

Life Cycle Assessment and Environmental Impacts of Building Materials: Evaluating Transport-Related Factors [†]

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Abstract: The construction industry plays a significant role in resource consumption and environmental degradation, making it crucial to analyze the sustainability aspects of construction materials and their transportation processes. This paper focuses on conducting a life cycle assessment (LCA) analysis of building materials, specifically considering the environmental impacts associated with their transportation to construction sites. By incorporating the transport phase into the assessment, a more holistic understanding of the environmental implications of construction materials can be achieved. The study aims to quantify the environmental burdens of both material production and transportation, providing valuable insights for sustainable decision making in the construction industry. The analysis revealed that transport of building materials for the studied house by diesel lorry, covering a distance of 150 km, contributed 16% to climate change and a significant 53.5% to abiotic resource depletion. Additionally, it had a 15–18% impact on acidification and photo-oxidant formation.

Keywords: LCA; construction materials; climate change; transportation; environmental impact



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1. Introduction

The construction sector is a key contributor to environmental degradation due to its extensive use of materials and energy, as well as associated transportation activities [1,2]. Construction materials, such as concrete, steel, and timber, are often sourced from remote locations, necessitating long-distance transportation [3]. This transportation phase introduces additional environmental burdens, including greenhouse gas emissions, air pollution, and habitat disruption. The construction sector's environmental impact extends beyond the production and use of building materials, transportation of these materials to construction sites plays a significant role as well [4]. Hence, it is essential to comprehensively evaluate the environmental impacts of both construction materials and their transportation to construction sites [5].

To evaluate the environmental impacts of construction materials, a life cycle assessment (LCA) approach is widely used in construction sector today [6–8]. This approach encompasses the entire life cycle of materials, from extraction and manufacturing to transportation and disposal [9]. Primary data can be collected from various sources, including construction material suppliers, transportation companies, and relevant industry databases [10]. The collected data are analyzed using appropriate LCA methodologies to quantify the environmental impacts associated with different materials and transportation modes. Many LCA studies have been employed recently evaluating construction materials and technologies and whole buildings as well [11–14]. However, previous LCA studies often neglect the transport phase, resulting in an incomplete assessment of the overall environmental performance of building materials. To accomplish the goal, a rigorous LCA

methodology is employed, encompassing the various stages of the building material life cycle, from extraction and manufacturing to transport and eventual disposal.

This paper addresses this gap by including transportation-related factors in the LCA analysis, aiming to provide an extended evaluation to the production phase of building materials. Through the integration of transport-related data into the LCA framework, the environmental impacts associated with material transportation were quantified.

2. Materials and Methods

The LCA analysis focused on evaluating the environmental impact of the materials used in a masonry family house during its product phase (A1–A3) and construction phase (A4), following the guidelines of the EN 15804 standard [15]. The selected house for the analysis is a single-story, L-shaped detached family house without a basement. It features a gable roof, while the garage has a flat roof design. The total built-up area of the house is 231.2 m², with a usable floor area of 178.5 m². The maximum height of the building is from ±0.000 to +6.373 m. The interior layout comprises a day section with an entrance hall, toilet, corridor, bathroom, utility room, kitchen with a pantry, and a living room with a dining area. The night section includes two rooms and a bedroom with a wardrobe. The house also includes an integrated garage.

The LCA procedure, based on ISO 14040 [16], consisted of the following 4 steps: (i.) definition of goal and scope, (ii.) analysis of life cycle inventory (LCI), (iii.) life cycle impact assessment (LCIA), and (iv.) interpretation.

2.1. LCA Goal and Scope

The objective of this LCA analysis was to quantify the environmental impact associated with the materials used in the selected family house. In addition to the standard evaluation of the production phase of materials, the assessment was expanded to include the transportation phase, from the material suppliers to the construction site. The analysis followed the guidelines set by the EN 15804 standard, which defines four life cycle phases for LCA assessments in building construction: the product phase (A1–A3), construction process phase (A4–A5), use phase (B1–B7), and end-of-life phase (C1–C4). For this study, modules A1–A3 and module A4 were evaluated.

The functional unit chosen for this study was a single building representing a total of 448 t of materials. To determine the projected lifespan of the building, various factors such as construction type, assemblies, and local climatic conditions were taken into account. The estimated duration of long-term elements was set at 50 years, while short-term construction elements were assumed to have a lifespan of 25 years [17].

2.2. Inventory (LCI)

To assess the environmental impact of the family house's materials, a detailed analysis of the construction material masses was performed during the inventory step. The foundation structures comprised concrete foundation strips, foundation footings, and reinforced concrete blocks. Beneath the base concrete, an embankment made of aggregate was used. The vertical structures were constructed using pre-cast concrete blocks, asphalt strips, and reinforced concrete crowns. For the horizontal structures, prefabricated monolithic reinforced concrete, steel beams, steel profiles, and extruded polystyrene for insulation were utilized. The roof structure consisted of a wooden gable roof with a ceramic covering, along with steel fasteners and asphalt insulating tape. Regarding thermal insulation, the house employed various materials of different thicknesses, including expanded polystyrene (EPS) boards, extruded polystyrene (XPS), and mineral wool. It should be noted that the evaluation did not consider doors and windows.

By analyzing the masses and types of materials used in the family house's construction, we gain insights into its potential environmental impact, which is crucial for making informed decisions in sustainable building practices.

2.3. Impact Assessment (LCIA)

The environmental impact assessment of the materials used in individual structures was conducted using the ReciPe method in SimaPro software, version 9.3.0.3 [18]. For the life cycle impact analysis in this study, the primary mid-point impact categories were employed to characterize environmental effects [19]. These categories include climate change, ozone depletion, photochemical ozone formation, acidification, eutrophication, depletion of abiotic resources, and water consumption.

To gather data for the materials' production phase (A1–A3), information was extracted from the Ecoinvent database. The data considered typical manufacturing processes of the materials, taking into account the associated energy consumption. The electricity mix used in Slovakia was also taken into consideration during this phase. In the assessment of transportation, various transport distances ranging from 5 to 150 km were modeled. The mean mode of transport for construction materials was considered to be lorries with emission standard EURO 5. Both gasoline and diesel fuels were compared in this context.

2.4. Interpretation

The LCA study's findings are presented in two parts. Firstly, the environmental impacts of materials integrated into the analyzed structures within the A1–A3 modules are provided, excluding considerations of material transport. Secondly, the impacts of construction material transportation to the building site are presented separately for module A4.

By presenting the results in this manner, we can gain a clear understanding of the environmental burdens associated with the materials themselves (A1–A3) and the additional impacts arising from their transportation to the construction site (A4). This comprehensive analysis allows for a more accurate assessment of the overall environmental impact of the building, facilitating informed decision-making and promoting sustainable construction practices.

3. Results

3.1. Impacts of Product Phase of Building (A1–A3 Modules)

The percentage share of the construction materials in individual structures on the overall environmental impacts during their production are illustrated in Figure 1. The environmental impacts are expressed through specific environmental indicators for each environmental category as follows: climate change by global warming potential (GWP), ozone depletion by depletion potential of the stratospheric ozone layer (ODP), photochemical ozone formation by formation potential of tropospheric ozone (POCP), acidification by acidification potential (AP), eutrophication by eutrophication potential (EP), depletion of abiotic resources by abiotic depletion potential (ADP), and water use by water (user) deprivation potential, deprivation-weighted water consumption (WDP).

3.1.1. Climate Change

The highest values of global warming potential (GWP) were observed in the foundation structures (25%) and insulation (29%) of the building which correlate to information in [20]. The vertical structures accounted for 19% of the total GWP, followed by horizontal structures (16%), and roof structures (11%). Load-bearing aerated concrete masonry stands out as the primary emitter of carbon dioxide (CO₂) into the air, contributing to 16% of the total GWP. Masonry is followed by foundation strips (13%) and mineral wool (10%) in terms of their carbon emissions. Ceramic roofing (7%) and cement screed (4%) exhibit lower GWP values but still significantly impact the overall structure. Conversely, materials like gravel, ŽB column, vapor-impermeable foil, and geotextile have a negligible carbon footprint, making them the least burdensome materials in the construction.

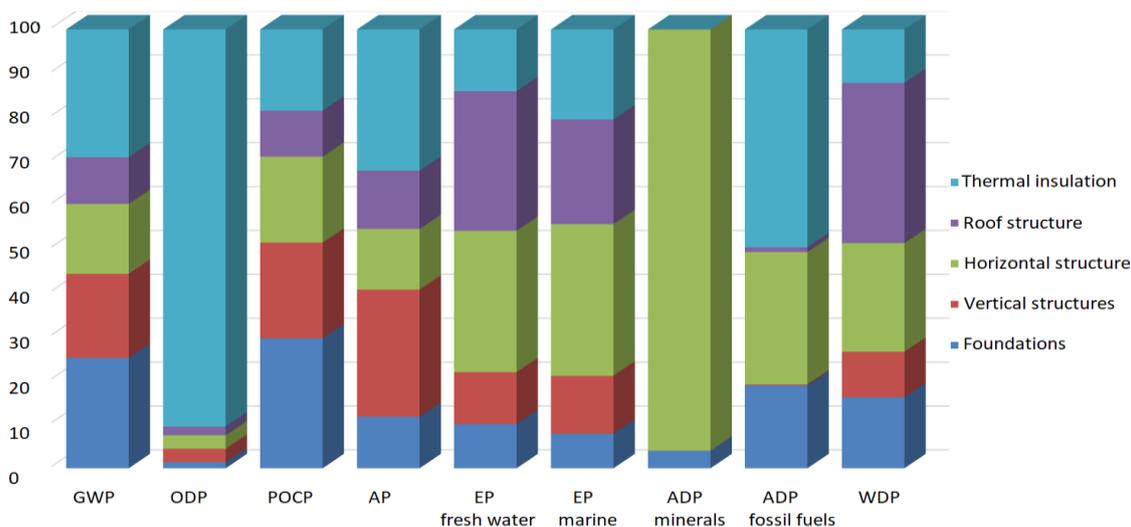


Figure 1. The contribution of materials in structures to the overall environmental impacts (%).

3.1.2. Ozone Depletion

Thermal insulation materials exert the most substantial influence on ozone depletion potential (ODP), constituting a significant portion (91%) of the total ODP. In comparison, foundations contribute only 1%, while vertical structures, horizontal structures, and roof structures contribute 3%, 3%, and 2%, respectively. Combined, these constructions represent a negligible fraction (9%) of the total ODP. Among the thermal insulation materials, XPS insulation boards account for 45% of the ODP, closely followed by EPS insulation boards at 44%. In contrast, concrete structures, screeds, construction timber, and plasterboard have an almost negligible impact on ODP. Additionally, materials such as geotextile, gravel, construction films, and lintels have minimal effects on ODP.

3.1.3. Photochemical Ozone Formation

The environmental impact on photochemical ozone creation potential (POCP) is most significant for foundation materials, contributing to 30% of the total impact. Vertical structures (22%) and horizontal structures (20%) also exert substantial ozone-forming effects. In contrast, insulation (18%) and roof structures (10%) have a relatively lower impact on POCP. Among the construction materials, load-bearing aerated concrete masonry exhibits the highest values (18%) in terms of POCP. Foundation belts show a similar significant impact at 14.5%. Other materials with notable contributions include mineral wool (10%), ceramic roofing (6.5%), and reinforced concrete wreath (4%) in the ozone formation. Conversely, several materials have little to no impact on POCP, including gravel, building foil, vapor-permeable and vapor-impermeable foil, geotextiles, and formwork blocks.

3.1.4. Acidification

Vertical structures (29%) and insulation (32%) account for the largest share of the acidification potential value in the construction. Other construction components have a relatively smaller influence on acidification; foundations contribute 12%, horizontal structures contribute 14%, and roof structures contribute 13%. Among the materials, aerated concrete masonry (24%) and mineral wool (22%) are the primary contributors to the high acidification potential values. Other materials with notable impact in construction include foundation strips (6%), cement screed (4%), and construction lumber (7%). In contrast, gravel, lintels, geotextiles, and foils have minimal effects on acidification potential.

3.1.5. Eutrofication

Horizontal constructions (32%) and roof constructions (32%) are prominent contributors to eutrophication potential (EP). Foundations (10%), vertical structures (12%), and

insulation (14%) show relatively lower impacts on eutrophication. Among the materials, cement screed has the most significant share of the total EP (17%), closely followed by ceramic roofing with a similarly substantial influence (16%). Aerated concrete blocks (12%) and foundation strips (8%) also contribute significantly to eutrophication. Conversely, insulating materials, foils, and plasterboard exhibit minimal impacts on eutrophication potential.

3.1.6. Abiotic Resource Depletion

Regarding the depletion of abiotic resources, specifically minerals and metals, horizontal structures account for a significant share (96%), while foundations have minimal impact (4%). Among these materials, steel profiles make up over half of the total depletion (58%). Anhydrite screeds (28%) and plasterboard (9%) exhibit smaller values in this category. However, in the case of fossil resource depletion, the impact is more evenly distributed. Insulation is the most burdensome structure (50%), closely followed by horizontal structures (30%) and foundations (19%). Vertical constructions have a negligible influence, as do roof structures (1%). Mineral wool contributes the most to fossil resource depletion, representing 50% of the total amount. Among horizontal structures, anhydrite screed has the largest share in resource depletion at 8%, while foundation boards represent the most substantial portion of foundations with 18%. Materials such as formwork blocks, cement screed, XPS, and EPS insulation boards show no depletion values.

3.1.7. Water Use

In terms of water use, horizontal constructions (25%) and roof constructions (37%) have the most significant share, followed by foundations (16%), insulation (12%), and vertical structures (10%). The materials contributing the most to water use include wooden elements of the roof (21.5%) and ceramic roofing (15%). Foundation strips also have a notable impact, accounting for 14.5% of water use, similar to the roofing. Load-bearing aerated concrete masonry (9%) and beam ceilings (8%) exhibit lower values of water use in comparison.

3.2. Impacts of Transportation (A4 Module)

This study focused on assessing the environmental impacts of transportation, considering variations in transportation distances and fuel types. Specifically, the impact of material transport on the overall environmental impact of the studied house was evaluated, focusing on the environmental categories with the most significant transportation contribution. Additionally, a new category was introduced to account for the emissions of particulate matter during transportation.

As expected, the environmental impacts show an increasing trend with the transportation distance (Figure 2). The highest increase in the impact of transport occurred in the depletion of abiotic resources, with a maximum increase of up to 2.3 times compared to the minimum distance (5 km). Similarly, transportation had a significant impact on the photochemical formation of ozone, showing an increase of 1.8 times, and on seawater eutrophication, with a recorded increase of 1.6 times. Smaller differences were observed in emissions of solid particles, with an increase of 1.6 times, and acidification, with a difference of 1.3 times. This analysis demonstrates the importance of considering transportation distance in the assessment of environmental impacts associated with material transport. Longer transportation distances can significantly exacerbate certain environmental impacts, highlighting the need for efficient logistics and sustainable transportation practices to minimize the overall environmental footprint of construction activities.

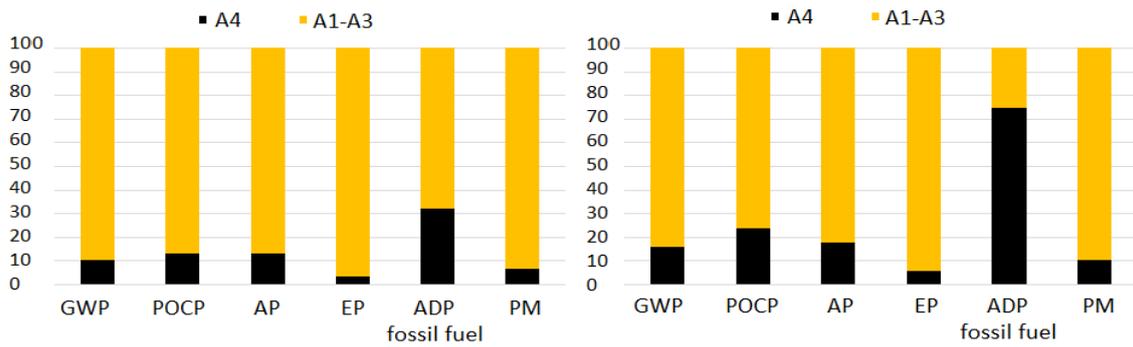


Figure 2. The contribution of transportation of construction materials by diesel lorry (A4 module) in % for distances of 5 km (left) and 150 km (right).

In the overall environmental impact of a family house, transportation plays a substantial role, particularly in the depletion of abiotic resources, constituting 53.48% of the total impact. Transportation also significantly influences the photochemical formation of ozone (18.35%) and acidification (15.44%). On the other hand, the lowest share is attributed to transport-related emissions of solid particles (8.5%) and eutrophication (4.77%).

Of particular interest is the contribution of transportation of construction materials to climate change. Figure 3 illustrates the percentage contribution of diesel lorries to the overall global warming potentials (GWPs).

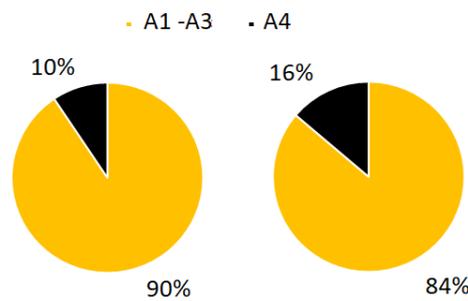


Figure 3. The percentage contribution of diesel lorry to the overall GWP for distances of 5 km (left) and 150 km (right).

According to Figure 3, the carbon footprint of transport from a distance of 5 km represents 10% of the total global warming potential (GWP), while at a distance of 150 km, this share increases to 16%. The difference in the increase in the carbon footprint of transport between the maximum and minimum distances is 1.5 times. On average, transport accounts for about 13.17% of the total GWP which is slightly higher than reported in [2].

Furthermore, the study also investigated the impact of different fuel types on climate change. Figure 4 compares the effect of fuel type, specifically gasoline versus diesel, on GWP values.

Figure 4 provides compelling evidence that gasoline cars exhibit higher values compared to diesel cars as the distance increases. At a distance of 5 km, the gasoline car has only 0.24% higher values than the diesel car. However, at a distance of 150 km, this difference increases significantly to 3.8%. If this upward trend were to continue, we can extrapolate that at 300 km, the gasoline car would have values 4.17% higher than the diesel car, and at 500 km, the difference would be 4.55%.

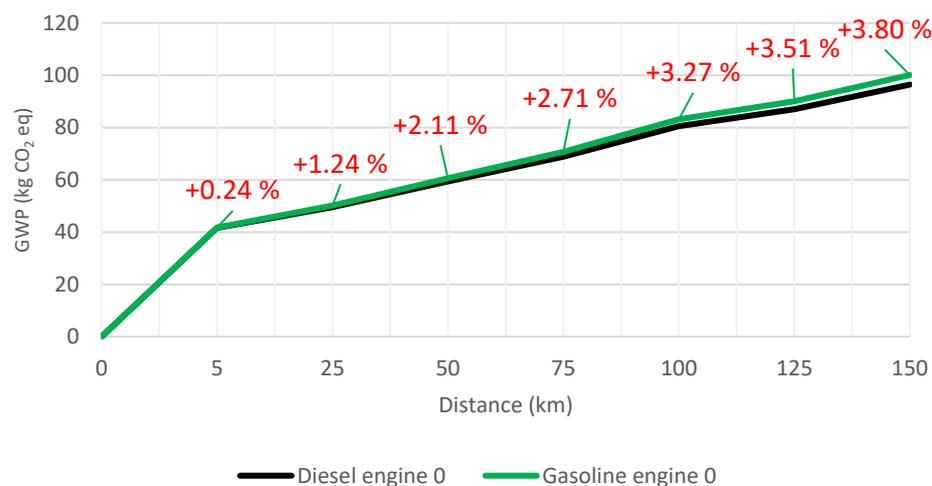


Figure 4. Comparison of the GWP due to transportation for gasoline and diesel car.

4. Conclusions

By incorporating the transport phase into the LCA analysis of building materials, this study provides a better understanding of the environmental impacts associated with construction materials. Based on the presented data and analysis the following conclusions could be drawn.

The materials used in construction have varying degrees of impact on different environmental categories. The analysis of the house construction process (A4 module) revealed significant contributions from the transport of building materials. Specifically, at a transport distance of 150 km, this transportation accounted for 16% of the overall impact on climate change. Surprisingly, transport's role in depleting abiotic resources was even more substantial, amounting to a striking 53.5%. Furthermore, the environmental impact of transport extended to other categories as well. The contributions to acidification and the formation of photo-oxidants ranged from 15% to 18%, signifying their relevance in the overall assessment. These findings emphasize the importance of considering transport-related emissions and resource usage when addressing environmental concerns in the construction industry.

Based on the findings, mitigation strategies to address the environmental impacts of building materials and their transportation should be proposed. These strategies may include optimizing transport routes, promoting regional sourcing of materials, adopting more sustainable transportation modes, and exploring alternative materials with lower environmental footprints.

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