A comparative LCA of external wall assemblies in context of Iranian market: considering embodied and operational energy through BIM application

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Abstract

Building envelopes have a critical role in the construction sector's sustainability. The main aim of this research is to assess the environmental impacts of typical exterior wall assemblies and present the best option to the Iranian market, taking into account both embodied and operational energy. Autodesk Green Building studio is used to determine the operating loads of each wall. Simapro, a life cycle assessment software, is used to help manage data on environmental impacts. The results show that the most severe damage category for all of the analyzed walls is human health. Also, the environmental impact of the end-of-life stage is insignificant in comparison with the production and use stages. If reducing carbon emissions is a major priority, replacing one square meter of masonry brick wall (the worst option) with Prefabricated extruded polystyrene (XPS) drywall (the best option) could save 1257.85 kgCO_2eq. The operational phase of the specified walls has a wide range of environmental impacts. Prefabricated Knauf drywall and prefabricated XPS drywall consume less energy for the operating phase since they use a sufficient quantity of isolations, leading to better total environmental performance. In conclusion, the thermal performance of building materials should be given more attention.

Introduction

The worldwide increasing energy demand has derived in overutilization of fossil fuels, which results in increasing Greenhouse Gas (GHG) emissions and consequently resource depletion and severe environmental issues (Zeng et al. 2021). Nowadays, resources can be recovered 50% slower than humans consume them, and the availability of metals (such as copper) would be incapable of fulfilling rising demand (Cruz Rios et al. 2019). Also, it is estimated that the worldwide population will reach more than nine billion people by 2050. Increases in resource usage will be considerably greater as the population grows (Cruz Rios et al. 2019). It should be noted that buildings and construction sector are accounted for 36% of worldwide final consumption of energy as well as 39% of energy and related processes for emissions of carbon dioxide (CO_2) (Bullen et al. 2021). It is predicted that 28% of total primary energy demand is related to residential buildings in the United States (Hong et al. 2020). Moreover, the manufacturing process of building materials, including concrete, requires a high amount of energy and thereby has a severe environmental impact mainly because of the high amount of CO_2 generation (Zeng et al. 2021). Generally, building energy consumption can be classified in two different stages, including embodied energy (EE) and operational energy consumption (Xue et al. 2021). Embodied energy (EE) can be defined as the amount of energy needed to establish a building from the purchase of raw materials to the ready- to- use product. Any energy used during the period of using product is defined as operational energy, such as energy used for heating, cooling, and maintenance (Meek et al. 2021). More mega projects are likely to be built, and thereby the usage of building materials in the mentioned projects will likely result in serious difficulties such as shortages of energy, environmental issues, and global warming if no enough care is made to lowering EE and embodied emissions (EC) (Zeng et al. 2021). Buildings clearly have remarkable environmental effects, which present opportunities for mitigation and reduction (Gardner et al. 2020).

The life cycle assessment (LCA) is a practical method that evaluates how buildings and related components contribute to undesirable environmental effects across their entire life cycle (Azari et al. 2016). In comparison to other similar approaches, which focus only on the operation phase of the life cycle and depend on metrics, LCA considers all phases together and thereby can provide a more reliable basis for making decisions (Azari et al. 2016). The resource inputs/outputs into and out of a product system, as well as the potential environmental implications, are determined via a LCA(Balasbaneh and Ramli 2020). The four steps of LCA is validated based on ISO14040

(2006) standards and includes scope and goal, life cycle impact assessment (LCIA), life cycle inventory (LCI), and interpretation.

The first step (scope and goal) determines the functional equivalent, system's boundary, and also set of materials. An assessment's objective might be to establish a guideline for upcoming studies or to compare a group of goods, materials, or processes. The most important step of the LCA analysis is the LCI, which collects data on construction materials, emissions, and usage of energy. This is related to the challenge of obtaining consistent and relevant data. At this step, the database is represented as a set of elementary flows that includes all emissions delivered into and out of the environment for each specific unit process in the production system (Valdivia et al. 2013). Flows, processes, and production systems are the three key navigations that must be precisely identified at this stage. The LCI database should be consistent and dependable; if not, inaccurate data will lead to bias and negative outcomes. The following phase is LCIA, which involves putting together the material amounts, energy usage, and input data using sustainability metrics. The results of the LCI analysis are then transformed into a set of impact categories during the LCIA stage. In this step, environmental intervention results at the LCI level (including emissions, extraction of raw material, and natural areas changes) are converted into environmental impacts through impact assessment procedures. The last step is interpretation, which enables the assessment of the LCI and LCIA results (Najjar et al. 2019b). The interpretation step generally generates final conclusions, highlights environmental concerns, and ends in environmentally friendly actions. This process enables the classification of the source of the impacts, comparing the solutions, and making helpful suggestions (Shi et al. 2019).

Integrating Building Information Modeling (BIM) and LCA for calculating EE and operational energy from the beginning of construction through demolition is gaining popularity in current studies (Pereira et al. 2021). BIM is a new technology that has recently gotten a lot of interest throughout the world (Ahmed et al. 2021; Nikolic et al. 2021). BIM is referred as an intelligent representation of data enriched objects developed via cooperation between parties to give early feedback, enhance making decisions, and boost efficiency of projects at all phases (Safari and AzariJafari 2021). BIM has been widely utilized for appropriately extracting the essential input data for performing LCA of buildings (Muller et al. 2019). In the literature, the capabilities of BIM in terms of giving input into LCA and integration with other technologies have been well accepted (Ahmadian F.F. et al. 2017). It should be noted that solutions using BIM parametric models and LCA can be generated while the project is still in the development stage making it more effective and sustainable (Crippa et al. 2018).

A novel isolation system was proposed by Gorshkov et al. (2015), considering achieved energy savings by using mineral wool insulation at the life cycle of a building with 12 stories in Moscow, Russia. Results demonstrated that a unit of mineral wool insulation is able to save 67.87 times more energy during its whole life cycle in comparison to energy amount used for its production, transportation, and installation. By taking into account entransy loss, Muddu et al. (2019) analyzed the environmental and economic combination of materials and source of fuel to optimize energy performance of buildings and also determine the optimum thickness of insulation for the solid external building wall. It was found that the optimal combination includes a lightweight concrete block (insulated with polyisocyanurate). Nevertheless, it does not imply that the best selection is the least environmentally friendly choice in all categories. Najjar et al. (2019b) examined the performance of operating energy and the endpoint effects of building components at an early design phase through two different approaches, including steel and concrete construction. The findings revealed that steel construction is more environmental friendly in comparison to concrete construction in a multi-story office building. Dickson and Pavía (2021) compared environmental effects, energy performance, and cost of 21 different insulations. A new scoring mechanism was developed that allows inputted data to be standardized and compared across the three categories of performance, resulting in a final score which measures the general performance of studied insulations. The findings showed that the insulation placed outside the wall provides the optimum thermal performance.

Prateep Na Talang and Sirivithayapakorn (2018) looked into the environmental performance, assessment of life cycle costs as well as the thermal resistance of fired brick exterior walls and autoclaved aerated concrete (AAC) blocks in tropical climate. The obtained results demonstrated that all of the AAC block wall systems had not only greater thermal resistance but a larger environmental impact than the corresponding fired-brick wall schemes. Based on an Analytic Hierarchy Process (AHP), it was shown that the most recommended option is a single-layer fired brick wall. A comprehensive study considering cradle to handover life cycle assessment of internal partition wall systems in Spain was carried out by Valencia-Barba et al. (2021). The outcomes revealed that the nature of the materials has a greater influence on the environment than any other attribute, such as thickness or weight. The study has proven the significance of evaluating the interior partition walls as a system rather than assessing each piece separately. Ferrández-García et al. (2016) coupled environmental and economic characteristics to conduct an economic efficiency analysis of five different kinds of interior walls. It was found that plasterboard and hollow concrete blocks had the best performance from both studied views. Mateus et al. (2013) has been compared the environmental impacts of light membrane walls and traditional walls. The derived results demonstrated that the light membrane walls provide potentially better environmental advantages than traditional approaches, in spite of the higher cost. Mahmoudkelaye et al. (2018) proposed a model to choose sustainable construction materials with respect to the environmental, economic, socio-cultural, and technical factors by the implementation of an analytic network process. The criteria's priorities were derived via expert consensus gleaned through paired comparison surveys. It was found that aluminum siding has the best performance in terms of sustainability. Another study was carried out by Paleari and Miliani (2018) with the goal of comparing the environmental performance of various building enclosure technologies, with the favorable behavior of AAC blocks being highlighted. For improving common wall structures in Tehran, Iran, a novel optimization approach according to the LCA was proposed by Ramin et al. (2017). The objective functions included energy, energy loss through the wall, global warming emissions, water embodied in materials, and cost of materials. The results were compared to the published findings in which the procedure of optimization was focused solely on the cost of insulating material and energy usage.

Jalaei and Jrade (2014) offered an approach for integrating BIM and LCA for making more simple assessment of environmental impacts of buildings in the conceptual stage. A material database housed in a BIM module is coupled to a pricing and LCA module, as well as a certification module in the proposed frame. Najjar et al. (2019a) integrated mathematical optimization models, LCA, and BIM to improve the efficiency in selecting the most efficient building envelopes from an energy perspective that also have the minimum environmental implications. The findings indicate that all components of building envelopes, mainly windows and external walls, have a significant effect on buildings' energy consumption. This study found that combining LCA with integrated optimization of BIM models can be considered as an optimum approach for predicting energy usage and cost in the building industry, as well as analyzing the environmental implications of construction materials. Shadram et al. (2016) developed an integrated BIM- based model to assess EE in the design development phase of the life cycle of buildings. To develop BIM-LCA compatibility, the workflow incorporates the extract transform load procedure. Hollberg et al. (2020) investigated the well-established method of integrating a quantity take-off from BIM with LCA database and a tool to evaluate embedded environmental effects. This methodology is applied to the design procedure of a real case study in Switzerland. It was found that with the existing designers' workflow, the automatic calculation leads to incorrect findings, according to the first deployment of such a method to an actual case study. This demonstrates the value of analytic tools that are tailored to the design workflow in practice. In another study carried out by Asare et al. (2020), the model based on BIM-LCA integration was developed in order to aid decision-makers for selecting sustainable construction material in Ghana. In this research, Green Building Studio, and Tally as a LCA and energy tool, Autodesk Revit as a BIM authoring tool, were applied on a conjectural house and a comprehensive guidance framework in BIM-LCA integration is also supported by energy analysis has been proposed.

A key study on the environmental performance of prefabricated components for a multi-residential building is that of Aye et al. (2012), in which the derived results showed that a steel-structured prefabricated system is able to decrease usage of material up to 78% (by mass) in comparison to the traditional concrete construction. Also, the mentioned system has the potential to profoundly enhance the environmental sustainability construction sector. Xu et al. (2019) proposed a BIM and LCA integrated strategy for extracting and calculating the consumption of energy in prefabricated components through the production phase for acquiring an accurate understanding of energy consumption in this sector. A study by Cavalliere et al. (2019) advocated BIM as a level of development (LOD) for evaluating the environmental effects of EE at various phases of extraction, manufacturing/process, and transportation to the site. The method's distinctive feature is the continual merging of multiple LCA databases based on the LOD of building elements at various design phases. A new framework proposed by Bueno et al. (2018) integrated BIM and LCA through integration of the programming and a spreadsheet application for developing automated environmental profiles at the initial design stage. Recent research by Tushar et al. (2021) is based on using BIM, an energy rating tool, and a BIM-enabled LCA to evaluate building design alternatives for reducing energy and carbon footprint consumption in buildings. It was shown in case of the wall systems, using the best-derived solution can reduce energy consumption by up to 90%.

Building envelopes have been demonstrated in earlier studies to have the greatest impact on the total life cycle energy performance in buildings (Hong et al. 2020; Tushar et al. 2021). Previous research in the mentioned research area have mostly focused on the environmental effect of particularly specific types of building, construction, and insulation materials, as well as comparative analysis of passive buildings. However, there was limited comparative research of masonry clay brick walls, autoclaved aerated concrete (AAC) block walls, lightweight expanded clay aggregate (LECA) block walls, 3D Sandwich Panel walls, prefabricated Knauf drywall, and prefabricated extruded polystyrene (XPS) drywall, which are all prevalent construction systems in Iran. Due to the great influence of building envelope on the energy and environmental performance of a building, the main goal of the current research is evaluating the environmental impacts of the common conventional and prefabricated external wall assemblies and introduce the optimized solution to the Iranian market, by considering both embodied and operational energy. Six exterior wall assemblies are evaluated in this study, two of which are prefabricated solutions.

Methodology

Six different external wall systems for residential buildings in climate of Tehran (Iran) will be compared in this study from an environmental standpoint to demonstrate how the common wall systems work in our climate since data on their performance is not generally available and has not been compared before. LCA technique is useful for evaluating and quantifying all environmental inputs and outputs, from raw material extraction stage (cradle stage) to operational and finally end of life stages (grave stage) (Amiri Fard et al. 2021). It should be mentioned that the proposed analysis for the current research is known as “cradle to grave”.

System, Boundaries, and Functional Unit

LCA methodology distinguishes between two approaches to product analysis. The first one is known as the attributional approach that states that the study of product has no impact on the system. The second one is referred as the consequential approach in which the final product is affected by the study of system(Balasbaneh et al. 2018). As a result of the adoption of the alternatives studied, no changes in flows within the supply chains would be expected, thereby an attributional LCA approach was chosen in the current research.

The BS EN 15978 standard (BRE 2018) defines the stages of the life cycle of building. Life cycle stages A, B6, and C are included in this research. Operational energy is defined to be only the consumed energy at stage B6 for heating and cooling loads, whereas all embodied energy is considered at stages A1–A5, and C1–C4, as illustrated in Fig. 1. It should be mentioned that life cycle stages of B1–B5 were left out of the system boundary because related impacts are hard to measure and thereby are presumed to be the same across all building types. Even though including these life cycle stages would offer more reliable results, it does not directly serve the study's purpose and are therefore excluded from the system boundary and scope (Hong et al. 2020).

The functional unit in the current research is the measurement value for quantification of the derived results in a LCA, according to ISO 14040 (ISO14040 2006). This is extremely important since each system/product might have a variety of functions, and the products would be compared on a common foundation. The emissions, energy consumption, and materials used in this study are based on 1 m^2 of exterior wall. Each wall sample studied is being used in new construction works in the region of Tehran (Iran). This selection of functional unit makes it easier to compare the six compositions that were tested, allowing for a more accurate assessment of the results. This criterion has been used for ensuring which functional unit produces credible findings in earlier studies (Llantoy et al. 2020). It was assumed that service life is 50 years for the mentioned building, as was assumed in the previously distinguished researches by Balasbaneh et al. (2022) and Balasbaneh et al. (2021).

Data Inventory

The materials' LCI and related applied processes in this research were calculated using the Ecoinvent 3.7.1 database. Ecoinvent is regarded as comprehensive and transparent on a global scale, with reliable data on resource exploitation, energy, and material supply(Frischknecht and Rebitzer 2005). It has been frequently used in past LCA evaluations of buildings (Batouli et al. 2014). Because of the lack of Iranian-specific LCI data, its application to the main goal of this study would be regarded as trustworthy and consistent when evaluating data primarily related to the Asian region. The Iranian national regulations for buildings provided the materials' quantity which compound elements in the project required. Nonetheless, due to the fact that some material information was not included in mentioned charts, additional sources were required, including information provided directly by companies and professionals.

Impact Assessment Method and Categories

The ReCiPe 2016 was picked as an environmental impact methodology due to the fact that it is suitable for use in the Iranian market and contains worldwide normalization factors. Furthermore, its indications are expressed in kilograms of substance equivalent, making them technically and objectively expressible and enabling comparison with other studies. The default approach was used, which was the hierarchist ReCiPe version with average weighting set as well as global normalization. It should be mentioned midpoint (problem-oriented) and endpoint (damage-oriented) impact classes are included in ReCiPe 2016.This research demonstrates how to classify various midpoint impacts that lead to endpoint classifications (as illustrated in Fig. 2). It should be noted that the endpoint and midpoint characterization has a robust relationship to the areas of protection the elementary flows with lower modeling uncertainty, respectively. It should be noted that the endpoint approach produces easier-to-understand results, yet they are less transparent and subjective. As a result, the endpoint categories can be seen as presenting more easily comprehendible data on the environmental significance of the defined flows (Huijbregts et al. 2017). A single score indication is used to make it easier to comprehend the impact of procedural selections in the LCI modeling on the derived results. This approach includes both endpoint and midpoint categories, and also a set of weighting criteria that allow a single score impact to be calculated (Buyle et al. 2019).

To assist in the administration of information on environmental impacts, the software Simapro version 9.0.0.48 was employed, which enabled the LCA methodology to be used to assess, organize, and classify the resources used and their environmental effects. This software has previously been utilized in researches with favorable findings(Günkaya et al. 2021; Özer and Yay 2021). Simapro provides comprehensive and unrestricted access to the ecoinvent database for compiling a data inventory for projects and production systems.

Case Study

Six different external wall systems which are commonly used in Iranian residential constructions were chosen for this study. The related details and properties are shown in Table 1 and Fig. 3. The external walls are made up of three layers. The exterior layer is the first layer that is normally exposed to the thermal environmental conditions. The next one is a structural layer and the last layer is an interior layer that is in direct exposure with the building habitational area. It was assumed that the exterior layer for all wall solutions is made of granite stone, which is a common choice between Iranian construction sector. Also, for the interior layer, a gypsum layer was considered.

Operational energy assessment

A conceptual design for a typical single-story residential building in Tehran, Iran was selected as the case study since it is one of the most frequent residential construction style in Tehran nowadays. The shape, typology, and area of the building are typical of a common residential building in Tehran. Thermal simulation in Autodesk Green Building Studio application in Autodesk Revit was used for determining the average cooling and heating loads for the house and various external wall alternatives. Green Building Studio is dynamic platform for building performance analysis which substantially simplifies the process of carrying out building performance analysis utilizing DOE2 as an established and verified simulation engine for delivering data on energy usage, water consumption, and carbon emissions (Autodesk.). Using basic thermal balance concepts, the software calculates usage of energy as a function of the building envelope. Only space heating and cooling are included in the operation energy calculation. The Green Building Studio software generates numerous building simulations based on the building's model design, requirements, and orientation, as well as the qualities of construction materials. The results of this phase aid in the development of a life cycle energy analysis for buildings in their operational period. The plan of the studied building model is shown in Fig. 4.

The characteristics of the building and the construction alternatives examined have a direct impact on operational energy usage. Natural gas and electricity are the most common heating and cooling sources in Iran. The impact of cooling and heating the building with a heat pump system (10 kW) was studied during the operational phase. Different assumptions, such as thermal characteristics, type of building, phase of project, operating schedule of building, location, information of outdoor air, building spaces and zone, and system of HVAC must be filled in accurately for achieving reliable results. Table 2 displays the energy building simulation settings used in Green Building Studio for evaluation of the building model.

It should be noted that thermal properties of different building's components are shown in Table 3.

The first phase involves selecting one of six detached house models with six different external wall types. Except for the type of wall type, which is necessary to differentiate models of buildings; the models are based 145 m^2 area house project with the same heating system, location, and construction assemblies. The sole distinction between the studied models is related to the indirect or direct result of a wall type connected with the relevant model. For LCA and energy efficiency analysis, all relevant wall assembly factors are taken into account. Other considerations, including as cost of construction, seismic performance, and structural performance, are not included in this study. The models selected for the assessment have a 50-year lifespan and are built with U-values that correspond to the Iranian national regulations for buildings. As shown in Fig. 5, the proposed approach can be visually displayed.

Life Cycle Inventory (LCI)

After the samples were described, their functional equivalence were confirmed, and the LCA's goals and scope were set, the research's inventory was carried out.

Production of material, transportation of material to the site, and construction procedures on-site were all part of the construction phase. The amounts of required material for configuring each component of the exterior wall were computed per the square meter for evaluation of the product stage (A1–A3). Waste coefficients were assigned to each element investigated.

This study assumes that roadways are the main route of transportation for all phases of construction projects in Iran. The weight of materials (tons) and the plant distances to site (km) are taken into account while assessing A4. The distances were calculated by beginning at each material's factory and ending at a central position in Tehran, which was done using route optimizer and geo-referencing program. The closest factory to the construction site is selected for each type of material. Movement impacts is obtained by multiplying average distances and weight of material. For carrying the external wall components, a lorry with the EURO3 standard and a load capacity of 10 tons was selected.

Stage A5 entails the employment of machinery to move materials to each story of the building, as well as the creation of the binders used in the wall construction. Many researches deemed the energy spent on construction sites to be of minor importance (Nemry et al. 2010; Monteiro et al. 2020). However, some researches proposed to consider the effect of assembly phases in site in terms of consumptions of water and electricity equal to five percent of the EE of all the building materials (Asdrubali et al. 2013; Cornaro et al. 2020). This study considers the assembly phase effect on the construction site similar to mentioned studies that is equal to five percent of the total EE of each external wall system.

As mentioned before, the Autodesk Green Building Studio tool in Autodesk Revit software is used for predicting operating cooling and heating loads for calculation of stage B6. The thermal characteristics of materials were presumed to remain constant over time due to the fact that thermal properties decay overtime is out of the scope of this study.

It should be noted that in Iran, the end-of-life stage is divided by disposal and recycling. It relates to the fact that less than 30% of construction waste is recycled in Iran, with the rest ending up in landfills and vacant lots (Khoshand et al. 2020). As a result, for the end of life phase, it was expected that the steel components of walls would be recycled and other parts would be dumped in landfills. Construction waste is headed for a landfill with 37 km distances from project site or is processed for recycling with a 91 km displacement at the final phase.

The proposed method was used in six different types of exterior walls in the case study of this research. The proposed approach can be used to any other components or an entire building. Nevertheless, because of its not only great frequency in building projects(Crippa et al. 2018) but also high environmental impacts (Hong et al. 2020; Tushar et al. 2021), the evaluation of mentioned specific construction element was selected for calculations.

Results And Discussion

An evaluation of LCA results delivers a comprehensive understanding of environmental impacts, restrictions identification, and making proper suggestions for further improvement. The results of the environmental calculations are presented in this section. Only heating and cooling loads are considered while evaluating the operational energy consumption of wall components over a 50-year timeframe, as previously stated. Table 4 shows the measured initial environmental impacts of the six wall assemblies. These are also illustrated in Fig. 6 in the form of a comparison graph.

In all sixteen categories, wall 1 has the greatest environmental impact. Wall 6 has the least negative environmental impact in fifteen of the eighteen categories, with the exceptions of scarcity of mineral resource, carcinogenic toxicity, and terrestrial ecotoxicity. In two areas (scarcity of mineral resource and terrestrial ecotoxicity), wall 4 demonstrated the lowest environmental impact, while wall 5 has the lowest environmental impact in the remaining category (human carcinogenic toxicity).

A comparison of various external wall options in terms of the environmental impacts is beneficial for determining which should be selected in order to minimize environmental effects. Nevertheless, examining the measured primary impacts alone is not able to provide a real understanding of which exact categories would be minimized on an individual basis. As a result, the findings of endpoint analyses for each stage of each external wall is presented in Fig. 7. The ReCiPe methodology is used to normalize the findings for easier comparability.

The environmental impact assessment provides a reliable connection between the system's inputs and the products' and processes' possible environmental repercussions. The ReCiPe Single score combines the damages associated with all human health, ecosystems, and resources categories. For all phases and all studied walls, the greatest damage to the environment is associated to the category of human health.

In spite of the fact that walls 1 to 3 are heavier than walls 4 to 6 and more amount of materials have been used in their manufacturing, in production to end of construction phase (A1-5 stages), conventional brick and block walls (walls 1 to 3) have lower environmental impact in comparison with walls 4 to 6. This could be due to the use of less environmentally friendly materials such glass wool, extruded or expanded polystyrene, and steel components in walls 4 to 6 (for instance, production of steel elements necessitates a considerable amount of energy). In the other word, the nature of the materials has a greater effect on the environment than any other attribute, such as weight or thickness. Wall 3 (AAC block wall) has the best environmental performance in this stage while wall 4 (3D Sandwich Panel wall) is the worst one with more than 44% higher impact than wall 3.

To keep the inside temperature within comfortable levels, prefabricated walls 5 and 6 require less heating and cooling loads than the other walls, resulting in lower emissions. This fact is highly related to the lower heat transfer coefficient of prefabricated walls 5 and 6. As it can be seen in Fig. 7, use phase (B6 stage) significantly affects the overall environmental performance of walls. The highest environmental impact (for walls 1 to 4) associated to the use stage whereas for prefabricated walls 5 and 6 it is related to production and construction stage. In the B6 stage, wall 6 (prefabricated XPS drywall) possesses total damage value of 7.9431 pt and it is the best option in this phase while wall 1(masonry clay brick wall) possesses total damage value of 84.7808 pt, which is more than ten times greater than wall 6. Figure 7 illustrates that overall damage value of end-of-life phase is not significant when compares to other stages. The weight of the items to be transported and maintained as construction and demolition waste is a major factor at this point. It's worth noting that damage value of this stage is negative in wall 4 because of high amount of steel rebars and recyclability of them.

Figure 8 demonstrates the derived results of an analysis of uncertainty on the single score indicator of ReCiPe models, which include damage all human health, ecosystems, and resources together. The final scores provide an overview of each external wall's overall performance, including the use phase. The impact of prefabricated walls 5 and 6 is substantially lower than that of other walls. It is clear that each wall assembly has a considerable dissimilar impact on the environment (environmental impact of walls 2 and 3 was more than 60 percent greater than that of walls 5 and 6 and also wall 1 has more than five-fold larger environmental impact than Wall 6). The variability of most flows from the Ecoinvent database, which was utilized in the current study, is characterized by a lognormal distribution around the stated central value, which is defined by related standard deviation. The mentioned variability is assessed using a pedigree matrix that describes the data quality through the related origin, collecting technique, chronological, geographical, and technical representativeness, rather than statistically determined using real measurements. A uniform statistical distribution (which is restricted by maximum and minimum values) has also been connected with some data (Maia de Souza et al. 2016). A distribution on variability represents more than 80% of the data model for all wall assemblies. Since the remaining data are from direct calculation, they have no uncertainty and are thus considered fixed data. A Monte Carlo analysis with 1000 variations and a 95% confidence range was applied for assessment of the life cycle analysis uncertainty for six different models as the results are shown in Fig. 8.

In recent decades, the connection between energy and construction materials has enhanced in a complex way. This relates to latest technological advancements that have investigated the various properties and capacities of certain materials. The life cycle of EE and operating energy consumption of six types of common external walls in the Iranian market is examined in the current research in order to identify the most suitable wall solution from an environmental standpoint. In terms of the life cycle of all wall choices, the results indicate a significant impact on human health, while the impact of resource depletion and ecosystem quality level is considerably low. The LCIA of walls revealed that prefabricated XPS drywall (wall 6) outperformed others in terms of environmental performance. The most favorable thermal resistance and transmittance values are found in wall 6, followed by Walls 5 to 1 respectively.

The results are on one per meter-squared basis. Nonetheless, it is necessary to assess the differences for the entire building in order to get a realistic picture of each wall system's performance. As an instance for the conceptual modeled house, if wall 6 instead of wall 3 was employed, more than 40000 $kgCO_2eq$ and 3000 m^3 of water would be conserved over 50 years lifespan. Or there would be 180000 $kgCO_2eq$ saving if wall 6 (the best option) was utilized instead of wall 1 (the worst option) over the whole life cycle. The difference between the results would become even more impressive when scaled up to a thousand houses or even entire new houses under construction in Tehran. This highlights the significant impact of external wall system selection.

In Iran, energy costs are very low due to the existence of large reserves of fossil fuel in this country. Consequently, much attention has not been paid to the material's thermal performance in the construction sector. Therefore, energy consumption in the construction sector differs significantly from the global average. The obtained results of the current study demonestrated that the optimal selection of building materials (in this particular case exterior walls) can make a huge difference in terms of environmental impacts. In order to move towards the goals of sustainable development, it is essential to impose stricter laws on the thermal performance of building materials in Iran (such as the requirement to use the minimum thickness of insulation materials). Companies who can provide proof of investing in materials with low energy and environmental impacts could be rewarded by the government. Also, funding investigations towards the creation of a national database and regulations requiring manufacturers to report their products' environmental effects is crucial. As it is clear from the results, the operation phase of the building can significantly influence the overall building environmental performance and also the greatest variation of environmental impacts is in the operation phase between the selective walls.

Some of the article's assumptions and simplifications might result in limitations and potential uncertainties. With increasing recycling rates and material recycled contents, end-of-life is predicted to be different in 50 years, although changes are difficult to predict. Also, there are no databases dedicated to the materials used in the Iranian market. The findings of this study were based on a specific model and location, and therefore may not apply to other building sizes or climatic zones.

Conclusions

It is critical to raise the degree of building sustainability around the world as the building industry is responsible for more than 36% of the total consumption of energy and greenhouse gas emissions. Some materials and products have better environmental performance in compare with others in construction sector. Consequently, project teams should choose technologies with good environmental performance to lessen the overall building's environmental impacts. Despite the enormous number of components in a building, external walls are one of the components with the greatest environmental damages. As a result, obtaining high levels of building sustainability cannot be separated from achieving excellent environmental performance for wall materials.

Six common external wall systems on the Iranian market, composed of various materials and characterized by different technologies, were analyzed and compared from environmental effect aspects. The environmental performance was evaluated through LCA approach, which took into account both midpoint and endpoint impacts by ReCiPe method, according to the ISO 14044 and ISO 14040 standards. This study covers stages A, B6, and C of the life cycle according to BS EN 15978 standard. For assessing the heating and cooling loads of each wall during operation phase, Autodesk Green Building Studio was utilized. Finally, all collected data were imported to LCA software (Simapro) to aid in the management of data on environmental impacts. 1 m^2 of wall was chosen as the functional unit, and all wall samples were assumed to be placed and operated in a same building in Tehran, Iran.

Human health was the most severe damage category for all of the studied walls. The findings revealed that for product to end of construction phase (A1 to A5) LECA and AAC block walls (wall 2,3) have the best environmental performance while for operation phase (B6) prefabricated Knauf drywall and prefabricated XPS drywall (wall 5,6) have the best performance. This asserts the importance of considering a building's whole life cycle (rather than just the production and construction phase). The end-of-life stage has no substantial impact on the total impact of alternative external walls. In wall 4 because of the significant amount of steel rebars and their recyclability, the damage value of this stage is negative.

The lowest total environmental effect was achieved by prefabricated Knauf drywall and prefabricated XPS drywall (wall 5, 6), whereas the overall environmental effect of the masonry clay brick wall (wall 1) was the highest. Due to using decent amount of isolations, walls 5, 6 require less energy for heating and cooling, resulting in better total environmental performance. In case lowering carbon emissions is a top goal, as it is nowadays on a global scale, then using one square meter of wall 6 (the finest alternative) instead of wall 1 (the worst alternative) could save 1257.85 $kgCO_2eq$. When scaled up this difference to a complete house or even entire new houses under development in a city, the difference between the results becomes much more astounding. Because of the wide range of environmental consequences in the operating phase of the chosen walls, policymakers should enact stronger restrictions regarding the thermal performance of construction materials in Iran.

In order to measure overall sustainability, future research should include life cycle costs and societal impacts. Furthermore, focusing on creating and maintaining a local database that represents the environmental effect of construction materials in Iranian construction sector should be crucial in arming engineers with the knowledge required for providing more sustainable solutions.

Declarations

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Consent to participate: Not applicable

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Tables

Table 1 Overview of the composition of the wall assemblies

Walls name	Interior layer (IL)	Substructure	Exterior layer (EL)	U-value or Heat transfer coefficient (W/m^2.K)
Wall 1. Masonry clay brick wall	Base plaster, gypsum plaster	Masonry clay bricks, cement mortar	Granite facades, cement mortar	3.4040
Wall 2. Lightweight expanded clay aggregate (LECA) wall	Base plaster, gypsum plaster	Hollow LECA blocks, cement mortar	Granite facades, cement mortar	1.0465
Wall 3. Autoclaved aerated concrete (AAC) wall	Base plaster, gypsum plaster	AAC blocks, cement mortar	Granite facades, cement mortar	0.9318
Wall 4. 3D Sandwich Panel wall	Base plaster, gypsum plaster	Shotcrete concrete, expanded polystyrene foam slab, rebar grid	Granite facades, cement mortar	0.5925
Wall 5. Prefabricated Knauf drywall	Gypsum plasterboard	Structure composed of combined C-shaped galvanized steel profiles , glass wool filling	Cement board, granite facades, cement mortar	0.3421
Wall 6. Prefabricated extruded polystyrene (XPS) drywall	Gypsum plasterboard, expanded metal	Structure composed of combined C-shaped galvanized steel profiles , extruded polystyrene foam slab	Expanded metal, granite facades, cement mortar	0.3072

Table 2 Building simulation settings

Living area	145 m^2
Conditioned volume	379.51 m^3
Total area of external walls	150.487 m^2
Project phase	New construction
Building type	Single family
Heating set-point air temperature	21 ˚C
Cooling set-point air temperature	23 ˚C
Summer dry bulb	39 ˚C
Summer wet bulb	24 ˚C
Winter dry bulb	-3 ˚C
Heating Ventilation and Air Conditioning (HVAC) schedule	24/7 Facility
Location	Tehran, Iran
Latitude/longitude (˚)	35.66˚ / 51.43˚
Elevation above sea	1200 m
Outdoor air per person	8 lit/sec

Table 3 Characteristics of other components of the building model

Building component	**Explanation**	**Heat transfer coefficient ($W/m^2.K$)**
Roof	Precast concrete roof; thickness = 0.4m	2.615
Ground floor	Concrete flooring; thickness = 0.4m	2.615
Interior walls	Masonry clay brick(0.1m); base and gypsum plaster total thickness = 0.154m	4.7118
Windows	Aluminum-frame; double glazing; 1.83*0.915m units =7	1.9873
Doors	Wooden doors; 2.134*0.915m; units = 8	3.8042

Table 4 Environmental impact results (midpoint) for wall 1 to 6 for 1 m^2

Impact category	Unit	Wall 1. Masonry clay brick wall	Wall 2. LECA block wall	Wall 3. AAC block wall	Wall 4. 3D Sandwich Panel wall	Wall 5. Prefabricated knauf drywall	Wall 6. Prefabricated XPS drywall
Global warming	kg CO_2 eq	1445.222	521.0937	459.5198	295.1223	230.7936	187.3735
Stratospheric ozone depletion	kg CFC-11 eq	0.002823	0.000983	0.000834	0.00053	0.000358	0.000292
Ionizing radiation	kBq Co-60 eq	3012.487	1038.333	877.6383	556.3317	333.7304	296.283
Ozone formation, Human health	kg NOx eq	3.454114	1.318308	1.158742	0.774204	0.670987	0.520851
Fine particulate matter formation	kg $PM_{2.5}$ eq	2.736151	1.315341	1.174005	0.920771	0.877746	0.793502
Ozone formation, Terrestrial ecosystems	kg NO_x eq	3.516948	1.340788	1.178725	0.788484	0.683923	0.530618
Terrestrial acidification	kg SO_2 eq	5.358763	2.013226	1.664014	1.081725	0.907086	0.695325
Freshwater eutrophication	kg P eq	1.235996	0.432866	0.364086	0.233593	0.168877	0.126805
Marine eutrophication	kg N eq	0.145248	0.050708	0.042927	0.027537	0.020674	0.015036
Terrestrial ecotoxicity	kg 1,4-DCB	4153.485	1462.6	1296.164	879.5482	942.4236	1180.627
Freshwater ecotoxicity	kg 1,4-DCB	220.2445	76.00239	64.20232	42.69591	27.09103	23.46005
Marine ecotoxicity	kg 1,4-DCB	992220.1	346285.6	293846.9	194268.9	126017.5	107532.1

Human carcinogenic toxicity	kg 1,4-DCB	17419.67	6124.801	5170.016	7137.955	4003.658	4567.72
Human non-carcinogenic toxicity	kg 1,4-DCB	834683.9	291701.3	247378.9	157436.4	104983.2	88439.23
Land use	m^2a crop eq	363.4696	128.1751	109.0803	69.90545	52.02518	38.7857
Mineral resource scarcity	kg Cu eq	17.4297	5.874627	4.432812	2.449319	2.901943	3.333072
Fossil resource scarcity	kg oil eq	368.6014	131.6908	113.5248	76.03669	60.89212	49.91154
Water consumption	m^3	107.3353	37.0733	31.38169	20.33474	12.53815	10.95428

Figures

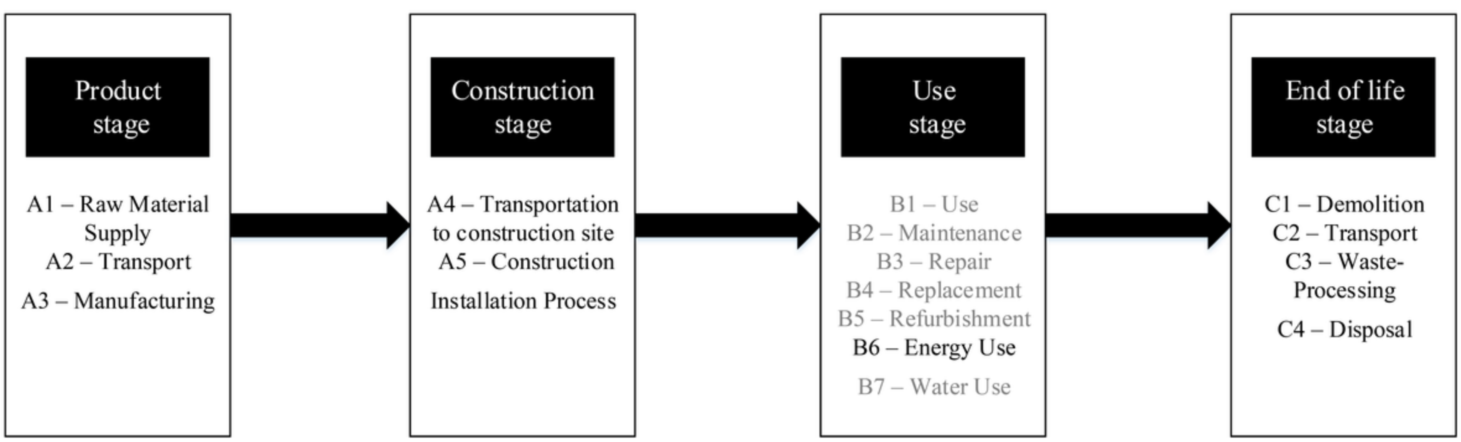


Figure 1

Included life cycle stages in the system boundaries

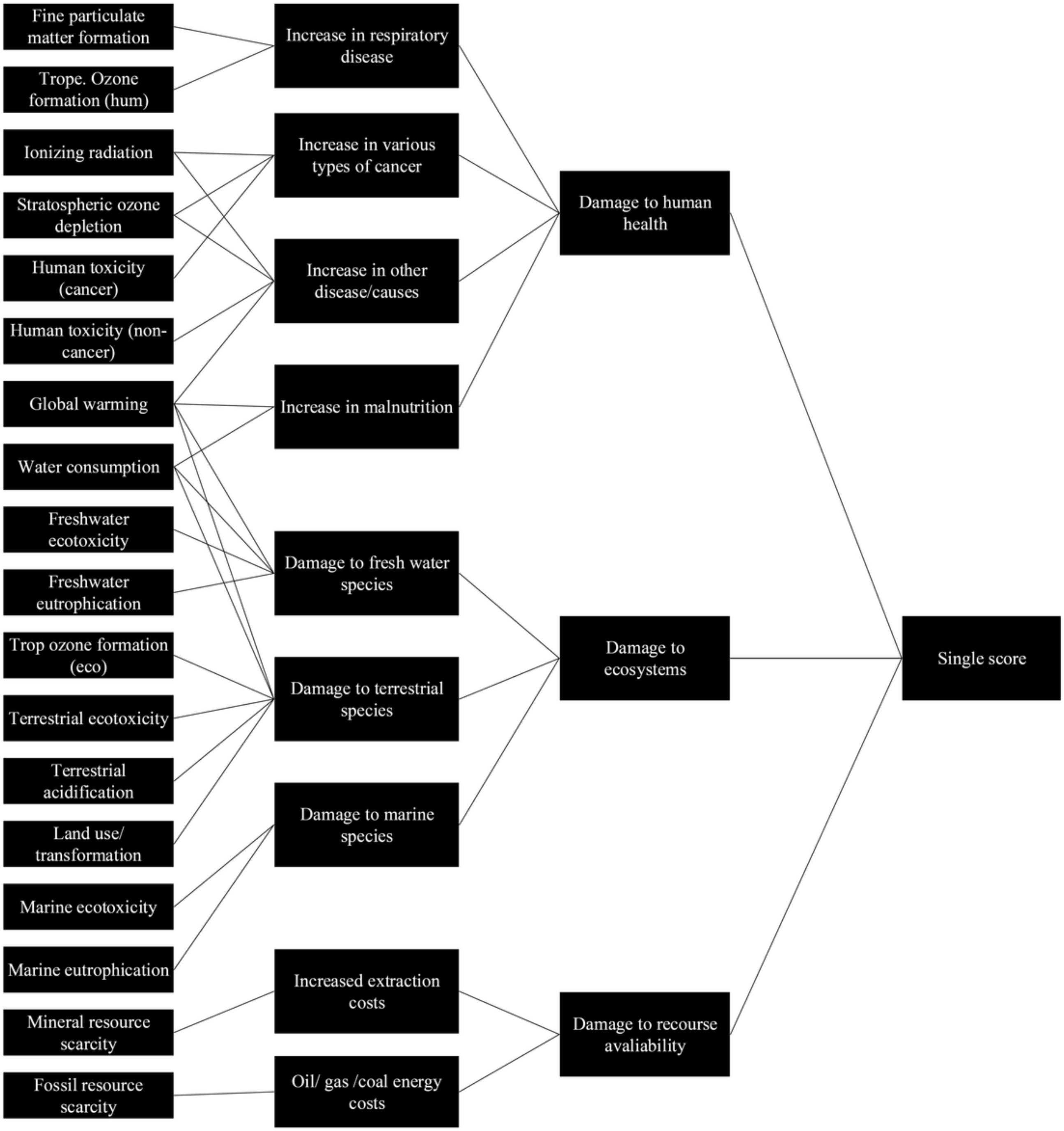


Figure 2

An overview of the impact categories covered by the ReCiPe2016 method

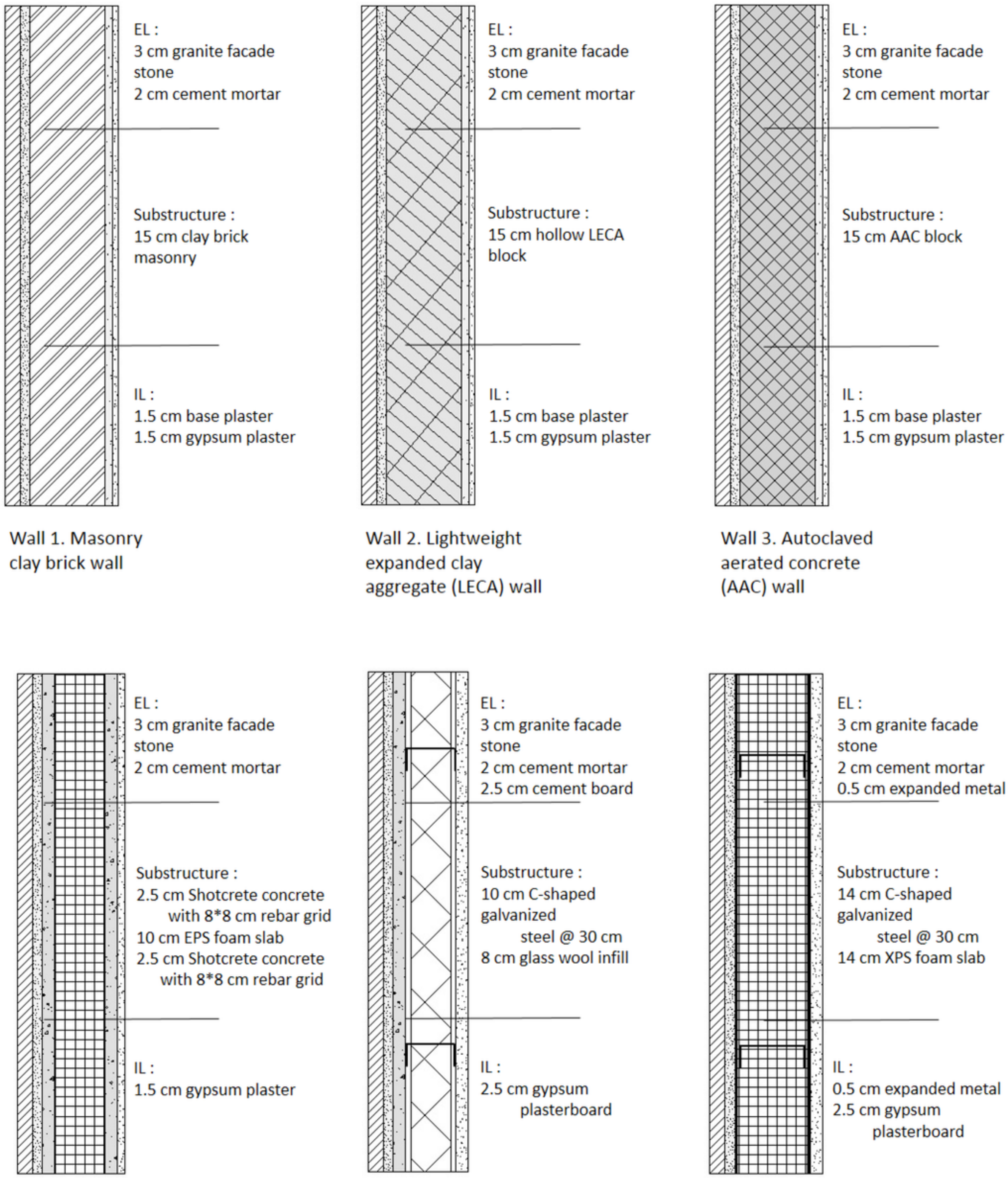


Figure 3

Conceptual representation of the investigated wall assemblies

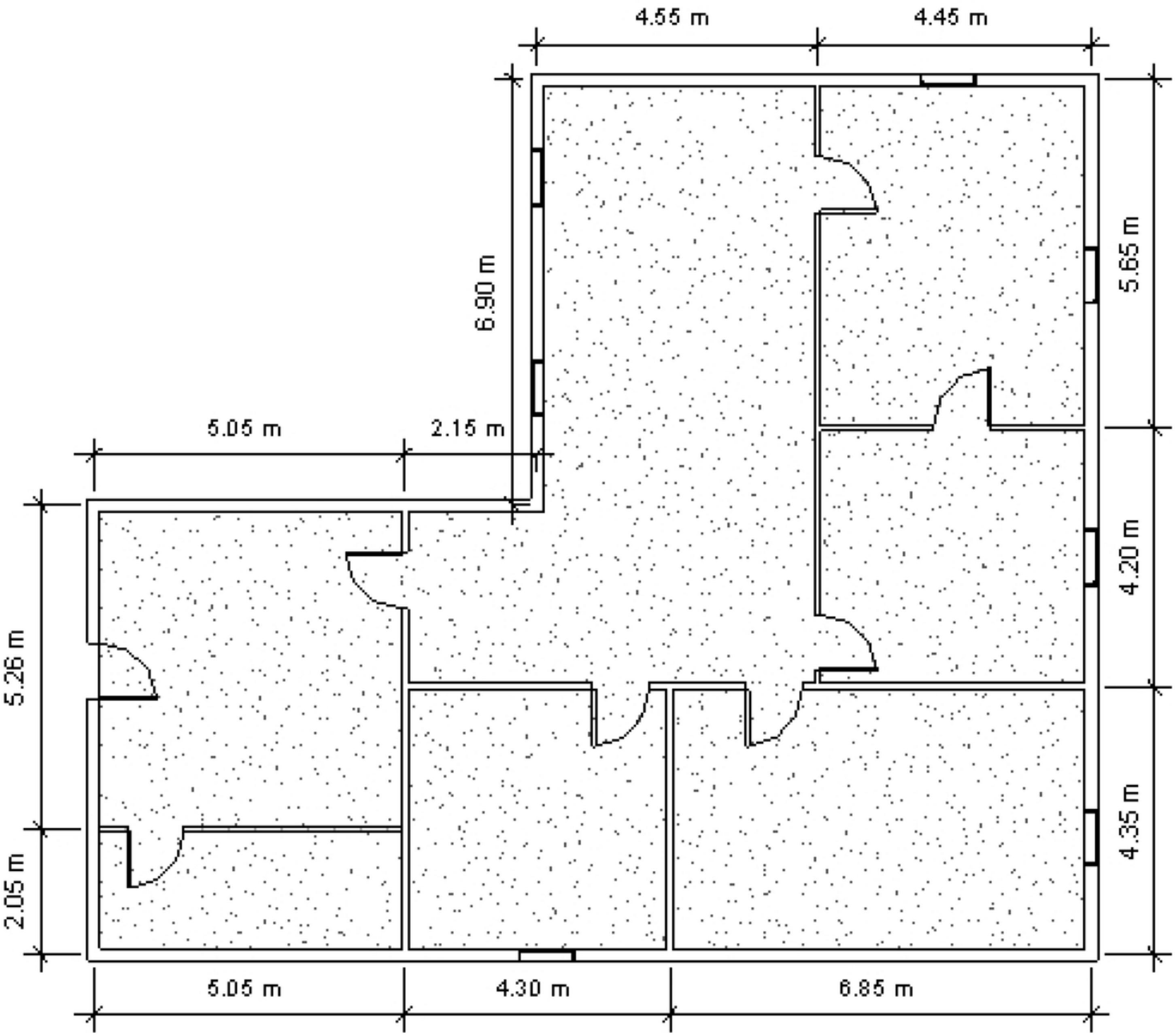


Figure 4

Plan of the studied model

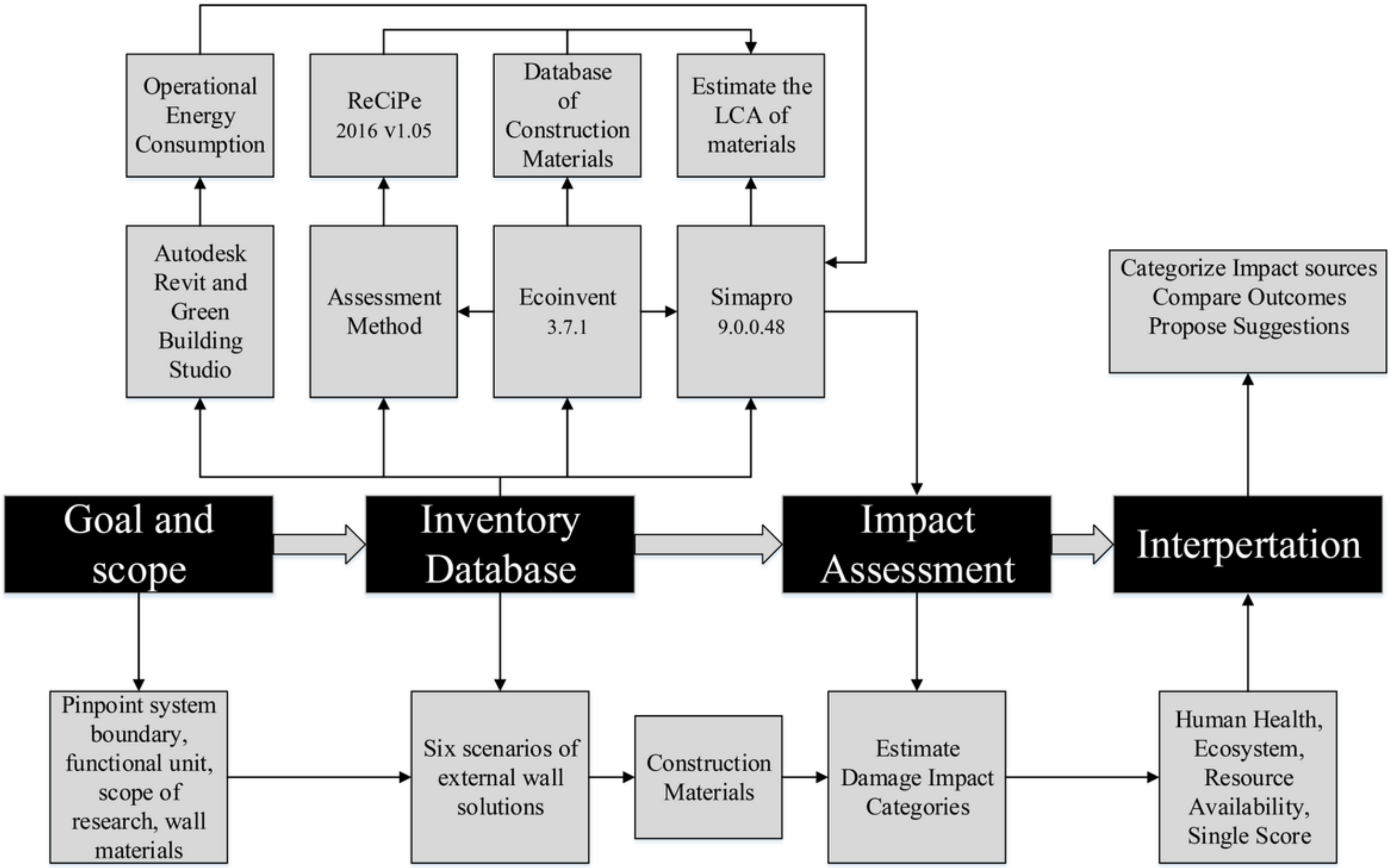


Figure 5

Research framework

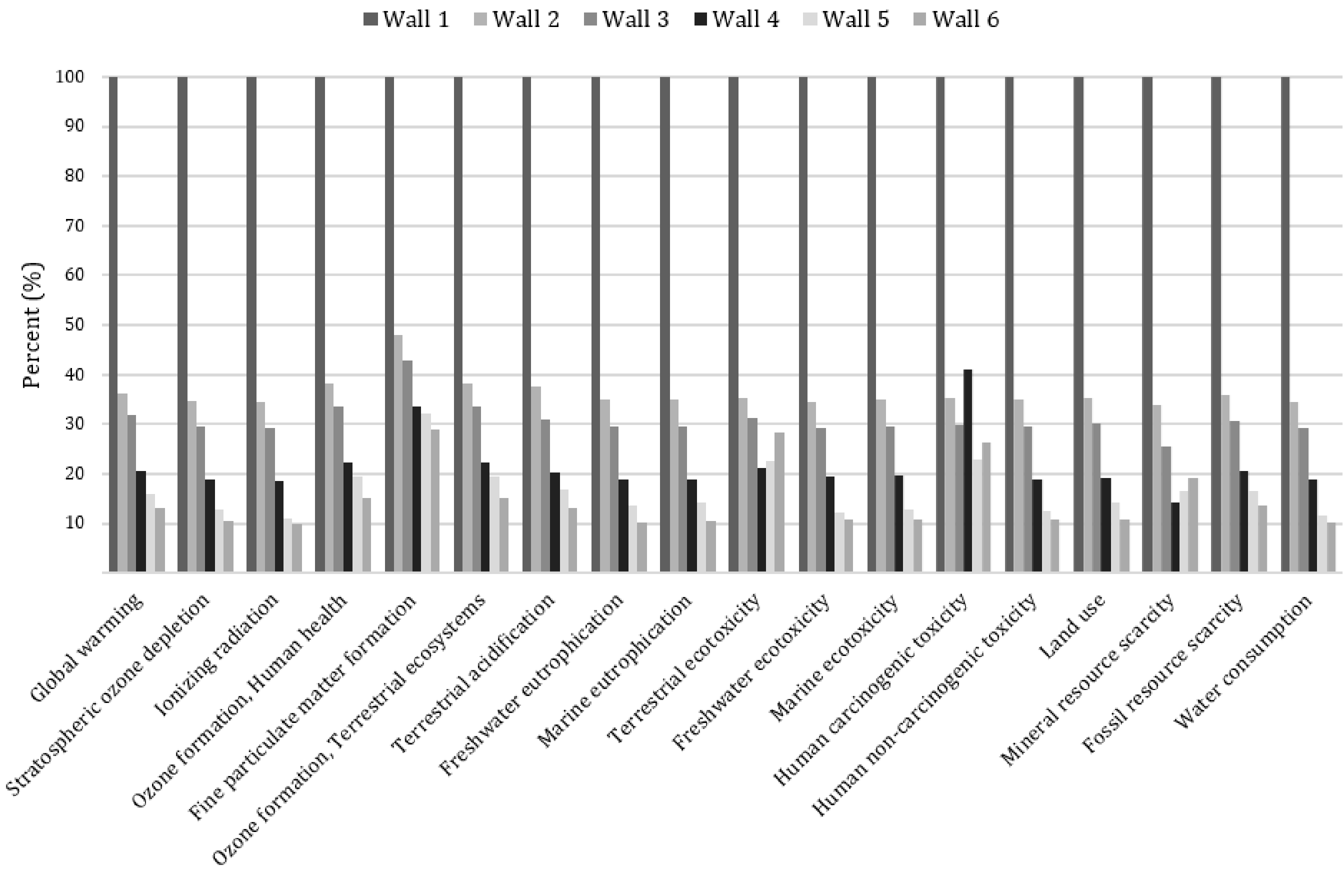
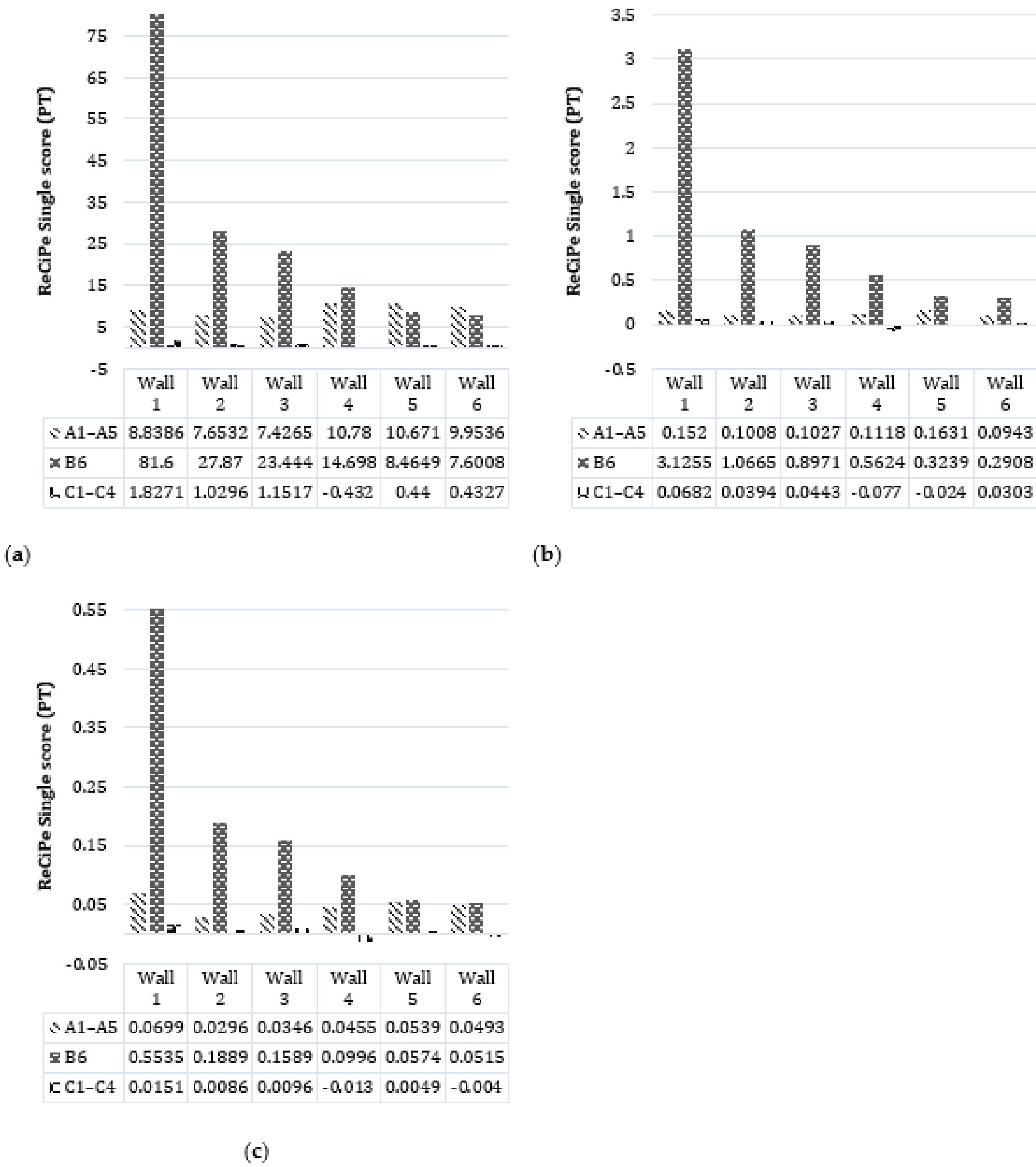


Figure 6

Midpoint environmental impact comparison of wall 1 to 6



(a)

	Wall 1	Wall 2	Wall 3	Wall 4	Wall 5	Wall 6
A1–A5	8.8386	7.6532	7.4265	10.78	10.671	9.9536
B6	81.6	27.87	23.444	14.698	8.4649	7.6008
C1–C4	1.8271	1.0296	1.1517	-0.432	0.44	0.4327

(b)

	Wall 1	Wall 2	Wall 3	Wall 4	Wall 5	Wall 6
A1–A5	0.152	0.1008	0.1027	0.1118	0.1631	0.0943
B6	3.1255	1.0665	0.8971	0.5624	0.3239	0.2908
C1–C4	0.0682	0.0394	0.0443	-0.077	-0.024	0.0303

(c)

	Wall 1	Wall 2	Wall 3	Wall 4	Wall 5	Wall 6
A1–A5	0.0699	0.0296	0.0346	0.0455	0.0539	0.0493
B6	0.5535	0.1889	0.1589	0.0996	0.0574	0.0515
C1–C4	0.0151	0.0086	0.0096	-0.013	0.0049	-0.004

Figure 7

Endpoint environmental impact comparison of wall 1 to 6 for each stage and (a) Damage to human health; (b) Damage to ecosystems; (c) Damage to resource availability

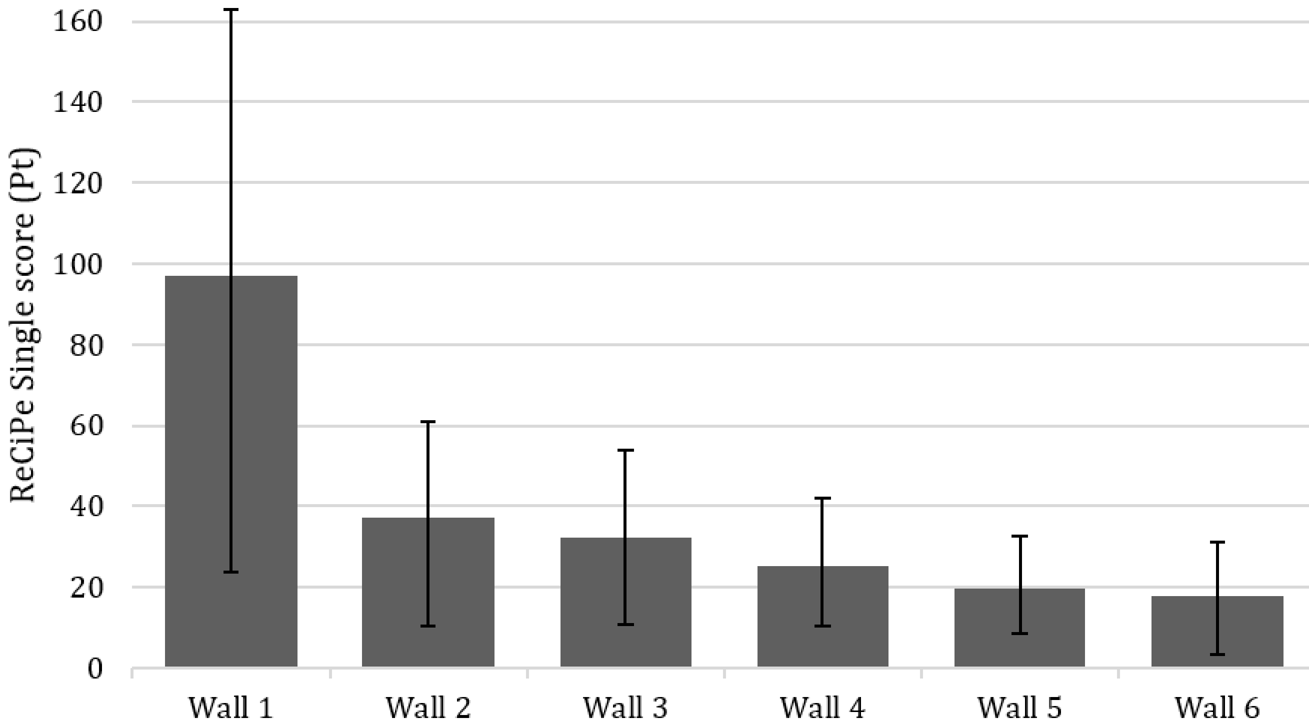


Figure 8

Total environmental score of wall 1 to 6 by ReCiPe method