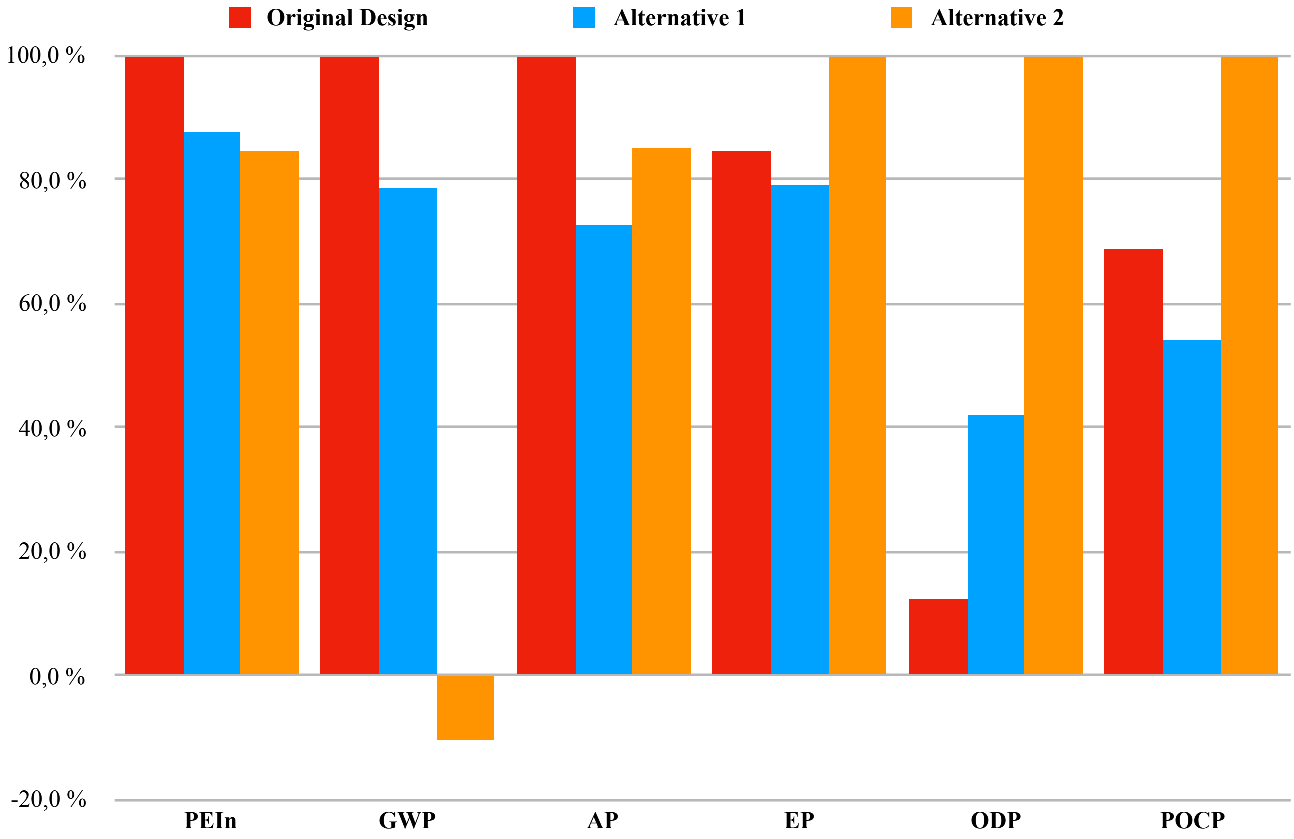


Figure 6.8. Relative comparison of each category for all alternatives (Ökobaudat).

6.3. SUMMARY

The results of the assessment show that the hybrid structural system of design alternative 2 made of reinforced concrete and CLT boards performs significantly better than the original design and Alternative 1. The overall scores of each alternative are presented in Table 7.1:

Table 7.1 - Relative score of design alternatives

Rank	Alternative	Ecoinvent score	Ökobaudat score
1	**Alternative 2 - RC walls + CLT boards**	**99,7 %**	**87,3 %**
2	Alternative 1 - RC + sand-lime blocks	87,1 %	67,7 %
3	Original - RC columns + hollow fired bricks	74,4 %	62,6 %

Although the absolute values of each category differ to a notable extent depending on the LCIA database used (Table 7.2), the ranking of design alternatives remains the same by a rather safe margin.

Table 7.2 - LCIA results - Ecoinvent vs. Ökobaudat comparison

design alternative	LCIA database	PEIn [GJ]	GWP [t_{CO2}]	AP [kg_{SO2}]	EP [$kg_{PO4^{3-},eqv}$]	ODP [$g_{CFC2,eqv}$]	POCP [$kg_{C2H4,eqv}$]
Original Design	**Ecoinvent**	**10254,0**	**1152,2**	**2910,8**	**917,8**	**52,4**	**200,9**
	Ökobaudat	**7207,0**	**982,6**	**1826,0**	**261,5**	**0,1**	**142,0**
	difference	-3046,9	-169,6	-1084,8	-656,2	-52,2	-59,0
		-29,7 %	-14,7 %	-37,3 %	-71,5 %	-99,7 %	-29,4 %
Alternative 1	**Ecoinvent**	**8581,4**	**1029,5**	**2227,4**	**774,8**	**49,2**	**180,3**
	Ökobaudat	**6303,3**	**770,5**	**1326,8**	**244,5**	**0,5**	**112,4**
	difference	-2278,1	-259,0	-900,6	-530,2	-48,7	-67,9
		-26,5 %	-25,2 %	-40,4 %	-68,4 %	-99,0 %	-37,7 %
Alternative 2	**Ecoinvent**	**7731,6**	**798,2**	**2197,7**	**844,4**	**38,3**	**166,6**
	Ökobaudat	**6088,0**	**-102,7**	**1551,1**	**309,9**	**1,2**	**207,3**
	difference	-1643,6	-900,9	-646,6	-534,5	-37,1	40,7
		-21,3 %	-112,9 %	-29,4 %	-63,3 %	-96,9 %	24,4 %

Tables and Figures 6.1 - 6.3 and 6.5 - 6.7 point out the most influential items of the assessment. In cases of the Original Design and Alternative 1, reinforced concrete made up the most notable portion of the total impact in each category. Replacing of the concrete by cross-laminated timber boards lead to considerable savings in terms of needed primary energy and $CO_{2,eqv}$ emissions —in accordance with Ökobaudat dataset—or even in all evaluated categories—based on the Ecoinvent dataset.

7. DISCUSSION

The fact that the overall ranking of design alternatives remained unaffected by the selection of LCIA datasets adds to the credibility of the assessment results. These results also correspond to the outcomes of the researched case studies presented in 4.1 - 4.4.

7.1. CASE STUDIES COMPARISON

All of the reviewed studies show that timber design alternatives perform better in the global warming potential category by 25 - 80 %. This is true in the case of Retirement Home in Horoměřice, as well. Based on the Ecoinvent results, the GWP improvement is equal to 30 %. In the instance of Ökobaudat results, the improvement even exceeds 100% as Alternative 2 attained negative values of $CO_{2,eqv}$ emissions production (due to different system boundaries used).

The case study of two residential building in Canada (4.2) claims that improvements in all but one category (i.e. evaluated in this study) are achieved when timber structure is implemented. This correlates with the Ecoinvent results (Figure 7.1) whereas the Ökobaudat results have proven to be parallel to the findings of the case study 4.3 (Figure 7.2).

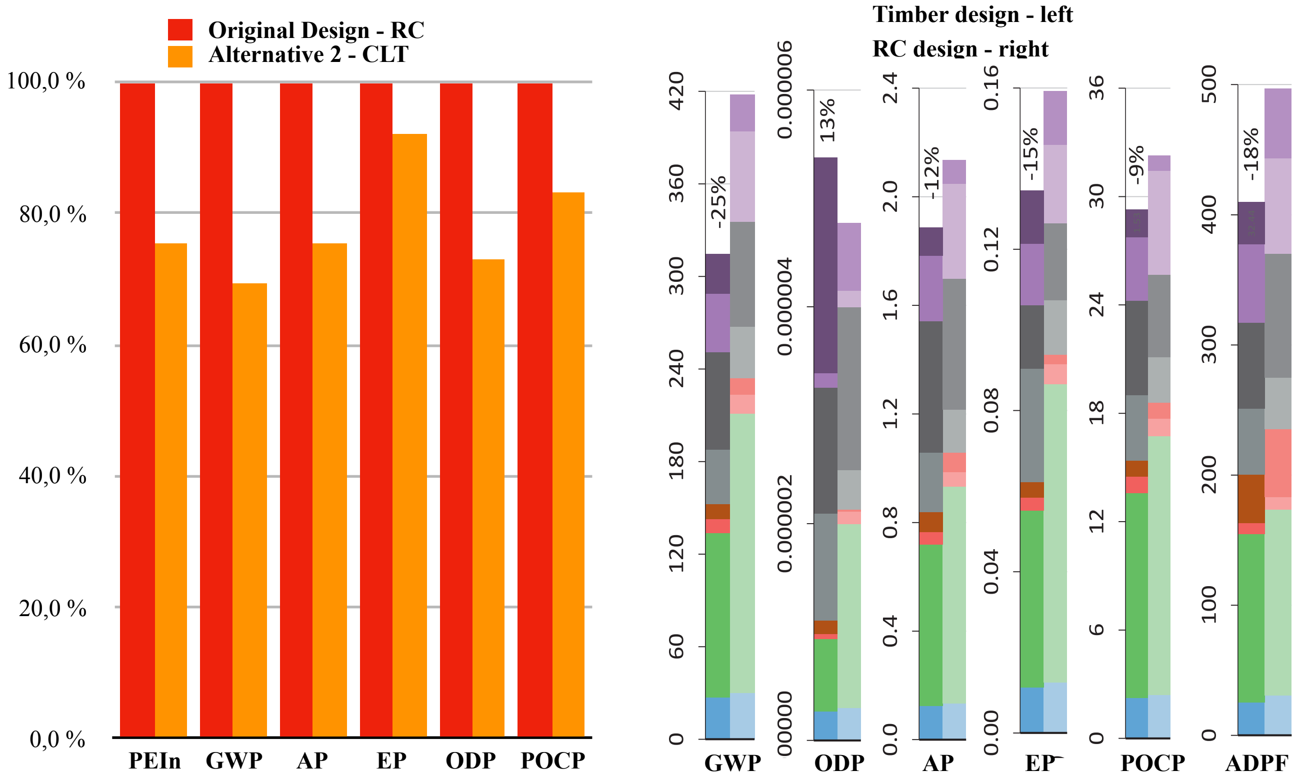


Figure 7.1. Comparison of LCA results (Ecoinvent) with reviewed case study (4.2) results [13].

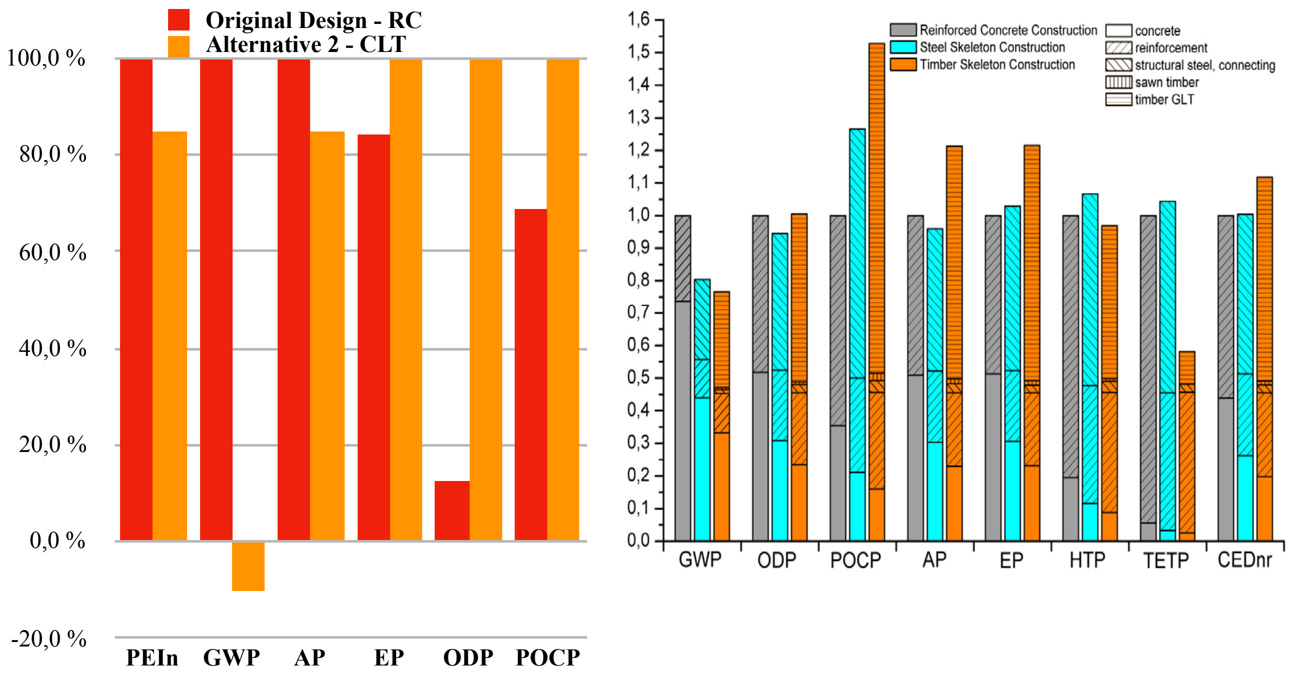


Figure 7.2. Comparison of LCA results (Ökobaudat) with reviewed case study (4.3) results [12].

7.2. UNCERTAINTIES

It is necessary, however, to also address the uncertainties of the conducted LCA. Figures 7.1 and 7.2 show that the presented results are dependent on the chosen LCA methodology.

While the results based on the Ecoinvent database clearly favor the timber design alternative, the Ökobaudat results, without the use of weighting, are rather inconclusive (Figure 7.2). This demonstrates the importance of scope definition, especially the definition of **system boundaries** and the selection of **environmental categories**, as various LCIA input databases may produce different outcomes.

The process of **weighting** brings uncertainties in the assessment as weighting sets are always subjective. Many studies propose numerous strategies of weighting based on extensive surveys of this issue. The results of this LCA may vary significantly depending on the selected weights of individual impact indicators.

Another uncertainty arises from the **location coverage** of input LCIA data. As mentioned in 5.1.4, Ecoinvent data specified for the region “Europe without Switzerland” was used in this LCA. The broadness of this location coverage may prove to be significant. In order to obtain more accurate results, environmental product declarations (EPDs) of local manufacturers should be used as LCIA input sources. A large percentage of the Ökobaudat database is based precisely on EPDs provided by local producers. Depending on the states of Czech and German production technology and procedures, this database may be more suitable.

Reinforcement percentage of concrete structures plays a noteworthy role in the impact assessment and it is, therefore, crucial to account for appropriate values in the analysis. The reinforcement percentages considered for all RC elements in this study are presented in Annex I. These are based on the preliminary design of structural system of Alternative 1 [6] and reinforcement detailing according to ČSN EN 1992-1-1 [35]. Preliminary design is a subject to change, however, and, ultimately, the reinforcement percentages of concrete structures considered in the LCA might not reflect the final state of the design. The LCA results show that reinforced concrete makes up a key share of total environmental impacts in all considered design alternatives. Consequently, final results of the assessment may vary depending on the amount of reinforcement steel used.

8. CONCLUSION

The goal of the thesis was to determine the environmental impacts of design alternatives of the Retirement Home in Horoměřice, Czech Republic. Three alternatives were considered: the Original Design (RC structural system), Alternative 1 (RC + sand-lime masonry) and Alternative 2 (RC + CLT boards). A "cradle-to-gate" life cycle assessment was conducted based on two LCIA data sources - Ecoinvent and Ökobaudat

The Ecoinvent results show that substantial improvements in all but one evaluated category can be achieved by replacing reinforced concrete by timber elements. Comparison with the Ökobaudat results does not confirm the conclusively better performance of the CLT system, but the overall weighted score of the Alternative 2 remains to be the highest in both cases nonetheless. Alternative 2 (Figure 8.1) was, therefore, selected as the design with the lowest environmental impact.

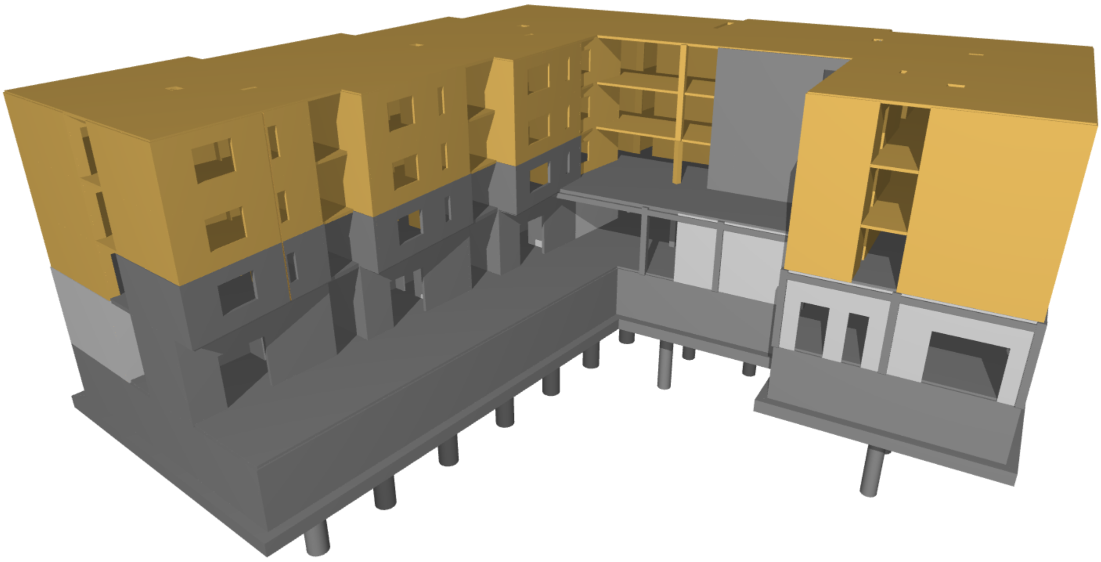


Figure 8.1. BIM-model of Alternative 2.

The study suggests that timber structures provide a way of mitigation of environmental footprints of buildings. It acknowledges, however, the uncertainties of the assessment and the fact that the greatest potential for improvements in the present state of the construction industry lies in the operational phase of the life cycle.

In the case of the retirement home other design modifications could be applied in order to decrease its environmental impacts that would require cooperation with the architect and other specialists (such as possible removal of underground car park, more compact architectural design, renewable energy usage, etc.).

9. ANNEX I: CONCRETE REINFORCEMENT PERCENTAGE ESTIMATION

The percentage of reinforcement was estimated for all considered structural elements. The values were either taken over from *Bearing Structure of Retirement Home in Horoměřice* [6] or reinforcement detailing according to ČSN EN 1992-1-1 [35].

Reinforcement percentage of concrete **slabs** is assumed at 0,5 % [6]. This corresponds with a 240 mm thick two way slab reinforced by ∅10 bars with 120 mm spacing.

Reinforcement of concrete **walls** is assumed at 0,25 %. Based on the structural analysis performed in [6], the reinforcement of the walls was not necessary. The value was, therefore, taken over from [35] as the lowest amount of reinforcement possible.

Reinforcement percentage of concrete **columns** is assumed at 2,0 % [6]. This is roughly equal to a 300 x 300 mm column reinforced by 4 ∅22 bars and ∅10 stirrups with 300 mm spacing.

Reinforcement percentage of concrete **foundation piles** is assumed at 0,5 % [6].

Reinforcement percentage of the concrete **beam grid** (first floor / second floor slabs) supporting the load-bearing walls of upper floors is assumed at 6,0 % [6] for the Alternative 1 (sand-lime walls + RC slabs) and 3,0 % for the Alternative 2 (CLT walls + CLT slabs).

10. ANNEX II: ENVIRONMENTAL IMPACT INDICATOR VALUES OF USED MATERIALS

The following Tables present the values of selected midpoint impact categories of materials used in the life cycle assessment. Values for reinforced concrete were calculated manually based on the values of plain concrete and reinforcement steel, and the percentage of reinforcement. Ecoinvent values are shown first, Ökobaudat values second.

Table 10.1 - Environmental Indicators of Selected Materials - Ecoinvent

	material	ρ_{avg} [kg/m^3]	PEIn [MJ/kg]	GWP [kg$_{CO2}$/kg]	AP [g$_{SO2}$/kg]	EP [g$_{PO_4^{3-},eqv}$/kg]	ODP [g$_{CFC2,eqv}$/kg]	POCP [g$_{C2H4,eqv}$/kg]
masonry	hollow fired brick	825,0	2,574E+00	2,386E-01	5,456E-01	1,720E-01	1,780E-05	3,972E-02
	sand-lime block	2000,0	1,279E+00	1,304E-01	2,128E-01	5,700E-02	1,174E-05	2,223E-02
concrete and reinforced concrete	plain concrete	2300,0	5,749E-01	1,099E-01	1,849E-01	4,600E-02	3,706E-06	6,778E-03
	reinforced concrete (0,25 %)	2310,0	7,611E-01	1,215E-01	2,265E-01	7,218E-02	4,183E-06	1,360E-02
	reinforced concrete (0,5 %)	2330,0	9,451E-01	1,330E-01	2,677E-01	9,805E-02	4,655E-06	2,035E-02
	reinforced concrete (2,0 %)	2410,0	2,004E+00	1,992E-01	5,046E-01	2,470E-01	7,371E-06	5,919E-02
	reinforced concrete (3,0 %)	2470,0	2,671E+00	2,409E-01	6,537E-01	3,407E-01	9,081E-06	8,362E-02
	reinforced concrete (6,0 %)	2630,0	4,502E+00	3,553E-01	1,063E+00	5,982E-01	1,378E-05	1,507E-01
thermal insulation	polystyren, expanded	15,0	1,051E+02	4,212E+00	1,490E+01	2,549E+00	1,320E-04	6,755E+00
	polystyren, extruded	25,0	9,651E+01	3,821E+00	1,339E+01	3,012E+00	8,839E-05	1,537E+00
	mineral wool	115,0	2,019E+01	1,133E+00	8,358E+00	1,830E+00	5,537E-05	4,454E-01
	wood fibre	160,0	1,869E+00	1,757E-01	1,029E+00	4,241E-01	8,055E-06	3,022E-02
	cellulose fibre	50,0	7,144E+00	3,678E-01	2,905E+00	6,380E-01	4,046E-05	1,218E-01
other	CLT	500,0	5,360E+00	2,795E-01	1,556E+00	7,440E-01	2,380E-05	1,235E-01
	reinforcement steel	7850,0	2,253E+01	1,482E+00	5,095E+00	3,133E+00	6,000E-05	8,116E-01
	steel	7850,0	2,907E+01	2,092E+00	8,274E+00	4,772E+00	5,777E-05	1,184E+00

Table 10.2 - Environmental Indicators of Selected Materials - Ökobaudat

	material	ρ_{avg} [kg/m^3]	PEI [MJ/kg]	GWP [kg$_{CO2}$/kg]	AP [g$_{SO2}$/kg]	EP [g$_{PO_4^{3-},eqv}$/kg]	ODP [g$_{CFC2,eqv}$/kg]	POCP [g$_{C2H4,eqv}$/kg]
masonry	hollow fired brick	825,0	2,252E+00	2,405E-01	3,421E-01	3,689E-02	2,539E-09	2,294E-02
	sand-lime block	2000,0	1,013E+00	1,517E-01	1,102E-01	2,722E-02	7,029E-13	-7,185E-03
concrete and reinforced concrete	plain concrete	2300,0	4,583E-01	9,125E-02	1,321E-01	2,463E-02	2,488E-08	1,075E-02
	reinforced concrete (0,25 %)	2310,0	5,298E-01	9,633E-02	1,434E-01	2,597E-02	2,466E-08	1,297E-02
	reinforced concrete (0,5 %)	2330,0	6,004E-01	1,014E-01	1,546E-01	2,729E-02	2,446E-08	1,516E-02
	reinforced concrete (2,0 %)	2410,0	1,007E+00	1,303E-01	2,190E-01	3,493E-02	2,326E-08	2,780E-02
	reinforced concrete (3,0 %)	2470,0	1,263E+00	1,485E-01	2,595E-01	3,974E-02	2,250E-08	3,575E-02
	reinforced concrete (6,0 %)	2630,0	1,965E+00	1,984E-01	3,708E-01	5,294E-02	2,043E-08	5,758E-02
thermal insulation	polystyren, expanded	15,0	7,974E+01	2,621E+00	5,991E+00	5,507E-01	1,502E-05	1,969E+01
	polystyren, extruded	25,0	8,859E+01	2,894E+00	4,620E+00	5,930E-01	2,979E-11	1,428E+00
	mineral wool	115,0	1,185E+01	1,269E+00	6,094E+00	6,792E-01	1,625E-09	3,010E-01
	wood fibre	160,0	1,157E+01	-1,097E+00	1,937E+00	4,431E-01	4,989E-06	4,299E-01
	cellulose fibre	50,0	2,006E+00	-1,281E+00	1,000E+00	1,786E-01	3,689E-06	8,571E-02
other	CLT	500,0	4,632E+00	-1,305E+00	1,392E+00	3,250E-01	1,767E-06	2,632E-01
	reinforcement steel	7850,0	8,883E+00	6,904E-01	1,466E+00	1,829E-01	2,119E-11	2,725E-01
	steel	7850,0	1,780E+01	1,735E+00	3,520E+00	3,700E-01	1,390E-07	6,980E-01

Table 10.3 - Environmental Indicators of Reinforced Concrete - Ecoinvent

relative reinforcement volume	material	PEIn [MJ/kg]	GWP [kg$_{CO2}$/kg]	AP [g$_{SO2}$/kg]	EP [g$_{PO4^{3-},eqv}$/kg]	ODP [g$_{CFC2,eqv}$/kg]	POCP [g$_{C2H4,eqv}$/kg]	bulk density [kg/m³]	relative volume [%]	relative mass [-]	weighted PEIn [MJ/kg]	weighted GWP [kg$_{CO2}$/kg]	weighted AP [g$_{SO2}$/kg]	weighted EP [g$_{PO4^{3-},eqv}$/kg]	weighted ODP [g$_{CFC2,eqv}$/kg]	weighted POCP [g$_{C2H4,eqv}$/kg]
0,25 %	plain concrete	5,749E-01	1,099E-01	1,849E-01	4,600E-02	3,706E-06	6,778E-03	2300	99,75	116,90	7,611E-01	1,215E-01	2,265E-01	7,218E-02	4,183E-06	1,360E-02
	reinforcement steel	2,253E+01	1,482E+00	5,095E+00	3,133E+00	6,000E-05	8,116E-01	7850	0,25	1,00						
0,5 %	plain concrete	5,749E-01	1,099E-01	1,849E-01	4,600E-02	3,706E-06	6,778E-03	2300	99,5	58,31	9,451E-01	1,330E-01	2,677E-01	9,805E-02	4,655E-06	2,035E-02
	reinforcement steel	2,253E+01	1,482E+00	5,095E+00	3,133E+00	6,000E-05	8,116E-01	7850	0,5	1,00						
2,0 %	plain concrete	5,749E-01	1,099E-01	1,849E-01	4,600E-02	3,706E-06	6,778E-03	2300	98,0	14,36	2,004E+00	1,992E-01	5,046E-01	2,470E-01	7,371E-06	5,919E-02
	reinforcement steel	2,253E+01	1,482E+00	5,095E+00	3,133E+00	6,000E-05	8,116E-01	7850	2,0	1,00						
3,0 %	plain concrete	5,749E-01	1,099E-01	1,849E-01	4,600E-02	3,706E-06	6,778E-03	2300	97,0	9,47	2,671E+00	2,409E-01	6,537E-01	3,407E-01	9,081E-06	8,362E-02
	reinforcement steel	2,253E+01	1,482E+00	5,095E+00	3,133E+00	6,000E-05	8,116E-01	7850	3,0	1,00						
6,0 %	plain concrete	5,749E-01	1,099E-01	1,849E-01	4,600E-02	3,706E-06	6,778E-03	2300	94,0	4,59	4,502E+00	3,553E-01	1,063E+00	5,982E-01	1,378E-05	1,507E-01
	reinforcement steel	2,253E+01	1,482E+00	5,095E+00	3,133E+00	6,000E-05	8,116E-01	7850	6,0	1,00						

Table 10.4 - Environmental Indicators of Reinforced Concrete - Ökobaudat

relative reinforcement volume	materiál	PEI [MJ/kg]	GWP [kg$_{CO2}$/kg]	AP [g$_{SO2}$/kg]	EP [g$_{PO4^{3-},eqv}$/kg]	ODP [g$_{CFC2,eqv}$/kg]	POCP [g$_{C2H4,eqv}$/kg]	bulk density [kg/m³]	relative volume [-]	relative mass [-]	weighted PEI [MJ/kg]	weighted GWP [kg$_{CO2}$/kg]	weighted AP [g$_{SO2}$/kg]	weighted EP [g$_{PO4^{3-},eqv}$/kg]	weighted ODP [g$_{CFC2,eqv}$/kg]	weighted POCP [g$_{C2H4,eqv}$/kg]
0,25 %	plain concrete	4,583E-01	9,125E-02	1,321E-01	2,463E-02	2,488E-08	1,075E-02	2300	99,75	116,90	5,298E-01	9,633E-02	1,434E-01	2,597E-02	2,466E-08	1,297E-02
	reinforcement steel	8,883E+00	6,904E-01	1,466E+00	1,829E-01	2,119E-11	2,725E-01	7850	0,25	1,00						
0,5 %	plain concrete	4,583E-01	9,125E-02	1,321E-01	2,463E-02	2,488E-08	1,075E-02	2300	99,5	58,31	6,004E-01	1,014E-01	1,546E-01	2,729E-02	2,446E-08	1,516E-02
	reinforcement steel	8,883E+00	6,904E-01	1,466E+00	1,829E-01	2,119E-11	2,725E-01	7850	0,5	1,00						
2,0 %	plain concrete	4,583E-01	9,125E-02	1,321E-01	2,463E-02	2,488E-08	1,075E-02	2300	98,0	14,36	1,007E+00	1,303E-01	2,190E-01	3,493E-02	2,326E-08	2,780E-02
	reinforcement steel	8,883E+00	6,904E-01	1,466E+00	1,829E-01	2,119E-11	2,725E-01	7850	2,0	1,00						
3,0 %	plain concrete	4,583E-01	9,125E-02	1,321E-01	2,463E-02	2,488E-08	1,075E-02	2300	97,0	9,47	1,263E+00	1,485E-01	2,595E-01	3,974E-02	2,250E-08	3,575E-02
	reinforcement steel	8,883E+00	6,904E-01	1,466E+00	1,829E-01	2,119E-11	2,725E-01	7850	3,0	1,00						
6,0 %	plain concrete	4,583E-01	9,125E-02	1,321E-01	2,463E-02	2,488E-08	1,075E-02	2300	94,0	4,59	1,965E+00	1,984E-01	3,708E-01	5,294E-02	2,043E-08	5,758E-02
	reinforcement steel	8,883E+00	6,904E-01	1,466E+00	1,829E-01	2,119E-11	2,725E-01	7850	6,0	1,00						

11. ANNEX III: DRAWINGS

12. USED SOURCES AND LITERATURE

[1] The Causes of Climate Change [online]. National Aeronautics and Space Administration. [seen 12. 11. 2019]. Retrieved from: https://climate.nasa.gov/causes/

[2] CO_2 and Greenhouse Gas Emissions [online]. Our World in Data. [seen 12. 11. 2019]. Retrieved from: https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions

[3] Why the Building Sector? [online]. Architecture 2030. [seen 12. 11. 2019]. Retrieved from: https://architecture2030.org/buildings_problem_why/2/

[4] Envimat - Databáze environmentálních vlastností výrobků pro hodnocení komplexní kvality budov [online]. Envimat.cz. [seen 14. 11. 2019]. Retrieved from: http://www.envimat.cz/public/files/Envimat_skoleni_2.pdf

[5] ŠÁDKOVÁ, Barbora. Domov pro seniory v Horoměřicích. Prague, 2017. Master's thesis. Czech Technical University in Prague, Faculty of Civil Engineering, Department of Architecture.
Online version:
Domov pro seniory v Horoměřicích [online]. Czech Technical University in Prague. [seen 15. 2. 2019]. Retrieved from: https://dspace.cvut.cz/handle/10467/70703

[6] VERNER, Vít. Návrh nosné konstrukce domova pro seniory v Horoměřicích. Prague, 2019. Master's thesis. Czech Technical University in Prague, Faculty of Civil Engineering, Department of Concrete and Masonry Structures.

[7] Model for Life Cycle Assessment (LCA) of buildings [online]. European Commission, Joint Research Centre. [seen 14. 11. 2019]. Retrieved from: https://publications.jrc.ec.europa.eu/repository/bitstream/JRC110082/report_d1_online_final.pdf

[8] Environmental Improvement Potential of Residential Buildings (IMPRO-Building) [online]. European Commission, Joint Research Centre. [seen 14. 11. 2019]. Retrieved from: http://ccsl.iccip.net/jrc46667.pdf

[9] Metodika - SBToolCZ [online]. SBToolCZ. [seen 18. 11. 2019]. Retrieved from: https://www.sbtool.cz/cs/metodika

[10] LCA [online]. Envimat.cz. [seen 14. 11. 2019]. Retrieved from: http://www.envimat.cz/metodika/lca/

[11] Ecoinvent - The World’s Most Consistent & Transparent Life Cycle Inventory Database [online]. Ecoinvent. [seen 14. 11. 2019]. Retrieved from: https://www.ecoinvent.org

[12] SKULLESTAD, Julie Lyslo, BOHNE, Rolf André, LOHNE, Jardar. High-Rise Timber Buildings as a Climate Change Mitigation Measure - A Comparative LCA of Structural System Alternatives. In: ScienceDirect [online]. Norwegian University of Science and Technology, Trondheim, 2016. [seen 20. 11. 2019]. Retrieved from: https://www.sciencedirect.com/science/article/pii/S1876610216307512

[13] TESHNIZI, Zahra, PILON, Angelique, STOREY, Stefan, LOPEZ, Diana, FROESE, Thomas M. Lessons Learned from Life Cycle Assessment and Life Cycle Costing of Two Residential Towers at the University of British Columbia. In: ScienceDirect [online]. University of British Columbia, Vancouver, 2018. [seen 20. 11. 2019]. Retrieved from: https://www.sciencedirect.com/science/article/pii/S221282711730906X

[14] PASSER, Alexander, SCHULTER, Danilo, CRESNIK, Guido and MAYDL, Peter. Life Cycle Assessment of buildings comparing structural steelwork with other construction techniques. In: 3rd International Conference on Life Cycle Management [online]. Graz University of Technology, 2007. [seen 20. 11. 2019]. Retrieved from: http://www.lcm2007.ethz.ch/paper/300.pdf

[15] LUPÍŠEK, Antonín. Environmental Life Cycle Assessment [lecture]. Czech Technical University in Prague, Faculty of Civil Engineering, October 2019.

[16] SHI, Junli, LIU, Zhichao, ZHANG, Hongchao, JIANG, Qiuhong, LI, Tao: Life Cycle Assessment: State of the Art and Future Perspectives. In: ResearchGate [online]. Dalian University of Technology, Dalian, 2015. [seen 21. 12. 2019]. Retrieved from: https://www.researchgate.net/publication281369985_Life_Cycle_Assessment_State_of_the_Art_and_Future_Perspectives

[17] EN ISO 14040. Environmental management — Life cycle assessment — Principles and framework. ICS 13.020.10. 2nd edition. Czech Standards Institute, July 2006.

[18] Defining the goal and scope of the LCA study [online]. Rowan University. [seen 22. 12. 2019]. Retrieved from: http://users.rowan.edu/~everett/courses/SCEE/docs/LCA-Goal&scope-2011.pdf

[19] LCA International Standards [online]. Advanced Material and Nanotechnology Cluster. [seen 22. 12. 2019]. Retrieved from: http://amanac.eu/wiki/international-standards/

[20] Central Concepts in LCA [online]. TOSCA project partners. [seen 22. 12. 2019]. Retrieved from: https://tosca-life.info/getting-started-guides/life-cycle-assessment/how-to-perform-an-lca/central-concepts-in-lca/

[21] Updated Impact Assessment Methodology ReCiPe2016 [online]. PRÉ Consultants B. V. [seen 22. 12. 2019]. Retrieved from: https://simapro.com/2017/updated-impact-assessment-methodology-recipe-2016/

[22] Phases in an LCA Study [online]. TOSCA project partners. [seen 22. 12. 2019]. Retrieved from: https://tosca-life.info/getting-started-guides/life-cycle-assessment/how-to-perform-an-lca/phases-in-an-lca-study/

[23] Performing the inventory in an LCA Study [online]. TOSCA project partners. [seen 22. 12. 2019]. Retrieved from: https://tosca-life.info/getting-started-guides/life-cycle-assessment/how-to-perform-an-lca/phases-in-an-lca-study/inventory/

[24] Characterization: New Developments for Toxicity [online]. PRÉ Consultants B. V. [seen 25. 12. 2019]. Retrieved from: https://www.pre-sustainability.com/news/characterisation-new-developments-for-toxicity

[25] Performing the Environmental Impact Assessment in the LCA [online]. TOSCA project partners. [seen 25. 12. 2019]. Retrieved from: https://tosca-life.info/getting-started-guides/life-cycle-assessment/how-to-perform-an-lca/phases-in-an-lca-study/impact-assessment/

[26] Guide for Interpreting Life Cycle Assessment Result [online]. European Commission, Joint Research Centre. [seen 22. 12. 2019]. Retrieved from: https://publications.jrc.ec.europa.eu/repository/bitstream/JRC104415/lb-na-28266-en-n.pdf

[27] Performing the Interpretation in the LCA [online]. TOSCA project partners. [seen 22. 12. 2019]. Retrieved from: https://tosca-life.info/getting-started-guides/life-cycle-assessment/how-to-perform-an-lca/phases-in-an-lca-study/interpretation/

[28] ELIASSEN, A., R., FAANES, S., BOHNE, R., A. Comparative LCA of a Concrete and Steel Apartment Building and a Cross Laminated Timber Apartment Building. In: IOPScience [online]. Norwegian University of Science and Technology, Trondheim, 2019. [seen 22. 12. 2019]. Retrieved from: https://iopscience.iop.org/article/10.1088/1755-1315/323/1/012017

[29] Ökobaudat: Sustainable Construction Information Portal [online]. Federal Ministry of the Interior, Building and Community. [seen 14. 11. 2019]. Retrieved from: https://www.oekobaudat.de

[30] HERE WeGo Maps [online]. HERE, Eurographics. [seen 15. 3. 2019]. Retrieved from: https://wego.here.com

[31] Tabulková únosnost zemin [online]. Czech Technical University in Prague. [seen 20. 11. 2019]. Retrieved from: http://departments.fsv.cvut.cz/k135/data/wp-upload/2008/03/11_meze-unosnost-f.pdf

[32] Structural Analysis - Two-span Beam - Deformation [online]. Stora Enso. [seen 25. 12. 2019]. Retrieved from: http://www.clt.info/wp-content/uploads/2015/10/Floor-Two-Span-Beam-Deformation-EN.pdf

[33] Structural Analysis - External Walls [online]. Stora Enso. [seen 25. 12. 2019]. Retrieved from: http://www.clt.info/wp-content/uploads/2015/10/Wall-External-walls-EN.pdf

[34] Stora Enso Wood Products: Building Solutions [online]. Stora Enso. [seen 25. 12. 2019]. Retrieved from: http://www.clt.info/wp-content/uploads/2015/10/Technical-folder-CLT-EN.pdf

[35] Konstrukční zásady pro vyztužování železobetonových prvků podle EN 1992-1-1 a NA CZ [online]. Brno University of Technology. [seen 28. 12. 2019]. Retrieved from: https://www.fce.vutbr.cz/bzk/simunek.p/prvky/06_cv3_konstrucni_zasady.pdf

13. USED SOFTWARE

[S1] SCIA Engineer 18.1.57. (2018). SCIA CZ s.r.o.

[S2] AutoCAD 2018. (2018). Autodesk, Inc.

[S3] Microsoft Excel for Mac v. 16.26. (2019). Microsoft Corporation

[S4] Pages v. 7.3. (2019). Apple Inc.

[S5] Numbers v. 5.3. (2019). Apple Inc.

[S6] Archicad 22. (2018). Graphisoft SE.