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The effect of material selection on life cycle energy balance: A case study on a hypothetical building model in Finland

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ABSTRACT

A building is a complex system consisting of many different materials. The material selection, therefore, has a significant role in sustainable building design. This study has demonstrated the influence of material selection on the life cycle energy balance of a building based on current building codes and common building service systems in Finland. The influences of the selection were investigated on a relative basis using a hypothetical building model and in the three building component categories (structural frame, surface components and inner components).

The results showed that, in general, the differences between the alternative materials are rather visible in the production stage of the building and the energy benefit from material recycling. But it was also revealed that the influences of the selection appear differently in each life cycle stage of the building depending on the building component categories. The selection of the structural materials has larger effect than the other two component categories and a combination of different structural frame materials seems to be effective in some cases. The material selection for sheathing, exterior cladding and thermal insulation has a relatively greater influence than the others in the surface and inner components categories. The energy recovery benefits of wood and plastic products have a great influence on the life cycle energy balance of the building.

1. Introduction

The life cycle energy use of buildings – the energy used in their construction (embodied energy) as well as their functioning (operational energy) – has been extensively studied over the past few decades. Energy is one of the most important resources used in a building's life cycle and since the building sector contributes significantly to global primary energy consumption [1,2] a reduction in the life cycle energy use of buildings is an important target in attempts to mitigate climate change. In the effort to reduce life cycle energy consumption, most attention has thus far been focussed on operational energy aspects. As a result of efforts in this area, such as improvements in the thermal insulation performance of the building envelope and the development of building service equipment, operational energy demand has been significantly reduced. Although the operational energy still accounts for the major part of the life cycle energy use of buildings, the relative importance of embodied energy has increased, especially in the case of low energy buildings [3–8]. Sartori and Hestnes [7] have, for instance, reported that embodied energy account for up to 46% of the life cycle energy use (service life of 50 years) in the case of low energy building and up to 38% in the case of conventional buildings.

A building is a complex system consisting of many different materials. The material selection, therefore, directly influences the environmental impacts of a building. Several researchers have investigated the relationship between the choice of building materials and the resulting impacts. Basbagill et al. [9], for instance, investigated the influence of material choice and thickness on a building's embodied impact in four building elements (Substructure, Shell, Interiors and Services). They noted that a significant reduction in the embodied impact can be achieved by changes to

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the cladding materials, piles, glazing material and flooring material, whereas changes to materials and thicknesses were not important in the case of the doors, stairs and building service equipment. Thormark [10] investigated the effect of material choice on both the embodied energy and recycling potential in an energy efficient apartment block in Sweden. He noted that embodied energy could be decreased by approximately 17% (or increased by about 6%) by implementing a simple material change.

The material choice can have appreciable effect on the construction process itself. Cole [11], for instance, observed the energy consumption and greenhouse gas emissions associated with the on-site construction of buildings. He found that there were significant differences when alternative frame materials (wood, steel and concrete) were used. The steel structure was found to consume the lowest energy during construction and the concrete structure the highest (the concrete structure requiring up to 40 times more energy than the steel construction). Wood construction typically required 2–3 times more construction energy than steel. Although this study is rather dated, it shows an interesting aspect.

The effects of building material choice on the operational energy have also been investigated. Dodoo et al. [12] analysed the effect of thermal mass on the space heating energy demand and life cycle primary energy balances of a building. They calculated the energy saving benefits of thermal mass during the operation phase of a reference building located in Växjö in southern Sweden, having either a concrete or a wood frame. They found that the concrete frame building had a slightly lower space heating energy demand (0.5–2.4%) than the wooden framed alternative due to the higher thermal mass of the concrete-based materials. Jokisalo and Kurnitski [13] and Ståhl [14] conducted simulations using a similar approach and found that the space heating energy savings benefits of thermal mass to be about 0.7–2.0% for buildings in the Nordic climate. Zhu et al. [15] compared identical wood and concrete constructions in Las Vegas and found that the wood construction required higher space heating energy, but lower space cooling energy than the concrete construction. In order to determine a set of possible energy efficient exterior wall configurations for ZEBs (zero energy buildings) situated in the Mediterranean region, Baglivo et al. [16] carried out a multi-criteria optimization analysis focusing on the thermal mass and thermal inertia of the envelope. They noted that the best sequences of layers are those with high surface mass (e.g. concrete) for the first interior layer, followed by common insulation materials for the middle layer and eco-friendly insulating materials (e.g. hemp fibre) for the external layer. The effect of thermal mass in buildings is swayed by several parameters such as climatic location, orientation, window area, thermal insulation, ventilation and the occupancy pattern of the buildings [17,18].

Although to date there has been little research carried out about the end of life (EoL) stage of buildings [4], the recycling aspect has been highlighted as potentially being a significant factor in reducing the life cycle energy use of buildings [10,12,19]. For instance, Thormark [10] found that recycling in low energy buildings in Sweden brought about 40% recovery of the embodied energy. In addition, Höglmeier et al. [20] analysed the cascading potential of wood used in the building stock of south-east Germany finding that more than half of the recovered wood could be utilized for high-quality secondary applications. These studies indicate the importance of considering the EoL scenarios of building materials from the beginning of the construction project.

The effect of material selection on the life cycle energy balance of a building is clearly a complex issue. For this reason, some researchers have suggested that the adoption of an index of building materials would assist in multi-criteria decision-making in the construction industry. Takano et al. [21], for instance, investigated the influence of building material selection on the embodied environmental impacts, environmental benefits and materials costs of a building in the three building component categories (structural frame, inner components and surface components) and expressed the results as an index of relative difference between the alternative materials studied. Emmanuel [22] compared the five most common wall materials in Sri Lanka in terms of three parameters: embodied energy, life-cycle costs and re-usability, summarizing the results as an environmental sustainability index. These authors commonly noted the importance of a multidisciplinary approach, since a multi-parametric perspective is significant for decision-making in building design.

2. Objectives and scope

The objective of this study was to demonstrate how the selection of building material affects the life cycle primary energy balance of a building in a Finnish context. A previous study [21] demonstrated the influence of material choice on several environmental and economic indicators focusing on the production stage of a building, whilst this study assessed the influence on the primary energy balance of a reference building model, covering the whole building life cycle; the production, operation (including maintenance) and EoL stages. In addition, the net primary energy benefits resulting from the reuse and recycling of materials exiting the system boundary was described as a potential resource for future use. The present approaches in these studies show a primary framework of a multidisciplinary system for sustainable building material selection. This study was carried out in a comparative manner based on the building materials typically used in Finland for the following three building component categories: structural frame, surface components and inner components. The aim was to describe the general relationship between the life cycle primary energy balance of the building and the building materials used rather than investigating the effect of a specific material in detail. The features of the building materials would vary according to the life cycle phase of the building. Quantifying such diversity would thus aid informed decision-making by professionals associated with the construction industry, leading to improved sustainability in building design.

3. Method

3.1. Reference building model

A hypothetical building model was used as the case study. Fig. 1 shows the basic plan and section of the building model with an indication of the building elements (e.g. exterior wall, party wall, intermediate floor etc.), whilst Table 1 shows the area of each building element used in the calculation. Net heated floor area was used as the functional unit in this study. The interior partition wall (non-structural) was excluded from the model since its layout strongly depends upon the case. The interior space of the model is, thus, simply defined as a continuous space surrounded by exterior wall, roof and floor. The embodied energy associated with building service equipment and furniture was also excluded from the calculation because they are out of the scope of this study. The reasons for using a hypothetical model in this paper were 1) to observe the general relationship between building material selection and the life cycle primary energy balance of a building, 2) to make the assessment conditions as comparable as possible between the alternatives and, as a consequence, 3) to generalize the results as much as possible. The reference building was assumed to be located in Helsinki (60°N, 25°E). The dimensions of the model were scaled to those of a detached house. In accordance with