Life-Cycle Assessment of Sustainable Foundation Systems of Buildings

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Abstract. According to laws in force, the construction process is required to be as efficient as possible in terms of energy. The reason is that the building sector is growing and more and more energy is needed. Buildings are responsible for 40% of energy consumption and 36% of CO₂ emissions in the member states of the European Union. Sustainable foundation systems of buildings are not only energy efficient but also environmentally friendly. According to the research project Heartland Green Sheets, the recommended criteria for evaluating sustainable buildings materials are low embodied energy, recyclable, use renewable resources, locally or regionally produced, energy efficient, low environmental impact, durable, minimize waste, positive social impact and affordable. This study focuses on selecting the most sustainable foundation system based on life-cycle assessment (LCA) and sustainability assessment of alternate shallow foundation systems. The multi-criteria analysis of the most used and modern foundation systems with sustainable materials in term of life cycle assessment is presented within the paper. Sustainability assessment of alternate shallow foundations is performed based on three pillars of the sustainability (environmental, economic, and social). The variants are assessed in terms of labor, time and financial demands, energy and environmental performance.

1. Introduction
Sustainable building refers to both a structure and the application of processes that are environmentally responsible and resource-efficient throughout a building's life-cycle: from planning to design, construction, operation, maintenance, renovation, and demolition. This requires close cooperation of the contractor, the architects, the engineers, and the client at all project stages. The Green Building practice expands and complements the classical building design concerns of economy, utility, durability, and comfort. Building sector demands materials and energy flows during all life cycle both directly and indirectly. Material and energy flows are irregular during the lifecycle [1]. Buildings are responsible for about 40% of the total energy consumption and 36% of the total CO₂ emission worldwide [2]. The buildings consume approximately 60% of the earth raw materials and produced over 50% waste [3,4]. Contemporary building constructions are especially focused mainly on the time demands and financial performance. According to the principles of sustainable development, the future construction should be more focused on the reduction of pollution of the environment and the effective using of material resources [5].
2. Traditional and modern types of foundation

The foundation structures have to provide a durable interface between the surrounding ground (soil) and the building. Fundamentals must transfer all load from the building to the foundation soil in the foundation joint. Foundations are an integral part of supporting structures of all types of buildings. The design of the foundation structure requires the knowledge of the foundation soil, its physical-mechanical properties and the lord of the superstructure. In the view of thermal properties and energy performance, building foundations account for up to 40% of heat losses through the envelope of the building. The building foundations have to resist the interaction of bulk water, radon, water vapour, and even, occasionally, hydrogen sulphide, frost, biotic activity, and pest infestation [6].

The majority of energy-efficient buildings is designed without a basement. The floor of the first floor of the house is situated on the ground. There are many designs of solutions with sufficient thickness of thermal insulation, such as standard foundation on foundation strips, concrete slab foundation or foundation piles with a grid. The method of foundation on strip footings predominates in contemporary individual residential constructions. Foundation strips are made along the entire circumference of the outer walls and also under the load-bearing walls inside the building. The thermal insulation of the floor is above the waterproof layer and therefore it is possible to use expanded polystyrene (EPS) which is absorbent. Another method of buildings foundation is a reinforced concrete slab, which is stored in a tub made of sufficiently absorbent non-absorbent extruded polystyrene (XPS). It is a progressive foundation where the heat insulating layer is perfectly airtightly bonded around the whole foundation structure. The thickness of the insulation is determined by calculation and is normally in the range of 240-300 mm. A relatively new and promising solution is to use loose thermal insulation (granulated foamed glass). Thermal insulation of the structure forms a layer of gravel from a foamed glass granulate that is deposited in the excavation. This layer forms a base for a reinforced concrete foundation slab. The layer of granulate is usually designed in thicknesses of 450 - 600 mm. The layer must be sufficiently compacted to avoid undesirable sedimentation. Detailed information, such as types and ways of building foundation, construction principles and risks in the context of energy-efficient construction, are described in detail in [7].

3. Assessment of sustainable foundation systems of buildings

The assessment of the possibilities of implementation of the building foundations is carried out on a new family house located near the town of Domažlice, Czech Republic. The house is designed for a four-member family. From the architectural point of view, the object is a two-storey rectangular ground plan with a penthouse roof. The entrance to the building is situated to the northeast and the main living quarters are oriented to the southwest. The ground plan dimensions of the building are 12.1 x 9.15 m. The floor area of the house is 163,1 m². The superstructure is designed from aerated concrete blocks (peripheral walls 300 mm, internal bearing masonry walls of 240 mm and 150 mm). The horizontal ceiling structure consists of prestressed 200 mm reinforced concrete panels with 50 mm thick reinforced concrete. The roof structure is made of wooden truss trusses.

An engineering and geological survey was carried out on the site with the help of the probes carried out. This survey revealed the composition of base soil and groundwater level. The entire area of the site is sandy clay in places with boulders up to a diameter of 100 mm. According to CSN 73 3050 Earthworks, the soil is in the second class of exploitation. The groundwater level is located at a depth of 2.530 m below the level of ± 0.000. The ground conditions at the site are favourable, the soil is well permeable. In presented case study 4 variants of the foundation construction were evaluated:

- Variant A - Strip foundation with thermal insulation above the concrete slab.
- Variant B - Foundation on non-absorbent thermal insulation (XPS) – lost formwork.
- Variant C – Foundation on the granulated foamed glass into the pit of the excavation.
- Variant D - Foundation on the granulated foamed glass with lost formwork (XPS).
Variant A is used today in the most common foundations on concrete strip foundation. Due to the good permeability of the soil on the site, there is no need to carry out drainage system, and therefore there is a possibility of pouring concrete directly into the excavation without the need for formwork. However, if the geological conditions on the construction site were inappropriate, the construction would be financially more time-consuming. Only the grooves will be excavated for the foundations. Prepared concrete with perimeter thermal insulation will be placed directly into the grooves. Detail of this variant is processed in Figure 1.

![Figure 1. Variant A - Strip foundation with thermal insulation above the concrete slab](image)

Variant B uses the progressive way of establishing an object on a layer of extruded polystyrene (XPS). This polystyrene forms a bathtub into which a concrete foundation slab will be poured. This variant is carried out in an excavation pit and is deposited on a level surface, made of compacted gravel in several layers. Variant B must be drained by drainage. The XPS bathtub creates the thermal insulation of the floor and forms the uninterrupted insulation of the building envelope. The floor composition is made with waterproofing above the thermal insulation. Therefore, the polystyrene must be non-absorbent. More detail of this variant is shown in Figure 2.

![Figure 2. Variant B - Foundation on non-absorbent thermal insulation (XPS) – lost formwork.](image)
Variant C is another progressive way of buildings foundation with thermal insulation under the waterproofing layer. The thermal insulation is made here by two compacted layers of granulated foamed glass. In this way, the so-called floating subsoil is formed. As variant B, the variation C must be drained using a drainage pipeline. The foam glass is deposited on a balanced layer of compacted gravel and is spread over the area of the entire trench. The overlap of the foam layer must be 600 - 1000 mm across the edges of the building. The floor composition above the foam layer is the same as for variant B. Figure 3 shows the detail of variant C.

The last variant is the composition of layers as variant C. Foam glass is poured into a pit formed from XPS formwork, which defines the boundaries of the building. Overlapping around the building is not considered. A smaller amount of granulate is needed than variant C. Costs will be lower than variant C because the foam glass is expensive. This variant must also be drained by drainage. Variant D is shown in Figure 4.
4. Results and discussion

A total of 8 criteria are evaluated. Variants are evaluated from the point of view of thermo-technical parameters, economic costs, time-consuming and labour-intensive and environmental aspects. Environmental assessment includes Global Warming Potential (GWP), Acidification Potential (AP), the share of used recycled and renewable materials, the share of recyclable materials and the specific weight.

The itemized budgets for each individual variant of foundation structures are designed to assess the financial performance of the construction. Budgets include only constructions, building materials and assembly that will vary in the different variants (substructure). Figure 5 shown the financial costs for all variants of foundation. Variation A (strip foundation) is the cheapest. Variant B is the worst compared to other variants. Costs of variant B are more than twice higher than variant A.

![Figure 5. Financial costs (material and assembly) for assessed variants of the foundation](image)

Labour significantly affects the time-length of the building. This can be a heavily influencing factor if the investor requires the shortest construction duration. The necessary construction machines must also be taken into account. Consideration must be given to transporting and manipulating machinery on site. Duration of construction is expressed by conversion of the materials or amount of soil removed by the number of man-hour for the activity. Total labour (time) is expressed on the basis of the amount of material in the required units of measurement (m, m², m³), the standardized man-hour for the activity per worker (machine) and the number of workers in the working platoon for the execution of the construction phase. Figure 6 shows the duration of the construction, including technological breaks. The graph implies that the shortest construction time will be at the foundation structure variant A.

![Figure 6. Duration of the construction for assessed variants including technological breaks](image)
The extraction of raw materials for the production of building materials, their production, transport, installation into construction and other steps of the life cycle of building materials and structures are associated with emissions and energy consumption. The current trend leads to the use of recycled and recyclable materials for building construction, the maximum use of renewable resources and the reduction of dependence on non-renewable natural resources. Consideration is also given to the number of emissions associated with the use of materials in the construction works. This means emissions that produce the material itself during the build-in period, but also the emissions produced during the production of these materials. For the purposes of this study, the amount of carbon dioxide (CO$_2$) and Sulfur dioxide (SO$_2$) emissions is assessed. In addition, the percentage of recycled and recyclable materials is evaluated for the used structures. The calculation methodology is taken from the SBToolCZ methodology [8].

An indicator of global warming potential (GWP) is equivalent emissions of CO$_2$, expressed in kilograms [kg] per meter of floor area per year. The impact of the building sector on global warming potential due to the production of greenhouse gases emissions is undisputed [5]. The ratio between embodied emissions in building materials and operations emissions is constantly changing. According to OECD, the acidifying potential (AP) is defined as the aggregate measure of the acidifying potential of some substances, calculated through the conversion factor of sulphur oxides and nitrogen and ammonia into acidification equivalents (H$^+$ ion). The model does not take account of regional differences in terms of which areas are more or less susceptible to acidification. It accounts only for acidification caused by SO$_2$ and NO$_x$. An indicator of acidification potential is the equivalent emission of SO$_2$, expressed in kilograms [kg] per meter of floor area per year.

In this case, the embodied specific equivalent Carbon dioxide specific emissions and the embodied equivalent Sulfur dioxide emissions are monitored. The results are shown in Figure 7. It is clear from the calculations that variants based on granulated foamed glass produce many emissions associated with their use and production. The variant A is again the most suitable variant.

![Figure 7. Duration of the construction for assessed variants including technological breaks](image)
not include the use of recycled materials for concrete structures, but it is possible to use recycled concrete instead of the natural gravel subsoil. This is only possible if the recycled concrete meets the given parameters for the subsoil. The quality of recycled concrete has to be certified using the laboratory tests. Recycled concrete can be used instead of all sub-substrates, which are designed in the constructions except for the small fractions of 0/8 mm, which are mainly made of cement dust. Another parameter evaluated is the percentage share of fully and partly recyclable construction materials on the total weight of the foundation construction. It can be seen from the calculation that the materials used are relatively recyclable. However, this share is mainly composed of partially recyclable materials. The main components for recycling are concrete structures, subsoil and embankment soils that make up a large proportion of the total weight of the structure. Results of percentage share of recycled and renewable materials and percentage share of recyclable materials are shown in Figure 8.

Figure 8. The percentage share of recycled and renewable materials and the percentage share of recyclable materials

The third and last calculated value is the specific weight of the building (in this case only specific weight of foundation structure). It is the expression of the ratio of the weight of the foundation structure per one square meter of floor area [kg/m²]. The lowest specific weight of the foundation structures is in the case of variant A. To the fact that the other variants are placed in an excavation pit can be attributed, that there is a considerable amount of material processed.

A summary of the results is shown within Table 1. Variant A is the most appropriate type of foundation in 5 of 8 evaluated criteria. Due to the foundation conditions on the construction site, this variant is easily feasible and the construction time is the shortest, as well as the amount of material used and therefore the price is considerably lower than the other variants. The disadvantage of this variant is the potential interruption of the thermal insulation of the substructure by a vertical wall system. Variant B is more than twice expensive as variant A. Labor is also higher. Variant B can be assessed positively in terms of emission production. Due to the short life of the thermal insulation and due to the difficulty of restoration foundation structures, this variant is the least suitable for realizing the object. Variants C and D use the same principle of foundation based on granulated foamed glass. The difference is in the laying of granulated foamed glass. Granulated foamed glass into the area of the entire pit of the excavation was filled in the case of variant C. The foam glass of variant D is filled into the XPS thermal insulation boundary area, which borders the periphery of the future object. The
solution of variant D allows for the elimination of the material costs for execution since a lower amount of granulate is needed. Both of these variants are very labour-intensive but cost-effective. Emissions production is significantly higher than in the previous two variants.

**Table 1. Summary of results**

|                          | Variant A | Variant B | Variant C | Variant D |
|--------------------------|-----------|-----------|-----------|-----------|
| Heat transfer coefficient [W/(m²K)] | 0.142     | 0.111     | 0.085     | 0.085     |
| Financial costs [EUR]    | 14 714    | 31 440    | 25 265    | 21 956    |
| Labor [man-hour]         | 190.865   | 310.079   | 377.323   | 370.682   |
| Global Warming Potential [kg CO₂eq/(m².a)] | 1.42      | 2.16      | 10.00     | 7.37      |
| Acidification Potential [kg SO₂eq/(m².a)] | 0.01      | 0.01      | 0.06      | 0.04      |
| Share of used rec. and ren. materials [%] | 8.65      | 73.44     | 66.34     | 68.01     |
| Share of recyclable materials [%] | 96.81     | 98.18     | 93.24     | 95.27     |
| Specific weight [kg/m²]  | 612.86    | 1471.41   | 1352.37   | 1420.30   |

5. Conclusion
The green design strategy of building construction has great potential to provide the solution for lot of environmental challenges. Residential building foundation systems are the basis for sustainable building design. The careful and responsible selection of sustainable building materials and construction methods minimize the environmental impact in all parts of the life cycle significantly. The complexity of their environmental phenomenology combined with the imposed structural requirements make sustainable foundation design very challenging.

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