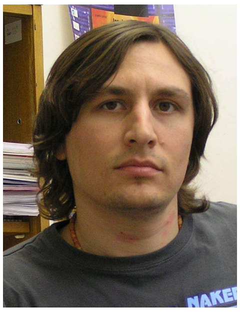
# ENVIRONMENTAL AND LIFE CYCLE ASSESSMENT OF STRUCTURAL DESIGN OF RESIDENTIAL HOUSE- CASE STUDY





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## Summary

The topic of sustainable constructions is very complex and includes a large number of parameters of various branches of civil engineering covering all technical as well as non technical sciences. Optimization of structural design of a building from the environmental point of view represents a wide multicriterion problem.

Basic principles of sustainable building are defined in [1] but general methodology of environmental assessment of building structures is still not available. The presented case study shows one possible approach to environmental optimization and assessment of structural design of a building. Several design alternatives of a residential building have been proposed and assessed. The alternatives differ in the choice of building materials and building technology.

**Keywords:** Environmental assessment, LCA, embodied energy, sustainable construction, BAT – best available technique

## 1 Introduction

For the environmental assessment a simple four storey residential building (**Fig. 1**) has been drafted. The aim was to design as flexible layout as possible and optimal planning module that enables to apply many structural and material alternatives. In each of the 2$^{nd}$ to 4$^{th}$ floors there are 3 dwelling units – two four-room flats (95,9 m$^2$) and one one-room flatlet (27,5 m$^2$), in the 1st floor there are two four-room flats and in the middle section is the entrance and the technical facility.

Following groups of criteria have been used for the environmental assessment: (i) embodied energy, embodied $CO_2$, embodied $SO_2$, amount of used materials, (ii) consumption of material resources (amount of renewable materials, recycled materials, recyclable materials, primary natural sources), (iii) materials from demolition of the building (fully recyclable materials, partially recyclable materials, non-recyclable materials, wastes). New developed tools for multicriterion analysis have been used for environmental assessment.

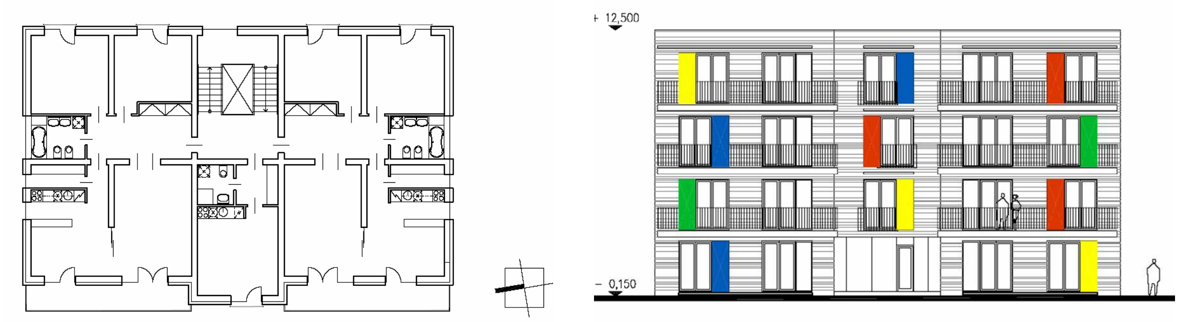


**Fig. 1** Four-storey residential building – typical floor and entrance facade

## 2 Environmental assessment methodology

On the defined structural variants of the building has been applied specialized software that calculates the environmental parameters from the sheets of areas and types of structures. The core of the software is based on a database [2] that includes specific values of the environmental indicators for different structures (i.e. for walls, floor structures, windows etc.).

The mentioned methodology was adopted on the basis of [3].

The applied software based on MS Excel sheets calculates the values of following indicators:

**1** Environmental parameters (conventional environmental performance measures of building materials) – (i) embodied energy use, (ii) embodied emissions $CO_2$,ekv., (iii) , embodied emissions $SO_2$,ekv. (iv) self weight,

**2** input materials (construction phase – used raw materials) – (i) renewable materials, (ii) recycled materials, (iii) other raw materials,

**3** output materials (deconstruction/demolition phase- possible further use of materials) – (i) fully recyclable materials, (ii) party recyclable materials (with down cycling effect), (iii) non-recyclable materials (waste).

The data of embodied energy and embodied emissions $CO_2$,ekv., $SO_2$,ekv. are taken from the catalogues of building structures [4], [5] and [6]. Operation emissions $CO_2$, ekv., $SO_2$,ekv. (global and regional) and fuels conversion factors were calculated using the GEMIS software with the Czech database [5].

## 3 Structural variants design

The design of specific structural variants has been completed according to the architectural study of the building. The internal layout, concerning the load bearing system, enables realization of numbers of structural systems. Structural systems used in the case study are: (i) crosswise wall bearing system, (ii) two-way/lengthwise wall bearing system, (iii) column system (**Fig. 2**). Considering technological variants monolithic, prefabricated, and composite reinforced concrete (RC) structures were applied.

The design of all the variants was done at the preliminary stage based on the study. The design of the load bearing structures is based upon the following standards: (i) ČSN P ENV 1996-1-1 Design of masonry structures. Part 1-1: General rules for buildings. Rules for reinforced and unreinforced masonry, (ii) ČSN P ENV 1992-1-1 Design of concrete structures. Part 1: General rules and rules for buildings, (iii) ČSN 731001 Foundation of structures. Subsoil under shallow foundations, (iv) ČSN P ENV 1991-2-1 Basis of design and actions on structures. Part 2-1: Action on structures. Densities, self weight and imposed loads, (v) ČSN P ENV 1991-2-3 Basis of design and actions on structures. Part 2-3: Actions on structures – Snow loads.

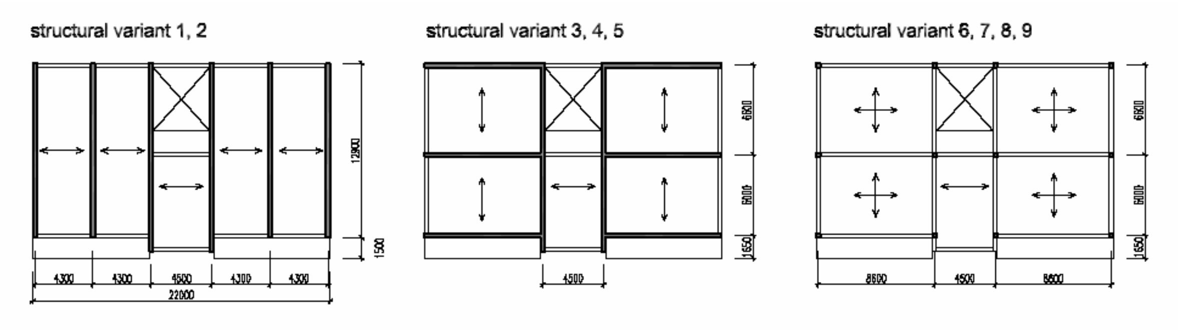


**Fig. 2** Structural variants of the load bearing systems of the residential building.

The design of the floor structures is based on the relevant company design fundamentals. The monolithic floor slabs are designed according to (ii) and reinforced with upper and lower steel mesh. The roof load bearing structures are considered identical to the floor structures. The girders are reinforced with bar steel and stirrups of R10505 steel. Balconies in all the variants are made of monolithic concrete slab with a thickness of 120 mm and connected by the ISO girder. The reinforcement of columns is preliminary estimated to 3 %, the footings have only structural reinforcement of 0,5 %.

The footing structures are designed according to the 1st geotechnical category and foundation bearing value of 0,2 $N/mm^2$ specifically for each variant. The footing design (footing area i.e. concrete and steel volume) is based on total weight of the building of each particular variant.

The building envelope in each variant is considered with an external insulation from mineral wool in timber grid with timber sheathing. All the building envelop structures are designed to recommended U-values according to the ČSN 73 0540-2 Thermal Protection of Buildings – Part 2: requirements, i.e. $U_N = 0{,}25\ W/m^2K$ for the peripheral walls (incl. variant with wood panels), $U_N = 0{,}16\ W/m^2K$ for the roof structures, and $U_N = 0{,}40\ W/m^2K$ for the floor structures adjacent to soil.

### 3.1 Crosswise masonry wall bearing system

This wall bearing system is designed for a short span with the crosswise bearing walls modular distance of 4,3 respectively 4,5 m. Material and technological variants were planed as complex systems of walls and floors using ceramic and concrete.

#### 3.1.1 V1 – complex system of ceramic components

The load bearing system consists of crosswise bearing walls made of hollow ceramic blocks with a thickness of 300 mm and external bearing walls with a thickness of 440 mm plus 50 mm insulation. The floor structure of the structural thickness 210 mm consists of filigran beams with ceramic fillers. The partition walls are designed as hollow ceramic blocks of a thickness 115 mm. The bearing walls are erected on the continuous footings 800 mm wide in case of external walls and 1000 mm wide in case of internal bearing walls.

#### 3.1.2 V2 – complex system of concrete components

The load bearing system consists of crosswise bearing walls made of hollow concrete blocks of a thickness 300 mm both for internal and external bearing walls. The external walls are insulated with 150 mm of insulation. The floor structure of the structural thickness 200 mm consists of filigran beams with concrete fillers. The partition walls are designed as hollow concrete blocks with a thickness of 120 mm. The bearing walls are erected on the continuous footings 800 mm wide in case of external walls and 1000 mm wide in case of internal bearing walls.

### 3.2 Two-way/lengthwise wall bearing system

This structural variant consists of lengthwise and crosswise monolithic bearing walls with a thickness of 150 mm and monolithic floor slabs with a thickness of 180 mm. The peripheral walls and partition walls are designed as non-structural linings of different material variants. The external monolithic walls are insulated with 200 mm of insulation.

#### 3.2.1 V3 – ceramic block linings

The peripheral gable walls are lined with hollow ceramic block with of a thickness 240 mm plus 170 mm of insulation. The partition walls are lined with ceramic blocks 115 mm thick and the partition walls between flats are lined with ceramic blocks 300 mm thick. The bearing walls are erected on the continuous footings 900 mm wide in case of external walls and 1500 mm wide in case of internal bearing walls.

#### 3.2.2 V4 – compressed earth brick lining

The peripheral gable walls and the partition walls between flats are lined with earth bricks with a thickness of 300 mm, the peripheral gable walls are additionally insulated with 170 mm of insulation. The partition walls are lined with earth brick 150 mm thick. The bearing walls are erected on the continuous footings 900 mm wide in case of external walls and 1500 mm wide in case of internal bearing walls.

#### 3.2.3 V5 – lightweight concrete block lining

The peripheral gable walls and the partition walls between flats are lined with lightweight concrete blocks with a thickness of 300 mm, the peripheral gable walls are additionally insulated with 80 mm of insulation. The partition walls are lined with lightweight concrete blocks 125 mm thick. The bearing walls are erected on the continuous footings 1400 mm wide in case of external walls and 850 mm wide in case of internal bearing walls.

### 3.3 Wide span monolithic column system

The load bearing structure consists of monolithic RC columns 300/300 mm with girders 300/500 mm and a two-way floor slab 180 mm thick with the span of 8,75×6,6 m and one-way floor slab with the span of 4,5 m. The internal columns are erected on footings 2500/2500 mm whereas the external columns are on footings 1600/1600 mm. The peripheral walls and the partition walls between flats are erected on footing beams 300/600 mm. The peripheral walls and partition walls are different in each variant.

### 3.3.1 V6 – ceramic block lining

The peripheral walls and the partition walls between flats are lined with ceramic hollow blocks with a thickness of 300 mm, the peripheral walls are additionally insulated with 130 mm of insulation. The partition walls are lined with ceramic blocks 115 mm thick.

### 3.3.2 V7 – compressed earth brick lining

The peripheral walls and the partition walls between flats are lined with earth bricks with a thickness of 300 mm, the peripheral walls are additionally insulated with 170 mm of insulation. The partition walls are lined with earth brick 150 mm thick.

### 3.3.3 V8 – lightweight concrete block lining

The peripheral walls and the partition walls between flats are lined with lightweight concrete blocks with a thickness of 300 mm, the peripheral walls are additionally insulated with 80 mm of insulation. The partition walls are lined with lightweight concrete blocks 125 mm thick.

### 3.3.4 V9 – prefabricated exterior wood panels

The peripheral walls are assembled of prefabricated sheathed wood panels with mineral thermal insulation. The partition walls consist of gypsum plasterboards fixed on wooden frame filled up with insulation, the partition walls between flats use a double sheathing in addition.

## 4 Sorting of building structures according to the environmental assessment needs

The goal of this case study was the evaluation of a structural design impact on the environmental assessment of a building. Structural design of a building incorporates a decision making process concerning structural system selection, material and technological design, and influences ambient structures and substructures. That's why the structures were divided into "fabric" and "others" even though this sorting doesn't match completely with the technological processes in construction.

Structural system design and material design of a building load bearing structure influences the material and technological design of ambient structures and substructures, e.g. staircases, balconies, partition structures assembling, surfaces treatment, peripheral walls treatment.

Within the scope of this case study following structures were placed into the group of "**fabric**": (i) vertical load bearing structures (bearing walls with surface treatments, columns, ...), (ii) horizontal load bearing structure (floor structures incl. surface treatments, ceilings; balconies, ...), (iii) peripheral walls (peripheral bearing walls incl. external insulation and internal and external surface treatments), (iv) partition structures (partition walls both within and between flats incl. surface treatments), (v) footing structures incl. concrete bed (based on structural context – footing/continuous footing, load action), (vi) staircase structures.

The group of "**others**" includes such structures and components that are identical to all the structural variants. These structures are: (i) windows and balcony doors, (ii) interior doors, (iii) floors above the floor bearing structures in typical floors and above the water-proofing in the ground floor, (iv) water proofing in the ground floor, (v) roof covering above the roof bearing structure incl. thermal insulation and roofing, (vi) plumbing (top closure, window sheeting, ...), (vii) joinery (internal parapets), (viii) metalwork (railings around staircases and balconies, shading elements, ...).

## 5 Environmental assessment – results

The environmental assessment data (**Tab. 2**) of the structural variants of the residential building presented in this paper give an important insight into the relationship between structural design considering technological and material solution and environmental impact of the building.

The results (**Fig. 3**) show environmental parameters of materials used for “fabric” and “other” constructions. The amount of “other” constructions is the same in every structural variant. The differences between “fabrics” of each structural variant corresponding with environmental impact are evident.

All variants of column systems seem to be optimal for this kind of building. Also two-way/lengthwise wall bearing system seems to be suitable. Crosswise system used ceramic elements is the most unsuitable.

Major differences among all structural variants are obvious in the input/output assessment (**Fig. 4, 5**). Increasing in environmental quality of the structure is evident in the amount of non-renewable and renewable materials (input – building up phase) and in the amount of fully recyclable materials (output – demolition phase).

**Tab. 1** Structural variants overview.

| Materials/technology | crosswise masonry wall bearing system | two-way/ /lengthwise wall bearing system | wide span monolithic column system |
|---|---|---|---|
| ceramic blocks | **V1** | **V3** | **V6** |
| concrete blocks | **V2** | | |
| earth structures | | **V4** | **V7** |
| lightweight concrete | | **V5** | **V8** |
| exterior wood panels + gypsum plasterboards | | | **V9** |

**Tab. 2** Environmental parameters of structural variants of residential building.

| criterion | | V1 | V2 | V3 | V4 | V5 | V6 | V7 | V8 | V9 | V1-V9 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | fabric | | | | | | | | | others |
| embodied energy | GJ | 2 593 | 1 774 | 2 081 | 1 906 | 2 016 | 2 052 | 1 689 | 1 972 | 1 418 | 1 362 |
| embodied CO2, eq. | kg | 229 236 | 234 816 | 221 895 | 214 464 | 235 971 | 193 299 | 181 862 | 230 496 | 154 079 | 83 781 |
| embodied SO2, eq. | kg | 811 | 863 | 876 | 886 | 913 | 734 | 763 | 845 | 656 | 512 |
| amount of used materials | tons | 1 461 | 1 520 | 1 498 | 1 768 | 1 407 | 1 238 | 1 687 | 1 097 | 919 | 254 |
| renewable materials | tons | 9,76 | 12,49 | 13,42 | 456,37 | 12,45 | 11,99 | 787,10 | 10,73 | 25,85 | 81,40 |
| recycled materials | tons | 2,92 | 6,34 | 7,62 | 7,62 | 6,29 | 5,69 | 7,06 | 3,96 | 21,78 | 8,22 |
| non-renewable material sources | tons | 1 448 | 1 501 | 1 477 | 1 304 | 1 388 | 1 220 | 892 | 1 082 | 871 | 164 |
| fully recyclable materials | tons | 20,92 | 22,64 | 46,21 | 489,17 | 43,83 | 35,41 | 810,74 | 33,84 | 57,28 | 78,58 |
| partially recyclable materials | tons | 1 439 | 1 478 | 1 450 | 1 277 | 1 361 | 1 200 | 874 | 1 061 | 848 | 167 |
| waste | tons | 1,69 | 1,69 | 1,98 | 1,98 | 1,98 | 2,09 | 2,09 | 2,09 | 13,73 | 6,75 |

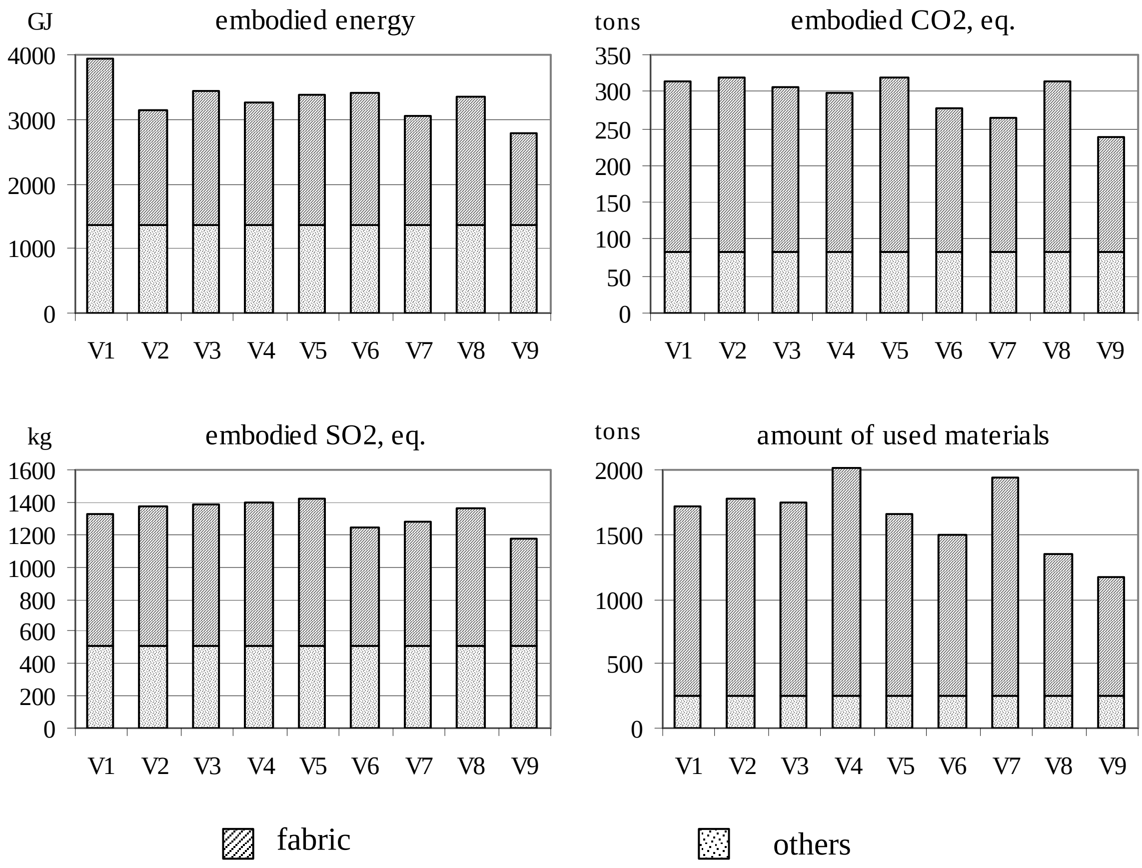


**Fig. 3** Environmental parameters of structural variants.

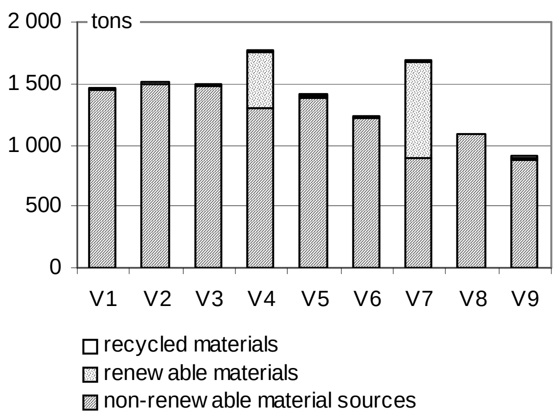


**Fig. 4** Environmental assessment of fabric: input materials (building up phase).

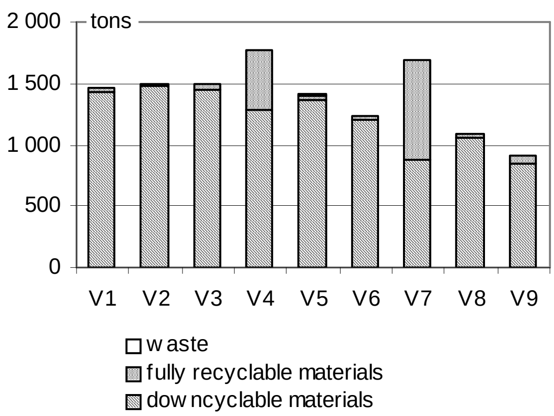


**Fig. 5** Environmental assessment of fabric: output materials (demolition phase).

## 6 Conclusions

Particular results of the case study illustrate among others how complicated interpretation of environmental assessment results is. There are several possible ways of reading depending on priorities or needs. One of the possible interpretations has been shown above but it is necessary to create global methodology and to set priorities to enable explicit assessment of building structures from the environmental point of view.

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