

## ENVIRONMENTAL OPTIMIZATION OF STRUCTURES IN TERMS OF USED MATERIALS

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**Abstract.** Building materials play important role in buildings construction as well as have massive contribution to impact of buildings on environment. Materials influence global climate by emitting greenhouse gasses, acidification becomes evident regionally, but building materials also have considerable effect on occupants' health. It is important to quantify effects of building on environment. However, some effects are easier to measure than others and also importance of certain effect needs to be defined. Life cycle assessment appears to be the most appropriate method for environmental evaluation.

This paper presents one example of environmental assessment of building materials and illustrates environmental profile of particular constructions of selected building in Slovak Republic. Environmental parameters, such as amount of embodied energy, global warming potential and acidification potential were evaluated. For selected constructions the optimization of materials was done with aim of minimizing the negative effect of building materials on environment. The decreasing of the values of primary energy, global warming potential and acidification potential were reached for evaluated structures as well as for whole building (at about 3.3 – 12.3 %) only by a change of building materials.

**Keywords:** environmental assessment, building materials, optimization, primal energy, greenhouse effect, acidification.

### 1. Introduction

Buildings represent the principal component of peoples' environment and are created to assure comfort of occupants. However buildings' build up, operation and demolition are responsible for more than 40 % of primal energy consumption, of which more than half belongs to residential buildings. In addition, high consumption of energy in processes related to building industry results in huge emissions of greenhouse gasses. It is estimated, that more than 1/3 of emissions of CO<sub>2</sub> has its origin in building industry. Buildings are accounted for more than 30 % of electricity consumption and this number is expected to rise up to 3/4 by 2025 (Department of Energy (2008)). Also other problems such as resources depletion, pollution and waste creation pose serious issues of building industry processes.

Selection of building materials is a complicated process, which belongs to the most important actions in creation of a suitable buildings construction to achieve appropriate technical properties (Shi *et al.* 2009). On the other hand, building materials play important role in buildings' negative effect on environment (Estokova 2009). Materials influence global climate by emitting greenhouse gasses, acidification becomes evident region-

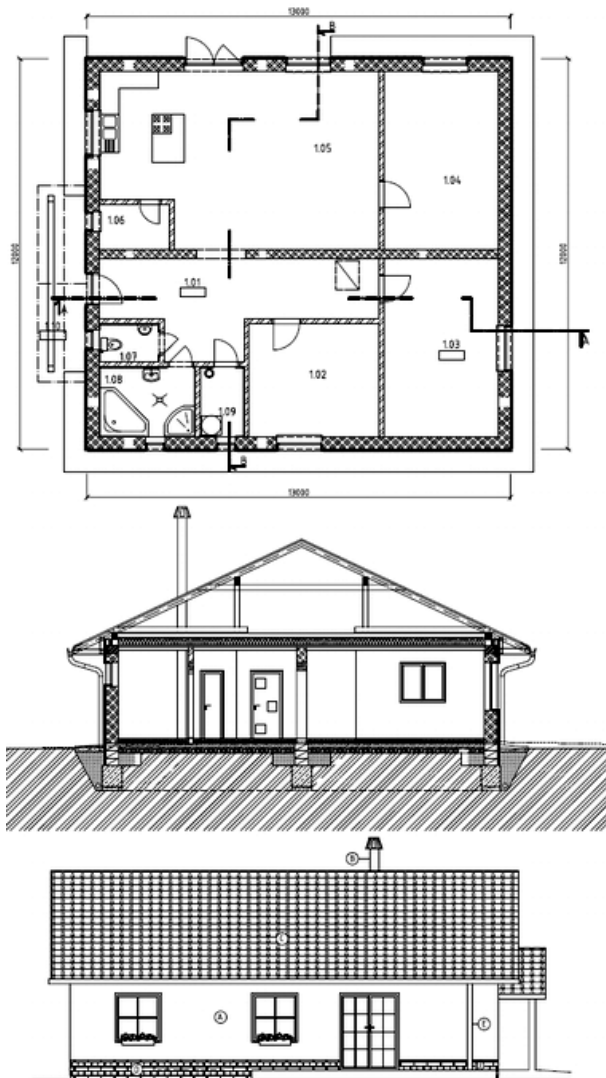
ally, but building materials also have considerable effect on occupants' health. Therefore is important to enumerate the negative effects of building on environment. However, some effects are easier to measure than others and also importance of certain effect needs to be defined. Life cycle assessment, which includes evaluation of environmental potentials, appears to be the most appropriate method for environmental assessment of building materials and the whole buildings (ISO 14040-14049). Impact on environment includes existing and potential effect of building material it term of whole life cycle of product.

In this paper an environmental assessment of building materials with implementation of Life Cycle Assessment is presented. Illustration of environmental effect of particular structures is included. Materials of external walls were selected for further optimization with the aim of minimization of Primal Energy Intensity (PEI), Global Warming Potential (GWP) and Acidification Potential (AP).

### 2. Material and methods

A one storey house with 2 bedrooms, living room, bathroom and toilet situated in Klčov was selected for

evaluation process (Fig. 1). Build up area of this bungalow-styled house is 178 m<sup>2</sup>, of which 170.5 m<sup>2</sup> belongs to house and 7.5 m<sup>2</sup> is storm lobby. Useful area is 129.9 m<sup>2</sup>, floorage is 84.3 m<sup>2</sup> and total capacity is 725 m<sup>3</sup>. More detailed information of house is presented by Ruzbacky (2010).



**Fig 1.** Illustration of assessed building

**Excavations and foundations:** A certain amount of organic soil and the rest of excavations were removed. Foundations and base plate are made of plain concrete. Some polystyrene (XPS) was used to eliminate heat bridges.

**Vertical load-bearing and partitioning structures:** External walls were made of 375 mm thick aerated concrete blocks. Same material was used for internal load-bearing walls with thickness of 300 mm. Material of partitioning structures was aerated concrete, where block of thickness of 150 mm were used.

**Horizontal load-bearing constructions:** Load bearing structures of ceiling (horizontal beams) were made of technically dried wood, while shuttering was made of OSB boards. Material of bond beams and capping was reinforced concrete.

**Roof:** Wood beams (technically dried) created the framework of the roof. Roof weatherproofing was secured by ceramic roof tiles.

**Surfacing:** Walkway surface of floors for the major part of house was made of wooden panels, while the rest was made of ceramic flooring tiles. Material for plastering of external walls was silicate plaster, while indoor plastering was designed of lime-cement plaster. Plasterboard was used in the lower ceiling.

**Insulation:** Thermal insulation of external walls is secured by material itself. However, 50 mm of glass wool was used to improve insulation value external walls. Mineral wool was also used to insulate the attic.

**Doors and windows:** Panels of windows were double glazed filled with argon, frames were made of plastic.

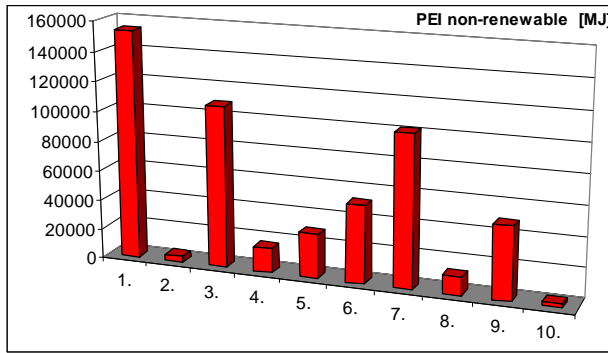
**Building materials of evaluated building were evaluated by modified MS Excel datasheet developed by a company Createrra. Program was modified for the purpose of this study to enable quantifying of several environmental parameters including weight of used materials, global warming potential, acidification potential and primary energy intensity. Values of potentials are based on available specific building materials database (Waltjen 1999).**

Materials used in building were divided into 10 groups in the dependence on structure to be used in (e.g. foundations, roof, load-bearing walls etc.). Amount (volume or area) of used materials in each group was calculated, what serves as input for assessment of environmental performance of particular group of materials. Parameters, such amount of embodied energy related to consumption of energy from non-renewable sources (PEI [MJ]), global warming potential, which represents the quantity of emission of greenhouse gasses (GWP [kg CO<sub>2</sub>eq]) and acidification potential, which expresses the quantity of emissions of acidifying gasses (AP [kg SO<sub>2</sub>eq]).

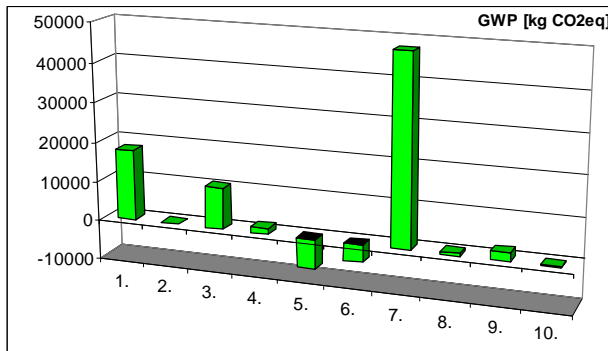
The principal problem of today's environmental assessment is missing general methodology for evaluation of building materials, structures or entire buildings (Levin 2009). However, a Life Cycle Assessment can serve for this purpose; the lack of relevant input data may cause a problem. E.g., inconsistency of input data from different sources may lead to incorrect evaluation or interpretation. In this case study the values of global warming potential don't include the data from the final phase of materials' life cycle (Kierulf 2008). Therefore in same group of structures, where high quantities of natural materials (including wood, hemp, straw etc.) are used it is possible to reach the negative value of GWP. These materials have ability to store carbon by consuming CO<sub>2</sub> during their growth. As long as they are not combusted or composted, no emissions of CO<sub>2</sub> are emitted into atmosphere. However, some databases may state zero or positive values of GWP (Hammond 2008).

### 3. Results of environmental assessment

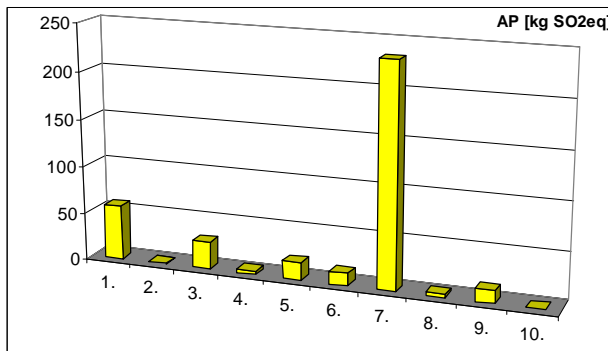
Environmental assessment was calculated for particular structures. Estimation of PEI, GWP and AP is illustrated in Figures 2–4.



**Fig 2.** Primal energy intensity PEI of building materials of evaluated structures [MJ]



**Fig 3.** Global warming potential GWP of building materials of evaluated structures [kg CO<sub>2</sub>eq]



**Fig 4.** Acidification potential AP of building materials of evaluated structures [kg SO<sub>2</sub>eq]

As illustrated in Figure 2, primal energy intensity reached the highest value in foundations (PEI=153350.37 MJ) as a result of relatively high density (and in consequence height weight) of materials of foundations. Primal energy consumption reached the second highest value in materials of vertical load-bearing walls (PEI=108459.86 MJ). High value of PEI was also calculated for materials of thermal insulation (PEI=101734.23 MJ).

Emissions of greenhouse gasses are twined with processes with high consumption of energy, which are mostly based on fossil fuels. Therefore the biggest contribution to global warming (Fig. 3) was reached in materials of thermal insulation (47665.82 kg CO<sub>2</sub>eq). As a result of high primal energy consumption in foundations, global warming potential reached fairly high value for the same structure

(GWP = 17770.53 kg CO<sub>2</sub>eq). Emissions of greenhouse gasses were also rated as high for vertical load-bearing structures (10555.74 kg CO<sub>2</sub>eq). However, in some structures it is possible to reach the negative value of GWP. By a comprehensive choice of building materials, what includes intense utilization of natural material (e.g. wood) it is possible to minimize the global warming. Negative values of GWP were calculated for materials of ceiling (-7348.00 kg CO<sub>2</sub>eq) and roof (-4284.37 kg CO<sub>2</sub>eq).

The highest effect of acidification (Fig. 4) was calculated for materials of thermal insulation (233.01 kg SO<sub>2</sub>eq) and foundations (57.1518 kg SO<sub>2</sub>eq).

For more explicit interpretation of result evaluation the values of PEI, GWP and AP were normalized by converting values of potentials from total values to values per kg of evaluated building materials. This relieves comparison of environmental parameters of structures in building and enables comparison of particular structures among several buildings (table 1).

**Table 1.** Weight-normalization of environmental assessment of particular structures (1. Foundation, 2. Thermal insulation of foundation, 3. Vertical load-bearing structures, 4. Partitioning structures, 5. Ceiling, 6. Roof, 7. Thermal insulation, 8. Facade, 9. Surfaces, 10. Doors and windows)

	Weight	PEI	GWP	AP
	kg	MJ/kg	kg CO <sub>2</sub> eq /kg	kg SO <sub>2</sub> eq /kg
1	176592.2	0.87	0.101	0.324
2	39.5	102.00	3.440	21.100
3	15455.0	7.02	0.683	1.885
4	7148.0	2.32	0.223	0.540
5	5698.6	5.21	-1.289	3.241
6	12351.7	4.22	-0.347	1.071
7	1885.0	40.69	2.041	9.236
8	1454.6	8.38	0.452	2.414
9	5047.6	9.73	0.411	2.732
10	27.7	87.31	3.980	24.482

Weight normalization may provide an easier comparison of structures between each other. E.g., values of PEI reached the highest values for materials of foundations (Fig. 2), however normalized value of PEI (table 1) for materials of foundations was the lowest (0.87 MJ/kg). The highest values of normalized PEI reached materials of thermal insulation, thermal insulation of foundation and doors & windows (values from 40.69 MJ/kg – 102 MJ/kg). Values of normalized GWP ranged from -1.289 kg CO<sub>2</sub>eq/kg in ceiling to 3.98 kg CO<sub>2</sub>eq/kg in doors & windows and values of AP reached values from 0.324 kg SO<sub>2</sub>eq/kg in foundations to 24.482 kg SO<sub>2</sub>eq/kg in materials doors & windows.

Similar normalization was done for total values of PEI, GWP and AP in evaluated building by converting these total values to areal and cubical ones (table 2). This provides data for further comparison of several building of the same type.

**Table 2.** Areal/cubical normalization of total values

	PEI	GWP	AP
	MJ/m <sup>2</sup>	kg CO <sub>2</sub> eq/m <sup>2</sup>	kg SO <sub>2</sub> eq/m <sup>2</sup>
Per built up area	2976.1	387.3	2.1
Per built up area (house only)	3107.0	404.3	2.2
Per useful area	4078.1	530.7	2.9
Per floorage	6284.0	817.8	4.4
Per total capacity	MJ/m <sup>3</sup>	kg CO <sub>2</sub> eq/m <sup>3</sup>	kg SO <sub>2</sub> eq/m <sup>3</sup>
	730.7	95.1	0.5

Normalized rates of PEI reached values from 2835.5 MJ/m<sup>2</sup> (per built up area) to 5987.1 MJ/m<sup>2</sup> (per floorage). Normalization was also calculated for GWP (values from 141.1 kg CO<sub>2</sub>eq/m<sup>2</sup> to 298 kg CO<sub>2</sub>eq/m<sup>2</sup>) and AP (reaching from 0.9 kg SO<sub>2</sub>eq/m<sup>2</sup> of build up area to 1.9 g SO<sub>2</sub>eq/m<sup>2</sup> of floorage).

Results of presented environmental assessment including normalization show one possible example of environmental assessment of buildings in terms of building materials; however it is to difficult to interpret them. Large size (weight) of used materials usually involves higher consumption of primal energy and gives rise to CO<sub>2</sub> and SO<sub>2</sub> emissions. However, this does not mean that the size of used material is decisive criterion. For example, in spite of relatively small quantity (weight) of thermal insulation based on fossil fuels, primal energy consumption, global warming and acidification potentials are usually relatively high (Berge 2009).

#### 4. Optimization of constructional design

Optimization was done with the aim of reduction of negative effect of building production. Materials of external walls were selected for illustration of environmental optimization. New composition of envelope was done on basis of corresponding U-value (coefficient of heat transmission).

In Slovakia, external walls have to accomplish the requirements of thermal technical standard (STN 73 0540). The U-value of these constructions should not exceed 0.32 W/m<sup>2</sup>K. The value only improves insulation ability. Material of external walls was originally designed of aerated concrete with thickness of 375 mm and remained unchanged; however, materials of thermal insulation were alternated. Thermal insulation was originally designed of 50 mm thick layer of glass wool. U-value for this composite construction (S1) calculated by program Teplo is approximately 0.243 W/m<sup>2</sup>K, including inner and outer plastering, as well as adhesive mortar. This construction fulfills requirements of Slovak technical standard STN 73 0540 for external walls, as the U-value is under 0.32 W/m<sup>2</sup>K.

Thicknesses of alternated materials of thermal insulation were calculated to retain the U-value unchanged. How-

ever, only thicknesses which are industrially produced were used. Therefore U-value in optimized structures did not reach the same value, but only similar to original scenario (S1). Composition of structures in scenarios S1-S4 contained: lime-cement plaster (10 mm), aerated concrete blocks (375 mm), adhesive mortar (3 mm), thermal insulation (50 mm) and silicate plaster with glass-textile mash (5 mm). Composition of materials with natural fibers in scenarios S5-S8 was similar to previous ones; however external plastering was replaced by wood paneling. Thicknesses of materials of thermal insulation in all scenarios were 50 mm, however the U-values ranged from 0.243 to 0.251 W/m<sup>2</sup>K. The U-value was calculated in the dependence on value of thermal conductivity (table 3).

**Table 3.** Thermal-technical properties of thermal insulation materials

	Insulation	λ	ρ	U
		W/(m.K)	kg/m <sup>3</sup>	W/m <sup>2</sup> K
S1	Glass wool	0.034	68	0.243
S2	Rock wool	0.040	147	0.254
S3	Polystyrene EPS F	0.038	18	0.250
S4	Polystyrene EPS with graphite	0.032	15	0.250
S5	Hemp with PE fiber	0.040	30	0.251
S6	Hemp without PE fiber	0.040	30	0.251
S7	Flax with PE fiber	0.040	30	0.251
S8	Flax without PE fiber	0.040	30	0.251

Results of optimization of constructional design of materials' composition of external walls are in table 4, where sector with area of 1 m<sup>2</sup> was evaluated (Only the material of thermal insulation is displayed.)

**Table 4.** Comparison of external walls in dependence on material of thermal insulation

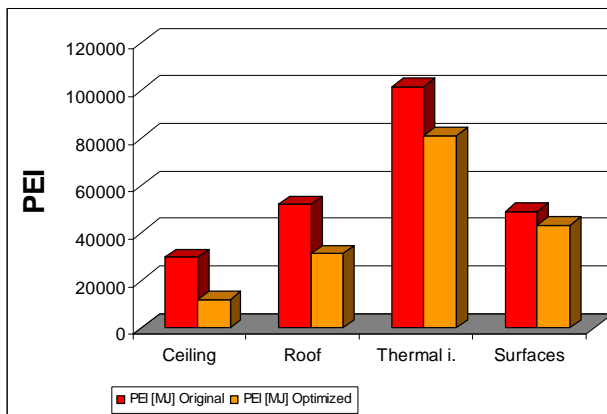
	Insulation	PEI	GWP	AP
		MJ/ m <sup>2</sup>	kgCO <sub>2</sub> eq /m <sup>2</sup>	kgSO <sub>2</sub> eq /m <sup>2</sup>
S1	Glass wool	783.90	63.89	0.1549
S2	Rock wool	785.84	68.26	0.2276
S3	Polystyrene EPS F	703.23	59.22	0.1698
S4	Polystyrene EPS with graphite	688.46	58.72	0.1666
S5	Hemp with PE fiber	613.86	43.59	0.1505
S6	Hemp without PE fiber	607.86	43.22	0.1490
S7	Flax with PE fiber	624.21	44.33	0.1555
S8	Flax without PE fiber	618.21	43.97	0.1540

As a result of optimization, the most suitable material for thermal insulation appears to be hemp without PE fiber. As illustrated in table 3, the least primal energy consumption was reached in hemp without PE fiber (607.86 MJ/m<sup>2</sup>). The lowest value of global warming potential was reached in the same structure (43.22 kg CO<sub>2</sub>eq/m<sup>2</sup>). Also AP was estimated to be the lowest in hemp without PE fiber.

An optimization of materials of buildings' envelope can be done on the similar basis. However, also other criteria can be taken into consideration and the rest of structures could be optimized. This may lead to a considerable reduction of primal energy consumption, as well as reduction of CO<sub>2</sub> or SO<sub>2</sub> emissions. Following structures were optimized, what has led to further reduction of energy and emissions.

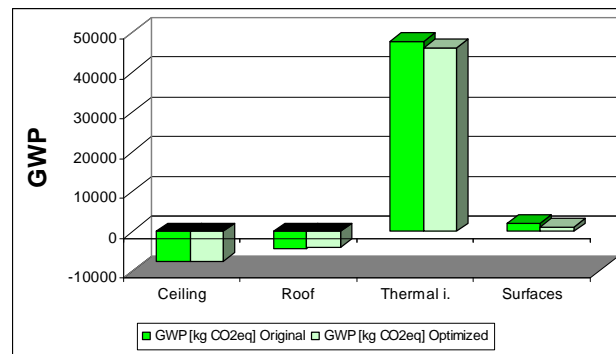
Construction of ceiling in original project was made of technically dried wood and sheathing was made of OSB. However, by changing material for air-dried wood it is possible to reduce the negative environmental effect. Beams and sheathing of roof had similar material basis than ceiling, therefore similar result of optimization were reached. In addition, the material of roof covering (ceramic clay tiles) was compared with other materials, of which the concrete tile appeared to be the most suitable for this building. Also plastering of walls and ceiling originally designed of lime-cement plaster has been chosen for optimization. The less negative effect was estimated when clay plaster was used.

After optimization of selected structures a new assessment was made. The reduction of negative environmental effect was reached for materials of thermal insulation, roof, ceiling and surfaces, as shown in Figures 5–7.

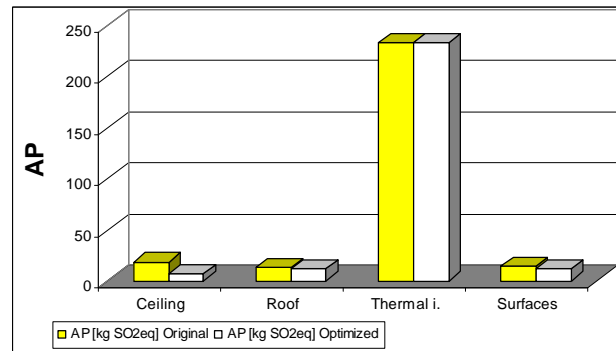


**Fig 5.** Comparison of environmental performance of original and optimized structures in terms of primal energy intensity [MJ]

As illustrated in Fig. 5, the highest reduction of primal energy intensity (59.8 %) was reached by alternating the materials of ceiling, what represents reduction by 17763.7 MJ. Even higher reduction by 11.4 g SO<sub>2</sub>eq (61.7 %) was also reached in optimized design in materials of ceiling (Fig. 7). The highest CO<sub>2</sub> emissions reduction was reached in surface materials (920.3 kg CO<sub>2</sub>eq). Reduction of 44.3 % was achieved just by changing of material basis.



**Fig 6.** Comparison of environmental performance of original and optimized structures in terms of global warming potential [kg CO<sub>2</sub>eq]



**Fig 7.** Comparison of environmental performance of original and optimized structures in terms of acidification potential [kg SO<sub>2</sub>eq]

At the end the comparison of original and optimized design of evaluated building was performed (table 5).

**Table 5.** Comparison of environmental assessment of original and optimized building

	PEI	GWP	AP
	MJ	kg CO <sub>2</sub> eq	kgSO <sub>2</sub> eq
Original	529740.91	68936.96	373.66
Optimized	464528.83	66639.35	359.19
Reduction	65212.08	2297.61	14.47
Reduction	12.3%	3.3%	3.9%

## 5. Conclusion

1. In this paper an assessment of building in terms of building materials was illustrated, as well as optimization of structures was implemented. Only small changes in composition of materials were done. In optimized building the 12.3 % reduction of primal energy was reached (65212.08 MJ). Emissions of CO<sub>2</sub> were reduced by 3.3 % (2297.61 kg CO<sub>2</sub>eq) and SO<sub>2</sub> emissions were reduced by 3.9 % (14.47 kg SO<sub>2</sub>eq). However, even small changes in material basis may lead to a considerable reduction of primal energy intensity, SO<sub>2</sub> emissions, as well as emissions of greenhouse gases.

2. This is only one possible way of reducing the negative environmental effect. Even higher reduction may be reached e.g. by a smart building operation or utilization of recycled or recyclable materials.

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