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Life-time Material Effectiveness Analysis of Building Components

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Abstract: The paper compares the life-time material effectiveness of five exterior walls used to build residential buildings. Effectiveness was measured by the MIPS method. The five exterior walls compared were: 1) a precast concrete wall, 2) a brick and concrete wall, 3) a brick and timber wall, 4) a timber wall, and 5) a straw wall. Expected service life of the exterior wall was 100 years. The precast concrete wall will consume about twice as much material over its 100-year lifespan as a wooden wall. The length of the service life of a wall affects the material effectiveness of concrete and brick walls significantly.

INTRODUCTION

The article compares the life-time material effectiveness of five exterior wall types used in residential buildings by the MIPS method. MIPS (Material Input Per Service Unit) is an indicator of the material flows of products and services, i.e. consumption. MIPS was developed in the 1990s at the Wuppertal Institute.

The exterior wall of a building is interesting from the viewpoint of material effectiveness since its mass constitutes a significant part of the building mass, and since exterior walls of highly different properties are found on the market. The exterior wall is also interesting in that its thermal-insulation capacity can affect the life-time energy consumption of the building. The ability of exterior walls to withstand weathering action also varies as does their maintenance need.

MATERIALS AND METHODOLOGY

The life-time material effectiveness of five exterior wall types used in residential construction was calculated by the MIPS method. In this study MIPS calculations consider natural material inputs. The calculations do not consider the material flows from the removal or demolition of products, nor emissions.

MIPS is calculated from Formula 1 [1].

$$MIPS = MI/S \quad (1)$$

where

MI = sum of all inputs required by a product or service over its life time including material inputs invisible during the use phase.

S = sum of all the times the product or service is used, i.e. sum of service units.

The material effectiveness calculations for exterior wall structures covered:

- natural materials used in construction including hidden flows (construction).
- natural materials, including hidden flows, used in repair of an external wall or its components (renewal).
- hidden flow of heating energy flowing through exterior wall during life-time of building (heat energy).

Hidden flows consist, for instance, of the country rock from mineral mining, fuel spent in transportation, and other substances not bound to the product itself. Hidden flows are factored into the MI factors for different materials. For example, if the MI factor of a building material is 5.1, the ratio of the net weight of the material to the weight of the natural materials not bound to the material used to produce it is 1:4.1. Thus, the "ecological rucksack" resulting from the production of the material is more than 4-fold compared to its net weight.

Mainly German factors are used for MI factors [2] – adapted to Finnish electricity generation. The MI factor of German electricity generation is 4.70 kg/kWh, on average, while the OECD average is 1.55 kg/kWh [2]. In this study the MI factors do not cover the water and air used in production.

The MI factors of the materials and energy used in the calculations were:

- concrete 1.2 kg/kg
- steel 5.1 “
- brick 2.0 “
- lumber (spruce) 2.2 “
- T & G board (spruce) 2.8 “
- mineral wool 2.1 “
- gypsum 1.3 “
- paint 2.2 “
- PE sheeting 5.4 “
- Cardboard 3.0 “

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- straw 1.0 "
- clay 1.0 "
- electrical energy 0.37 kg/kWh
- thermal energy 0.36"

The average Finnish electricity generation data from 2000 were used as MI factors of electrical energy (hidden flow) while the average district heat generation data from the same year were used as MI factors of heating energy. The electricity generation (TWh) and related fuel consumption data (PJ) used in the hidden flow calculation are from Statistics Finland [3]. In the year 2000 electricity generation was based on the following resources: hydropower 11.0 %, nuclear power 50.0 %, coal 13.1 %, oil 1.7 %, gas 8.0 %, peat 5.3 %, others 11.0 %. The data on fuels used to generate district heat and related electricity (PJ) are from Statistics Finland (2001). In the year 2000 district heat and related electricity generation was based on the following fuels: coal 26.5 %, heavy fuel oil 5.8 %, light fuel oil 0.5 %, natural gas 37.6 %, peat 17.5 %, industrial and forest chips 8.1 %, recycled fuel 0.2 %, industrial waste heat 1.0 %, electricity 0.1 %, others 2.9 %.

Five exterior wall types were selected for study. In the case of types 2 and 3 the walls of the apartment block and the row house are slightly different. The studied wall types were:

WALL-01 Precast sandwich panel wall, spray finished (apartment block)

- spray finish (5mm) + reinforced concrete (80mm) + mineral wool (140mm) +
- steel hairpins + reinforced concrete (80/150mm) + jointing concrete + jointing strip + jointing compound + jointing bars, U-value 0.28 W/m2K.

WALL-02 Brick-wool-concrete, single-coat plaster finish (apartment block)

- single-coat plaster finish (5kg/m2) + brickwork (NRT) + brick ties + working allowance (30mm) + mineral wool (150mm) + reinforced concrete (80/150mm), U-value 0.26 W/m2K.

WALL-03A Brick-wool-timber frame, single-coat plaster finish (apartment block)

- single-coat plaster finish (5kg/m2) + brickwork (NRT) + brick ties + working allowance (30mm) + fibreboard (12mm) + mineral wool (50mm) + bearing timber frame + mineral wool (150mm) + vapour barrier (PE 0.2mm) + gypsum board (13mm), U-value 0,26 W/m2K.

WALL-03B Brick-wool-timber frame, single-coat plaster finish (row house)

- single-coat plaster finish (5kg/m2) + brickwork (NRT)+ working allowance (30mm) + fibreboard (12mm) + mineral wool (50mm) + bearing timber frame + mineral wool (125mm) +
- vapour barrier (PE 0.2mm) + gypsum board (13mm), U-value 0.28 W/m2K.

WALL-04A Board-wool-timber frame, painted (apartment block)

- paint + external cladding board + studding + mineral wool (50mm) + building board (13mm) +
- bearing timber frame + mineral wool (150mm) + vapour barrier (PE 0.2mm) + gypsum board (13mm), U-value 0.26 W/m2K.

WALL-04B Board-wool-timber frame, painted (row house)

- paint + external cladding board + studding + mineral wool (50mm) + building board (13mm) +
- bearing timber frame + mineral wool (125mm) + vapour barrier (PE 0.2mm) +
- gypsum board (13mm), U-value 0.28 W/m2K.

WALL-05 Straw bale wall, painted board lining (row house)

- paint + external cladding board + studding + clay plaster (20mm) + straw bale (450mm) + bearing timber frame + clay plaster (30mm) + 2 x building paper (150 g/m2) + rough tongue-and-groove board (20mm) + wood fibre board, U-value 0.14 W/m2K.

Sandwich wall panels have been widely used in exterior walls of Finnish apartment blocks from 60's. The brick-wool-concrete wall has in recent years seen much use in apartment block construction, especially in the metropolitan area. A large share of one-family and row houses have been built with timber-framed exterior walls clad with board and brick. The comparison also includes the still rare straw bale wall which has future potential in one-family and row houses. Straw and clay are low-value-added products

The subject apartment block has five floors and a single entry. The building comprises 21 dwellings with a total living area of 1,180 m2. The building's exterior wall area is 1,089 m2. The studied row house is a two-storey, three-dwelling unit. The combined living area is 332 m2 and its exterior wall area is 335 m2. The calculated heating requirement assumes that the buildings are located in southern Finland.

The maintenance cycles used in the calculations are based partly on experience and partly on estimations. Therefore, their impact on the calculations was analyzed. Ten percent material waste was assumed. The road transport distance of materials used was 200 km, except in the case of straw bales (100 km) and clay (25 km). In practice, transport distances vary depending on the location of the construction site and where the construction materials are procured from.

RESULTS

Life-Time Material Flow of Exterior Walls

The consumption of natural materials during the construction of a precast concrete wall of an apartment block is nearly 8-fold compared to a wooden wall. The consumption of natural materials during the construction of a wood-brick wall of a row house is 4.5-fold compared to the construction of a wooden wall and double compared to a straw bale wall.

An extra environmental advantage provided by the wooden and straw-bale walls is that more than half of the natural resources going into them are renewable. Stone walls contain nothing but unrenewable natural resources.

On the whole, a precast concrete wall consumes twice as much natural resources in a 100 years as a wooden wall. The consumption of a precast concrete wall and the brick-wool-concrete wall are close to each other. On the other hand, the brick-wool-timber frame wall of the row house consumes about twice as much natural resources in a 100 years as the straw bale wall and 1.5 times as much as the wooden wall. This is partly explained by the higher thermal insulation capacity of the straw bale wall. If the mineral wool of the board-wool-timber frame wall was over 300 mm thick, the wooden wall would be more material effective than the straw bale wall. The results of the life-time material effectiveness calculations for exterior walls are presented in Tables **1** and **2**.

Comparison of the Results of MIPS and CO_2 Calculations

The results of the MIPS calculations on two types of exterior walls were also compared to the life-time CO_2 calculations on the same exterior walls.

The examination of the life-time material effectiveness (MIPS) of exterior walls gives a different result than the CO_2 equivalent examination. The latter places much more emphasis on energy consumption during the life cycle whereas the MIPS examination is more sensitive to differences in the masses of structures. The comparison calculations made showed that a heavier wall in terms of material effectiveness (WALL-02) is 50 % worse than a lightweight wall (WALL-04B), while on the basis of the CO_2 equivalent the heavier wall is only 3 % worse than the lightweight wall.

Table 1. Natural Material Consumption (kg/Dwelling-Floor-m^2/yr) of Finnish Exterior Wall Types in Block of Flats Over a life-Time of 100 Years

Wall Type	Construction	Renew	Heat Energy	Total
01	10.2	3.7	11.4	25.3
02	8.4	4.4	10.6	23.4
03A	4.9	4.6	10.6	20.1
04A	1.3	1.5	10.6	13.4

Table 2. Natural Material Consumption (kg/Dwelling-Floor-m^2/yr) of Finnish of Exterior Wall Types in Row-Houses over a Life-Time of 100 Years

Wall Type	Construction	Renew	Heat Energy	Total
03B	5.2	5.0	12.5	22.7
04B	1.2	1.7	12.5	15.4
05	2.6	1.6	6.9	11.1

Sensitivity Analysis

When calculating the material effectiveness of a product (here an exterior wall), one has to estimate the life cycle of the product. Things will not necessarily work out the way we now think. Thus, it is important to determine the sensitivity of the calculations to possible changes. Sensitivity analyses of performed calculations for the exterior wall types with respect to the following factors are presented in the following:

- length of maintenance cycles.
- size of hidden flows related to heating energy.
- life-time of exterior wall.

Sensitivity to length of maintenance cycles:

If the maintenance cycles of the examined exterior wall types are halved, the natural material consumption over their life-times increases 11–23 % depending on wall type. If the maintenance need of just the brick facade doubles, the wall's life-time natural material consumption exceeds that of the precast concrete wall. Otherwise, changes in maintenance need do not affect the rank order of the examined walls.

Sensitivity to hidden flow of heating energy:

The hidden flow of heat generation may decrease in the future if natural gas increasingly replaces coal. On the other hand, increased burning of coal would increase the hidden flow of district heat. If the hidden flows of district heat are halved, the natural material consumption of the examined exterior walls will drop 23–41 %. Should they double, the life-time consumption of the examined exterior walls will increase 45–81 %. The rank order of the material effectiveness of the wall types over their life-time stays the same independent of the changes in the hidden flows of district heat generation.

Sensitivity to life cycle:

The service life of a wall has a significant impact on material effectiveness in the case of concrete and brick walls. Their material effectiveness weakens essentially if the life cycle remains under 40 years (Fig. **1**). Life cycle has hardly any effect on the material effectiveness of the board-wool-timber frame or the straw bale wall.

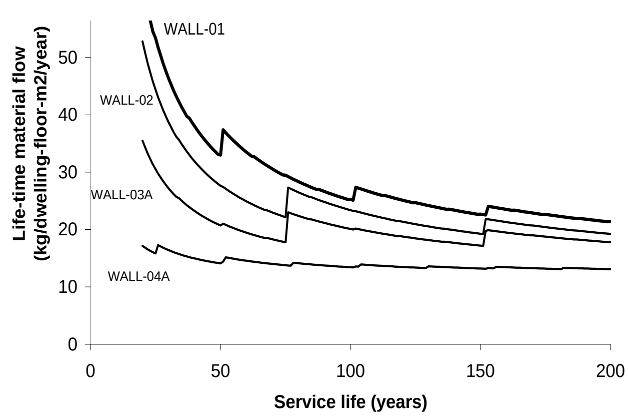

Fig. (1). Life time material flow calculations' sensitivity to service life length of exterior wall types.

CONCLUSIONS

From the viewpoint of life-time material effectiveness (MIPS) it pays to build with lightweight products, whose main materials have a low MI (Material Input) factor. Use of recycled materials and other by-products increases the material effectiveness of products. The products described above are material effective even if they require more frequent maintenance and renovation than heavier structures.

It appears that the impact of a product's life-time energy consumption gets less emphasis in life-time material effectiveness calculations than in the life-time CO_2 equivalent calculations for the same product. This holds true for products whose life-cycle energy consumption is significant. Thus, it pays to perform a life-time CO_2 equivalent calculation for such products in addition to a MIPS calculation. From the viewpoint of CO_2 it is worthwhile to favour solutions which lead to low building heat energy consumption.

In decision making we must consider the weight we wish to give to a product's consumption of natural resources, climatic impact and other factors affecting the value of the product.

The MIPS and CO_2 equivalent surveys do not consider the toxicity of construction materials or their impact on the health of builders and buildings. These issues have to be studied separately.

In the future also other building components besides exterior walls have to be studied. It would be especially worthwhile focusing on components that consume much natural materials and which could possibly be replaced by materials with different hidden flows.

Finally, it should be stressed that Finns have quite limited experience from the straw bale wall included in the comparison - it is only in the pilot construction phase. Straw construction products as well as the work methods need to be developed. The other exterior wall types of the comparison have been productified, and there is a lot of experience from them. On the other hand, there is no certainty about the service life of the modern outer wythe of a precast sandwich panel or brickwork facade or about the kinds of repairs they will need

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