Erciyes Üniversitesi
Fen Bilimleri Enstitüsü Dergisi
Cilt 38, Sayı 3, 2022

Erciyes University
Journal of Institue Of Science and Technology
Volume 38, Issue 3, 2022

Comparative Life Cycle Assessment of the Environmental Impacts of Precast Concrete and Brick Walls

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(Alınış / Received: 08.11.2022, Kabul / Accepted: 11.12.2022, Online Yayınlanma / Published Online: 30.12.2022)

Keywords
Life Cycle Assessment,
Precast Concrete Wall,
Brick Wall,
Environmental Performance,
Sustainability

Abstract: There is an increasing interest in assessing the environmental impacts of construction materials and their components in recent years. By considering these environmental impacts, the selection of suitable construction materials and technology is crucial for satisfying user needs and minimizing environmental impacts. The aim of this study is to compare the environmental impacts of precast concrete wall and brick wall production with cradle to gate approach by using Life Cycle Assessment (LCA) approach. In this study, LCA was applied based on ISO 14040 and 14044 by using SimaPro 9.2 software. CML-IA baseline method and Ecoinvent 3.7 database was used for the life cycle impact assessment. The obtained results revealed that brick wall has better environmental performance than precast concrete wall in all impact categories except abiotic depletion and marine aquatic ecotoxicity. The global warming potential of the precast concrete and brick wall per m^2 were calculated as 2.35E+02 kg CO_2 eq. and 2.10E+02 kg CO_2 eq, respectively.

Prefabrik Beton Duvar ve Tuğla Duvarın Çevresel Etkilerinin Karşılaştırmalı Yaşam Döngüsü Değerlendirmesi

Anahtar Kelimeler
Yaşam Döngüsü Değerlendirmesi,
Prefabrik Beton Duvar,
Tuğla Duvar,
Çevresel Performans,
Sürdürülebilirlik

Öz: Son yıllarda, yapı malzemelerinin ve bileşenlerinin çevresel etkilerinin değerlendirilmesine artan bir ilgi vardır. Bu çevresel etkiler göz önünde bulundurularak, kullanıcı ihtiyaçlarının karşılanması ve çevresel etkilerin en aza indirilmesi için uygun yapı malzemelerinin ve teknolojisinin seçimi çok önemlidir. Bu çalışmanın amacı, Yaşam Döngüsü Değerlendirmesi (YDD) metodolojisini kullanarak beşikten kapıya yaklaşımıyla prekast beton duvar ve tuğla duvar üretiminin çevresel etkilerini karşılaştırmaktır. Bu çalışmada, ISO 14040 ve 14044 standardlarına göre SimaPro 9.2 yazılımı kullanılarak YDD uygulanmıştır. Yaşam döngüsü etki değerlendirmesi için CML-IA baseline yöntemi ve Ecoinvent veri tabanı kullanılmıştır. Elde edilen sonuçlar, abiyotik tükenme ve deniz suyu ekotoksisitesi hariç tüm etki kategorilerinde tuğla duvarın prekast beton duvardan daha iyi çevresel performansa sahip olduğunu ortaya koymuştur. Prekast beton ve tuğla duvarın m^2 başına küresel ısınma potansiyeli sırasıyla 2.35E+02 kg CO_2 eq. ve 2.10E+02 kg CO_2 eq. olarak hesaplanmıştır.

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1. Introduction

In construction sector, the selection of the most suitable construction materials and technology is crucial for fulfilling user needs. Material selection can also influence the social consequences and environmental impacts of a project. As an alternative to the traditional in situ concrete construction, new construction technologies and tecniques such as precast concrete wall panels have evolved in recent years. This, along with other alternatives, has helped raise consciousness among industry and academia about the importance of taking environmental factors into account when selecting a structure's layout. In recent years, there has been an increase in the number of initiatives made to construct sustainable concrete buildings [1]. Greenhouse gas (GHG) emissions are a fundamental metric for assessing the severity of climate change and the environmental impacts of building projects. The building sector accounts for around 40% of overall energy consumption and up to 30% of annual GHG emissions. The United Nations Environment Programme (UNEP) predicted that in the next 20 years, GHG emissions will more than double due to the rapid growth of urbanization and the inefficiency of the current building stock unless mitigation measures are taken [2]. Cement, steel reinforcement, and concrete are well-known inputs in the construction of both traditionally reinforced and precast concrete panels. Because of this, the evaluation of the embodied carbon in these construction materials can have a considerable impact on the evaluation of the environmental impact that these structures have [1]. Additionally, used construction techniques affect GHG emissions throughout the construction phase [2].

Prefabrication is a manufacturing method that assembles numerous materials at a specialized facility to make a component part of the final installation. Prefabrication is the first stage of industrialization in the building industry, followed by mechanization, automation, robotics, and reproduction [3]. Compared to typical cast-in-place construction, prefabrication provides increased quality control, enhanced site safety, less material waste, better architectural appearance, and a reduction in construction time and labor demand [4]. Despite the benefits that prefabricated construction offers, the adoption of precast concrete technologies in Turkey remains low compared to the many European countries. The market share of precast concrete systems may be affected by a number of variables, including labor costs, climate, and the relative costs of alternative construction methods. Total prefabricated concrete production in Turkey in 2021 was 1,886,826 m^3, increased from 1,703,980 m^3 in 2020, as reported by the Turkish Precast Concrete Association [5].

The life cycle assessment (LCA) is a well-known and rigirous methodology for determining the overall impact that construction materials have on the environment. As more studies were conducted to determine environmental impacts of various products and proseses, LCA emerged as a reliable tool [6]. In recent decades, research on LCA has become increasingly focused on many aspects of construction materials. In literature, the LCA was used to conduct an analysis on the materials concrete, steel, glass, aluminum alloy, natural stone, and ceramics, which are all commonly used in the construction industry [7-24]. For instance, Kua and Kamath (2014) studied on determining the environmental impacts of replacing concrete with brick in Singapore. They utilized both contributional and attributional LCA with several alternative scenarios to compare and find alternative solutions to reduce environmental impacts of concrete and bricks. According to their LCA analysis, the potential reduction in global warming potential from using bricks instead of concrete is minimal [11]. Ozkan et. al. (2016) applied LCA and life cycle cost (LCC) analysis for magnesia spinel brick production. According to their findings, the manufacture of raw materials and the firing process in the production of magnesia spinel bricks had a number of negative environmental effects and were expensive. The firing process accounts for 68.6% of the total influence on global warming potential [10].

Numerous studies also employ LCAs for design or technology selection in an effort to reduce the environmental impact of prefabricated buildings. The biggest contributors to the energy footprint and carbon footprint of prefabricated buildings are determined to be concrete and steel [25]. Faludi et al. (2012) reveal that 11% to 14% of total GHG emissions can be decreased by substituting 25% of the cement in concrete with fly ash [26]. Bonamente and Cotana (2015) used LCA to quantify carbon and energy footprint of prefabricated industrial structures with a cradle-to-grave approach involving all phases from raw material production through in-situ assembly. Four buildings were analyzed and they found that the energy footprint and the carbon footprint are proportionate to one another, with the proportional factor being 0.222 kg CO_2eq/kWh with an accuracy of 0.5% or better [27]. Besides studies on material or technology selection, Wang and Sinha (2021) focused on affects of different prefabricated rates on conctruction activities. Using a reference building that was 26% prefabricated, they compared nine different scenarios where the percentage of prefabrication varied from 6% to 96% utilizing LCA. As the rate of prefabrication rises, their findigs indicates that the water footprint reduces but the total energy footprint and carbon footprint rise [24].

This study aims to define and compare of environmental impacts of precast concrete and brick wall production with the implementation of LCA approach. In literature, there are studies on the LCA of precast concrete and brick products, but no studies comparing the LCA of producing precast concrete and brick walls in Turkey. Thus, this study will assist civil engineers, architects, as well as researchers in making more environmental friendly material selections.

2. Material and Method

In this study, environmental performance of precast concrete and brick wall production were comparatively assessed using LCA methodology. According to ISO 14040 and 14044 [28, 29], LCA consists of four main phases: (i) goal and scope definition, (ii) life cycle inventory (LCI), (iii) life cycle impact assessment (LCIA), (iv) interpretation as described below.

2.1. Goal and scope

The main goal of this study was to define and compare the environmental impacts of precast concrete and brick wall production using LCA methodology. In this study, functional unit was chosen as 1 m^2 wall production. The LCAs of these two alternative wall production materials and techniques were calculated by using SimaPro 9.2. The system boundaries of this study based on cradle to gate approach and cover the stages from raw material extraction to wall production as indicated in Figure 1. The use and end of life stages were not included in the system boundaries.

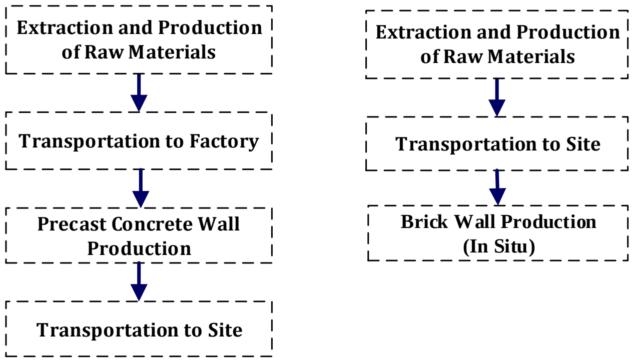

Figure 1. System boundaries of precast concrete and brick wall production

2.2. Life cycle inventory

Primary data concerning the amount of raw materials (cement, aggregate, crushed stone, reinforced steel bar, polystrene, admixture), energy consumption (electricity and natural gas), and water use were gathered from a local company in Turkey. The secondary data for production raw materials and transport data were collected from Ecoinvent 3.7 database [30] which is available in SimaPro 9.2 software [31].

2.3. Life cycle impact assessment

The CML-IA baseline method was used for calculation of life cycle impact assessments (LCIA) for precast concrete and brick wall production. This method has a problem-oriented (midpoint) approach and created by the University of Leiden in Holland [32]. It shows how a product or system affects the environment based on certain impact categories. The impact categories that are considered in this method are as follows: abiotic depletion (AD)-kg Sb eq, abiotic depletion on fossil fuels (AD-FF)-MJ, global warming potential (GWP)-kg CO_2 eq, ozone layer depletion (ODP)-kg CFC-11 eq, human toxicity (HT)-kg 1,4-DB eq, fresh water aquatic ecotoxicity (FWAE)-kg 1,4-DB eq, marine aquatic ecotoxicity (MAE)-kg 1,4-DB eq, terrestrial ecotoxicity (TE)-kg 1,4-DB eq, photochemical oxidation (PCO)-kg C_2H_4 eq, acidification potential (AP)-kg SO_2 eq, and eutrophication potential (EP)-kg PO_4 eq. Average values from all across the world and in Europe are used to characterization. SimaPro 9.2 global and European database values were utilized to characterize the environmental impacts of the selected products.

3. Results

The environmental impacts of precast concrete and brick wall by considering the cradle-to-gate approach were calculated with the CML-IA baseline method; the results are shown in Table 1. The LCIA consists of 11 environmental impact categories (AD, AD-FF GWP, ODP, HT, FWAE, MAE, TE, PCO, AP, and EP) to assess and compare the environmental performance of these two type wall production materials and techniques. The value of the AD was calculated as 1.23E-04 kg Sb eq for the brick wall, while AD for precast concrete wall accounted as

1.05E-04 kg Sb eq. The main contributor raw material on AD was lime for brick wall, cement for precast concrete wall. As another significant impact category for construction materials, GWP, was calculated to be 2.10E+02 kg CO_2 eq. for the brick wall, while it was 2.35E+02 kg CO_2 eq. for the precast concrete wall (Table 1).

Table 1. Impact category values for precast concrete and brick wall per m² of wall production (CML-IA baseline method)

Impact category	Unit	Brick Wall	Precast Concrete Wall
AD	kg Sb eq	1.23E-04	1.05E-04
AD-FF	MJ	2.58E+03	2.95E+03
GWP	kg CO_2 eq	2.10E+02	2.35E+02
ODP	kg CFC-11 eq	2.94E-05	3.49E-05
HT	kg 1,4-DB eq	5.41E+01	8.24E+01
FWAE	kg 1,4-DB eq	8.81E+00	5.07E+01
MAE	kg 1,4-DB eq	9.66E+04	8.10E+04
TE	kg 1,4-DB eq	1.52E-01	2.06E-01
PCO	kg C_2H_4 eq	2.68E-02	3.14E-02
AP	kg SO_2 eq	6.69E-01	7.93E-01
EP	kg PO_4 eq	1.44E-01	1.96E-01

The LCA was performed to compare the environmental performance of the production of precast concrete and brick walls. The LCA analysis consists of eleven impact categories calculated using the CML-IA baseline approach, and Figure 2 presents the comparison results. Except for AD and MAE, all impact category values for brick wall production were lower than those for precast concrete wall production. The greatest difference was observed in the category of FWAE impact, where a brick wall has 83% less impact than a precast concrete wall. Lime, an calcium-containing inorganic substance, is used in the manufacturing of mortar for brick walls, which is the fundamental cause of the distinction. The GWP impact category showed the smallest difference, with a brick wall having 11% less of an effect than a precast concrete wall. Reinforced steel bars used in precast concrete walls and the transportation of prefabricated walls from factory to construction site are the primary contributors to this difference.

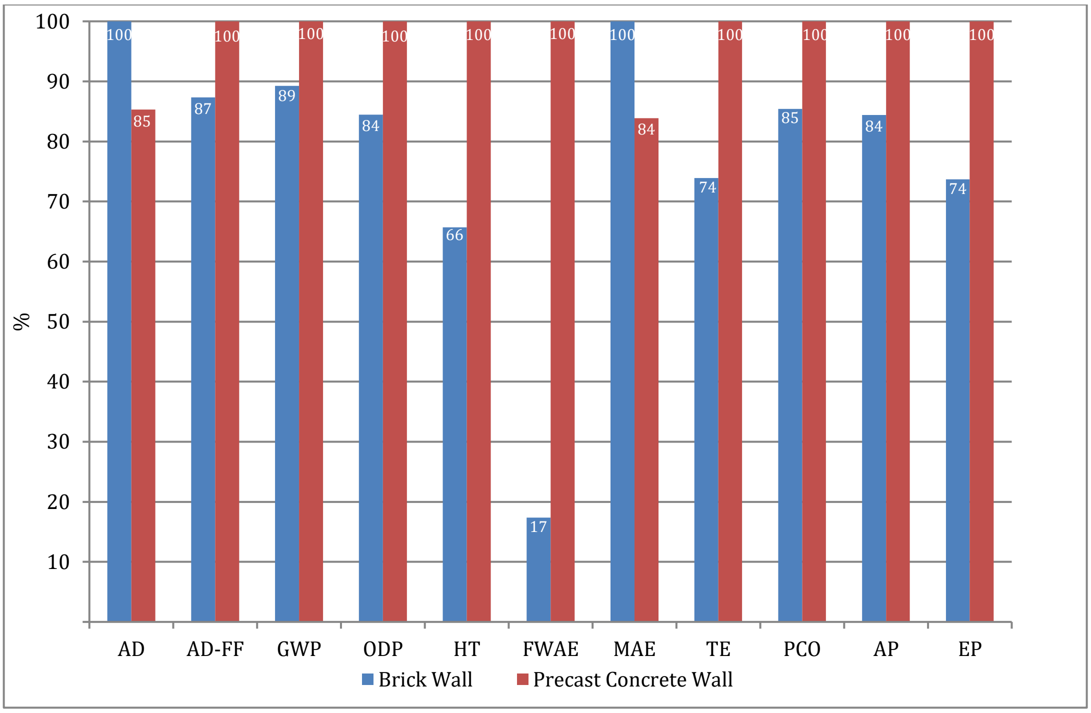

Figure 2. The comparison of environmental impacts of precast concrete and brick wall based on CML-IA baseline method: CML-IA baseline V3.06/EU25/Characterization (AD: abiotic depletion, AD-FF: abiotic depletion on fossil fuels, GWP: global warming potential, ODP: ozone layer depletion, HT: human toxicity, FWAE: fresh water aquatic ecotoxicity, MAE: marine aquatic ecotoxicity, TE: terrestrial ecotoxicity, PCO: photochemical oxidation, AP: acidification potential, EP: eutrophication potential)

For FWAE impact category, which the greatest difference was observed in the comparision results, network diagram indicates the hotspots of the environmental impacts of precast wall production (Figure 3). The diagram shows that reinforced steel bars used in precast concrete walls are the main contibutors with 83.8% of the total environmental impacts and cement follows with 6.1%.

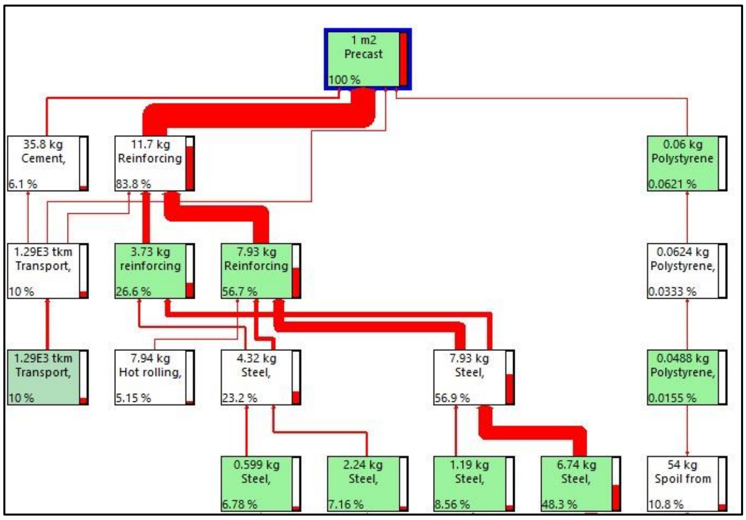

Figure 3. Network diagram of precast concrete wall production

Additionally, the network diagram outlines the level of contribution of used components in brick wall production for the FWAE impact category as indicated in Figure 4. The graphic reveals that 65.5% of the total environmental impacts come from bricks used in wall production, with cement coming in second at 25.5%. Beside, Figure 4 shows that 47.6% of the impacts of bricks (65.5%) are caused by transporting bricks from the production to the site.

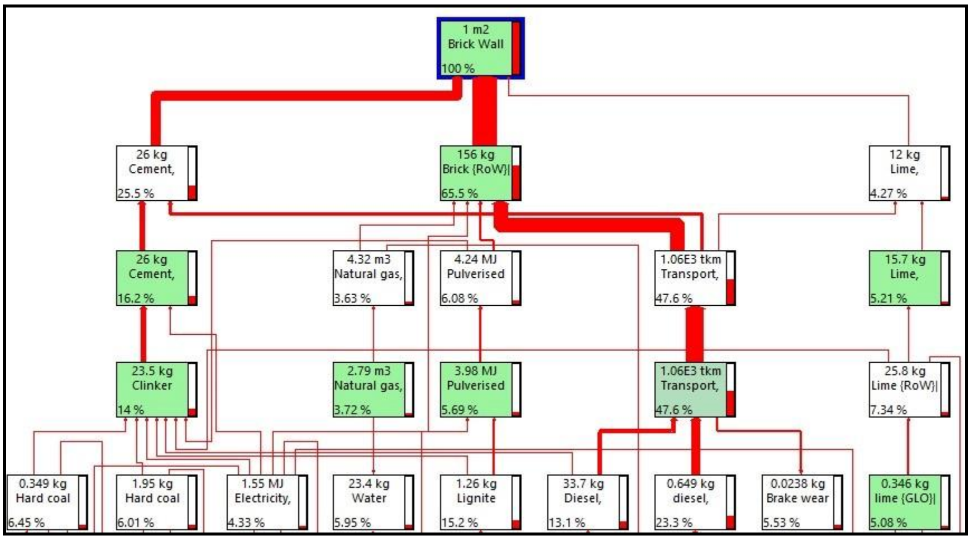

Figure 4. Network diagram of brick wall production

The obtained results were also coherent with the literature on construction materials of concrete and bricks. The environmental effects of switching from concrete to brick in Singapore were investigated by Kua and Kamath (2014). To assess and compare the environmental impacts of concrete and bricks, they used both contributional and attributional LCA with multiple possible scenarios to identify potential alternatives and identify potential solutions. They found that switching to bricks from concrete will have a minimal impact on global warming [11]. Besides, Wen et. et al. (2015) compared industrialized building systems (IBS), referred to as offsite construction in the British construction industry, with conventional cast in situ for residential apartment structures in Iskandar Malaysia using LCA during the assembly phase to determine life cycle effect assessment and hotspots for materials and construction stage. According to their findings, precast concrete has the greatest embodied energy and GWP of any IBS construction material, at 30.11% and 57.62%, respectively. This is due to the high quantity of concrete and steel reinforcements in precast concrete used in the construction of floor, ceiling, and wall panels [25]. Similarly, Omar et. al (2014) explained that the embodied carbon of concrete materials in the IBS system is greater since the wall system supports a heavier load bearing on the wall structures [1]. This research's findings align with those of other studies that have looked at the environmental implications of precast concrete and brick. Given this comparison, it is clear that, from the perspective of environmental impact, brick wall production is preferable to precast concrete wall production.

4. Discussion and Conclusion

The LCA approach was used to determine the environmental effects of precast concrete and brick wall manufacturing. Although the LCA of precast concrete and brick products have both been studied, there are no studies comparing the LCA of producing precast concrete walls and brick walls in Turkey. The findings revealed that brick wall manufacturing is better in nine of the eleven environmental impacts studied, while precast concrete wall production is better in the two environmental impact categories of AD and MAE. When comparing the manufacture of precast concrete and brick walls, significant differences in the range of 11-83% were detected, especially in the FWAE, HT, TE, and EP impact categories. This means that making walls out of bricks is better for the environment than making walls out of precast concrete.

Additionally, the production of precast concrete and brick wall have different experimental procedures which affect their environmental performance as well. Precast concrete wall production requies fabrication processes in which energy consumption is higher than in-situ brick wall production. This causes negative environmental impacts, especially on impact category of AD-FF which refers to measure of use of mineral and resources, due to fossil-based electricity and fuel consumption. The negative effects on the environment caused by the manufacturing of walls can be mitigated by the use of renewable energy sources and the decrease of energy consumption through the adoption of innovative production techniques.

A sensitivity analysis was performed to support the findings. According to the results, the cement and lime used in the production of precast concrete and brick walls have various detrimental environmental effects, respectively. Using "what-if" scenarios, a sensitivity analysis was conducted to examine the impact of potential variations on the LCA results. In two what-if scenarios, sensitivity analysis were conducted: (1) cement reduction in precast concrete wall production; and (2) lime reduction in brick wall production. Reducing the amount of cement by 10% has an effect on all environmental impact categories, particularly AD (6%), resulting in a 1-6% decrease in these impact categories. In addition, a 10% reduction in the amount of lime has an effect on all environmental impact categories, particularly AD (5%), and results in a 1-5% reduction in these impact categories. Consequently, sensitivity study show that cement and lime have significant environmental impacts on the AD impact category.

The outcomes of this research will assist civil engineers, architects, and researchers in selecting sustainable materials. These results showed that the selection of construstion materials and technologies can reduce the environmental impacts by selecting the green alternatives according to LCIA methods. To take a holistic perspective, future LCA studies can include the entire process of wall and building production. In addition, other alternative construction materials and technologies can be added to the comparison.

Acknowledgment

The authors gratefully acknowledge ALFA Prefabrike company and Eng. Can Argın for providing support in acquiring the inventory data for this research.

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