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Environmental Benefits of Timber-Concrete Prefabricated Construction System for Apartment Buildings – a Simplified Comparative LCA Study

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Environmental Benefits of Timber-Concrete Prefabricated Construction System for Apartment Buildings – a Simplified Comparative LCA Study

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Abstract. The aim of a research project TiCo (Timber Concrete) is to create a standardized flexible construction system for multifamily apartment buildings for central European climatic conditions with low environmental impact. It exploits advantages of advanced prefabrication and favourable material properties of its main elements. Prefabricated structural system was designed using concrete frame with thin columns and lightweight ceilings with reinforcing core. Façades and interior partition walls were designed from prefabricated timber frame panels. The paper presents a simplified comparative LCA study of the designed TiCo building system and conventional building solutions. The compared variants had the same key parameters – load bearing capacity and heat transfer coefficients of building's envelope. The analyses include load-bearing structures, façade, partition walls, foundations and roof. The others like HVAC systems, floors, doors, windows or tin work were not included. A simplified comparative LCA is based on procedure described in method SBToolCZ, which evaluates the quality of buildings in terms of sustainability. The assessment covered embodied environmental impacts of the construction system structures with their replacement based of their service lives. Prefabricated concrete frame structure with timber envelope was found environmentally friendlier compared to conventional solutions. The combination of the concrete load-bearing structure and lightweight timber frame panels that benefits from favourable characteristics of both materials for the given purpose appropriately used in the construction appeared to be an efficient way of minimizing building's environmental impact.

1. Introduction

The building sector is one of the major six sectors that have a substantial potential to reduce emissions of greenhouse gases [1] to support the mitigation of climate change [2] and it can also significantly contribute to improving energy efficiency of nations and lead to the mitigation of global warming [2].

Environmental impact from the perspective of existing buildings, in the Central Europe it means primarily reduction of operational energy for heating through thermal insulation of building envelope, heat source replacement or integration of renewable energy sources [3]. For the new construction, the range of possible environmental measures is greater, and part of the design optimization are also embodied impacts of materials.

The CTU UCEEB (Czech Technical University in Prague – University Centre of Energy Efficient Buildings) is pursuing research in reduction of environmental burden of buildings. In this paper is presented an outcome of a project TiCo (Timber + Concrete). It's in process. Main objective is to create an affordable, standardized apartment construction system with a fast assembly onsite and low environmental impact. The main structural function is carried out by the subtle precast reinforced concrete frame with ceilings lightened by expanded polystyrene boxes. Building envelope and the indoor partitions are made precast timber frame panels. The project is coordinated by RD Rýmařov (producer of prefab timber housing), CTU UCEEB is the R&D partner of the project and ŽPSV company is producer of precast concrete elements providing to the project the structural system.

The objective of this paper is to present outcomes of one part of the TiCo project, which compares TiCo system in design phase with conventional variants in terms of embodied emissions and energy.

2. Methods

2.1. Goals and scope definition

The goal of the study was to compare environmental impacts of the newly developed construction system developed in the TiCo project to impacts of regular solutions available in the Czech market. It was made as a simplified comparative LCA study for several variants of construction system designed for an apartment building. Environmental assessment, which should verify the correctness of the design choice, is necessary to be carried out in the initial phase of the project. However, in this stage of the project, only limited amount of data is available, therefore SBToolCZ method [4], which provides a simplified LCA that fits to the initial phase of the project, has been used. The main goal of this paper is a comparison of the newly developed construction system with conventional systems, so only the main construction elements were considered – ceilings, roofs, façades, floors, foundations, partitions between rooms and flats, stairs and balconies.

The included LCA phases were A1-A3 and partially B4 (replacement based on service lives of used elements).

The functional unit was one complete construction system of a 5-storey apartment building described in the chapter 2.4.

2.2. Indicators

SBToolCZ method is Czech multicriteria assessment scheme of building sustainability, similar to LEED or BREEAM. The method is applicable in a design phase, which was the case here. The main criteria categories are the same as the three pillars of sustainability. The environmental category has 14 criteria and 6 of them, which deal with quantified indicators (PEI – primary energy input, GWP – global warming potential, AP – acidification of soil and water, EP – eutrophication, ODP – ozone depletion potential, POCP – photochemical ozone creation potential). Indicators PEI and GWP in SBToolCZ are assigned the greatest importance. For residential buildings it is 32 % (PEI 22,3 % and GWP 9,7 %) from environmental criteria. The other 4 indicators have a maximum weight of 5 %. For that reason, only PEI respectively nPEI (non-renewable primary energy input) and GWP (global warming potential) were selected for this assessment.

Inputs for embodied parts of the values of indicators can be found in the Czech environmental database Envimat [5], but many materials were missing there. So at the end, for the purpose of this study data from more comprehensive Ecoinvent [6] database were used in order to use one source for the sake of consitency of the calculations.

Simplified LCA based on SBToolCZ method assesses embodied and operational GHG emissions and energy. For the purpose of this paper, comparison of embodied GHG emissions and energy was used, as the variants were designed for similar U-values of building envelopes and thus the operational impacts were considered to be identical.

2.3. Boundary conditions

The reference study period was 50 years and method to calculate with service lives of the conventional systems was in line with the SBToolCZ method. For instance, when an element had a service life of 25 years, its environmental impact was counted twice; for service life of 40 years was the environmental impact multiplied by 1.25. Maximum service life of each material was considered 50 years, which is identical with the reference study period.

Individual types of structures across variants have similar or identical basic parameters, for example heat transfer coefficient. This paper does not consider operational energy, because the energy consumption should be identical in all variants.

2.4. Variants

The investigated apartment building (Figure 1) had five storeys with a flat roof with a rectangular ground plan with dimensions of 18.3 x 10.9 m. Maximum height 15.5 m is limited by the Czech fire regulations. In the first floor there are one flat, storage rooms for each flat and a boiler room. On the other floors, there are only flats and a staircase with an elevator, 13 flats in total. Gross building volume is 3,100 m^3, gross floor area is 998.5 m^2 and net floor area is 832.5 m^2. Two types of flats are provided – four three-room flats with kitchenette and nine one-room flats with kitchenette.

Figure 1. The investigated apartment building.

For the purpose of a comparative LCA study of the construction systems were defined five construction variants (V1-V5) of the investigated building (Figure 1) that fulfil similar functional requirements and have the same thermal parameters of building envelope. A detailed description of the considered variants is summarized in Table 1. The V5 is a hypothetical variant that uses as much natural materials as possible (the lowest embodied environmental impacts has been expected), but this variant is not possible to build in Czechia due to strict legal fire safety requirements (but it might be possible to built in another Central Euroepan country).

Table 1. Variants of compared construction systems

Variant		Description
V1	TiCo (original)	Roof: wooden panel with MW + EPS + PVC foil External wall: wooden panel + grey EPS + cladding on an aluminum frame Wall: wooden panel with MW Ceiling: subtle precast RC + EPS Shear core: subtle precast RC Stairs: precast RC
V2	TiCo (cast-in-place concrete)	Roof: wooden panel with MW + EPS + PVC foil External wall: wooden panel + grey EPS + cladding on an aluminium frame Wall: wooden panel with MW Ceiling: cast-in-place RC + EPS Shear core: cast-in-place RC Stairs: precast RC
V3	RC frame + ceramic blocks	Roof: RC + EPS + PVC foil External wall: ceramic blocks + EPS Wall: ceramic blocks Ceiling: cast-in-place RC Shear core: cast-in-place RC Stairs: precast RC
V4	ceramic block	masonry system from ceramic blocks: Roof: wooden hollow rib element + EPS + PVC foil External wall: ceramic blocks + EPS Wall: ceramic blocks Ceiling: cast-in-place RC Shear core: ceramic blocks Stairs: precast RC
V5	wood	solid glue laminated timber walls: Roof: wooden hollow rib element + EPS + PVC foil External wall: CLT panels with wooden wool Wall: CLT panels Ceiling: wooden hollow rib element Shear core: RC Stairs: precast RC

(MW = mineral wool, EPS = expanded polystyrene, PVC = polyvinyl chloride, RC = reinforced concrete)

2.5. Inventory analysis
The study investigates differences in environmental impacts from the construction systems of the five variants. Other elements of the building like HVAC systems, tiling, lift, windows, door, floor, etc. were excluded from the study. It can be assumed, that these elements will be identical in all variants.

Service lives of the individual materials was basically taken from the SBToolCZ method [7] [8], but they were slightly modified depending on the type of installation and surrounding materials. For example: waterproof membrane has different service life when it is on the roof or when it is a part of foundations. When surrounding materials had similar expected service lives, they will be probably changed together, so they were assumed to have the same service life.

2.6. Impact assessment
The calculation was not conducted in any specialized LCA software, but in spreadsheet software MS Office Excel. Needed data were imported from the Ecoinvent database. These data were multiplied with a bill of quantities which was created from available documentation.

3. Results
The results of the comparison are presented in the charts in the following figures: Figure 2 for nPEI and Figure 3 for GWP. The lowest input of nPEI was calculated for V5 (3,039 GJ), the proposed variant of TiCo system (V1) ranked with 3,588 GJ and the greatest nPEI had V3 (reinforced concrete frame filled with ceramic blocks, 4,634 GJ). The variant V2 ranked with 3,704 GJ and V3 with ceramic blocks had the second highest value of nPEI 4,514 GJ.

The Figure 3 presents a chart of total global warming potential (GWP) expressed in embodied emissions of greenhouse gases (GHG). In this comparison, the ranking of variants was similar as for nPEI with the lowest amount of emitted GHG in V5 (224.5 t $CO_{2,eq}$) the proposed TiCo system ranked second (330.0 t $CO_{2,eq}$) and the greatest amount of GHG over 50 years was recorded for V3 (401.6 t $CO_{2,eq}$). Variant with cast-in-place RC with TiCo envelop had 345.1 t $CO_{2,eq}$ and GWP of V4 is calculated on 387.1 t $CO_{2,eq}$.

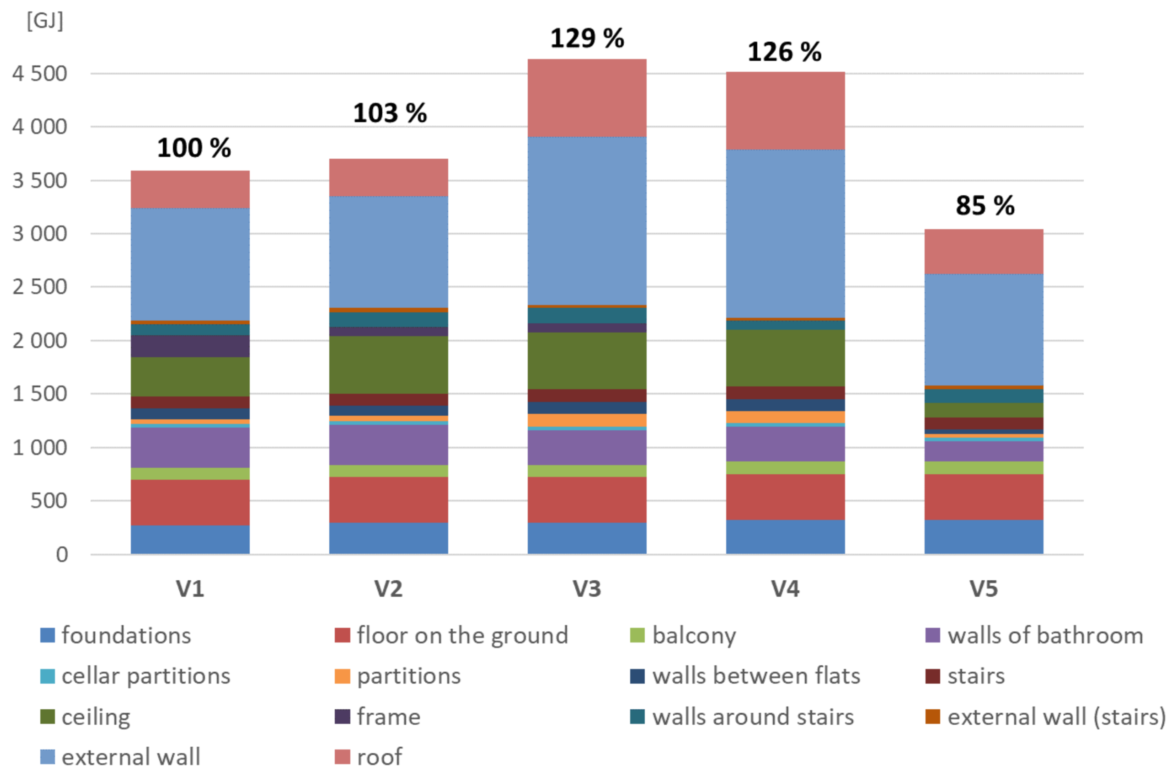

Figure 2. Proportions of individual constructions of embodied energy (nPEI) in the reference study period (50 years)

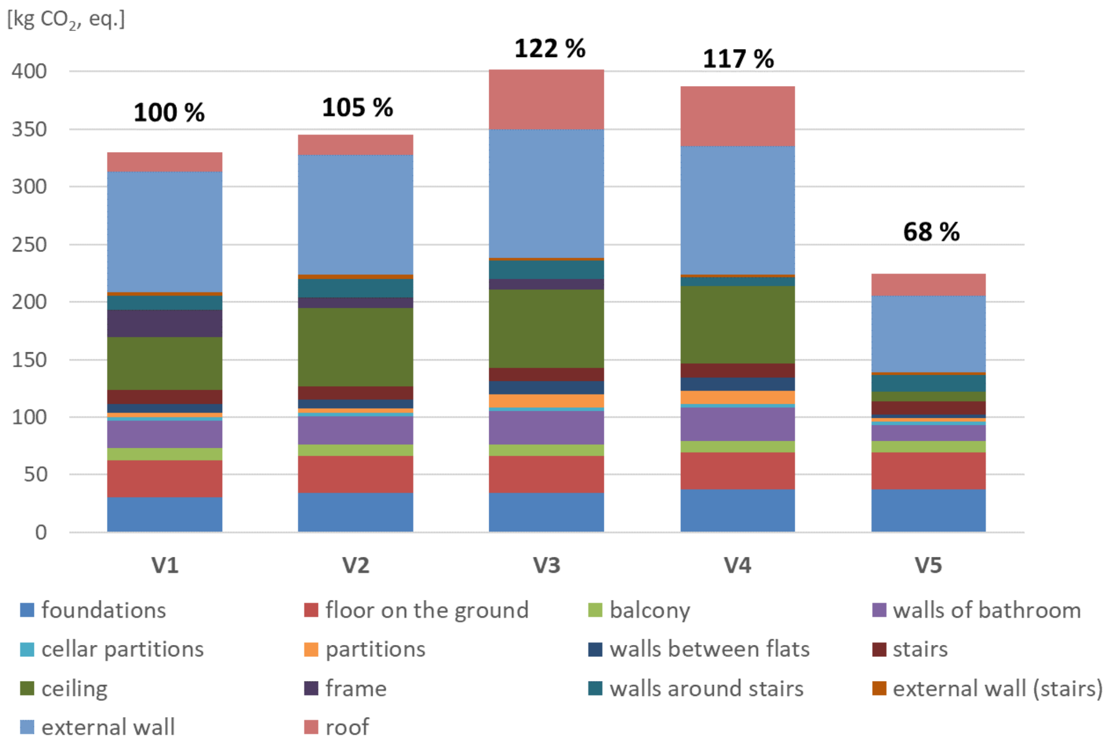

Figure 3. Proportions of individual constructions of embodied emissions (GWP) in the reference study period (50 years)

Differences between variants were not considerable but apparent. Average percentage difference of results of both environmental indicators from variant V1 between the least favourable (V3) and the most favourable (V5) option is about 25 %. The most environmentally friendly variant is V5 – completely wooden construction. This construction using primarily wooden construction is not possible in the Czech Republic due to strict fire safety regulations. However, V5 is a reference variant for future development and countries that are opened to multiple story houses entirely made of wooden structure.

The second most favourable option is the original TiCo variant. The difference between precast and cast-in-place RC frame is not significant (about 4 %). The variant V2 (cast-in-place RC frame) has a greater thickness of celling, but does not have beams and bracing. The volume of ceiling of V1 is lower than in variant V2 (dark green in graphs), but precast frame (dark violet in graphs) has higher environmental impact, because it needs more materials for bracing. The results of variants with ceramic bricks (V3, V4) come out the worst.

In both charts (Figure 2 and Figure 3) is evident, that constructions with a bigger amount of materials made of RC or envelope from ceramic blocks have a significant environmental impact. The highest impact is caused by the external wall, which is also construction with the biggest volume in this assessment Great impact have also roof, ceiling, foundations and floor on the ground. For example: in variant V3, external wall with roof have almost half of the total nPEI impact. Variants V1, V2 and V5 have wooden structure roof. In these charts (Figure 2 and Figure 3), it is possible to see differences between these wooden roofs (V1,V2 and V5) and RC roofs in variants V3 and V4. Also, partitions made by ceramic blocks (V3, V4) have a bigger environmental impact than wooden (V1,V2 and V5). Environmental impact of the wooden ceiling in variant V5 is the lowest of these 5 systems. On the other hand, using wood construction has also many disadvantages like fire resistance, plastic structure changes or risk of biological degradation.

4. Discussion

4.1. Limitations of the study
The study is limited in a sense, that a national approach to LCA of a building has been used, follwing the simplified boundary conditions of SBToolCZ. Results can vary, depending on the selected methods, database or only another dataset in one database (for example in another location, can be calculated differently). Results are also affected by selection of the assessed life cycle phases. Considering this and the simplification described above, it is necessary to evaluate the environmental result in a broader context.

Similar system has been evaluated by Ctislav Fiala [9]. Environmental comparison has been done for family house with used Passivhaus-Bauteilkatalog 2008. Comparison has been done, among others, for subtle column system with timber panels against ceramic block of thickness 24 and 44 mm. Column system with timber panels have 10 % of primary energy and 32 % of CO_2 eq. less than ceramic system. On the other hand, SO_x emissions of column system with timber panels are 21 % higher than ceramic system, due to steel reinforcing in concrete.

In a boader study, Endrit Hoxah and his colleagues have done LCA studies of 30 houses in France [10]. They have been focusing on uncertainties of LCA method. One of their results is, that LCA is able to distinguish significantly between 2 projects, when the difference between them is approximately 20 % or higher. In this paper, differences between variants are between 3–32 %. Results in this paper are on boundary of the distinguish ability of LCA studies.

4.2. Service life expectations
As already outlined in the LCA method used in this work, service life has a major impact on the resulting environmental loads. But at the same moment, the uncertainties associated with the estimation of the expected service life of a building element are not negligible. Method SBToolCZ for apartment house from year 2013, which was used, includes the condition: service life can't be higher than reference period of the object. On the other hand, it isn't clear in this method, how to consider service life of materials, which are connected together. Data of service life from SBToolCZ have been used, but they have been amended a little bit. For example, a roof: PVC foil has service life 20 years, but EPS under, has service life 30 years. They are usually replacement together. In this case with roof was used average service life 25 years.

4.3. Precast vs. cast-in-place reinforced concrete
In this paper, environmental comparison of precast vs. cast-in-place reinforced concrete was addressed. Only environmental impact of used materials in a given amount was included in the study. More favourable results for the precast variant were caused only because of precast RC is lighter. Precast production plant have better conditions for concrete curing, so it can use higher quality of concrete and make precise lighter elements.

Ctislav Fiala in his work "Environmental optimizations of concrete construction" [11] compared the environmental impact of these types of concrete. An important aspect for more environment-friendly RC structure is optimization of recipe and shape of elements. It is not easy to say which type is more favourable. Precast RC needs more energy to the operation of production plant, but the elements made of it are more precise and allow smaller dimensions (due to higher class of used concrete). Another important factor is also represented by transportation means and distances from production facility to construction site. There are less precast production plants than concrete mixing plants, so the distance travelled by the materials before they arrive to construction site might be longer.

Despite the optimization of shape of the precast RC skeleton in TiCo, it isn't possible to declare this variant as a better one in any case in comparison with the cast in place concrete structure. Means of transport of material and distance between site and factory can have important impact to such an extent that results can be reverse.

5. Conclusions

This paper was created as a part of the project TiCo. Its main goal is to design and test a flexible structure system based on timber and high-performance concrete for energy effective apartment building. One of the main requirements of TiCo project is a massive prefabrication, including outdoor finishes. This is the reason, why external cladding on aluminium frame is used. The environmental impact of aluminum is not low, but it was necessary to meet the goals of the project.

This study compared the desired TiCo system with 4 other conventional system in terms of environmental impact.

The results indicated, that TiCo (V1) belongs to the environment-friendlier group of structures. However, it is not the most favourable variant when compared to the entirely wooden based structure V5, which unfortunately is not allowed to be built in the Czech Republic due to the fire regulations. This fact makes the TiCo system (V1) the best one possible, but fire regulations might change in the future and it is likely that they will.

The difference between subtle precast and cast-in-place RC skeleton is not significant in this paper.

This paper is focused only on embodied emissions and energy and leaves aside social or economic sustainability indicators. However, it still presents tangible results that might be used in decision making process when comparing different structure systems and means of construction (prefabricated or not).

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