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Research Article

Life Cycle Assessment of Residential Buildings Construction (Case Study: Tehran)

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Abstract

The construction industry, currently, is encountered with several issues such as lack of proper supervision and generating and accumulating a lot of debris. Considering the building as a part of nature and an inanimate creature, it interacts with the natural ecosystem and contributes to the cycle of life. In this regard, building materials should be selected in coordination with the surrounding environment and impose the least negative impact on the natural environment. The current research has been done to apply Life Cycle Assessment (LCA) approach on residential buildings construction and assess the impacts of building material, solely and altogether, on the environment. For this purpose, IMPACT 2002+ method utilizing SimaPro software has been applied to evaluate the processes and materials used for construction of a five-floor concrete structure building in Tehran. The results indicate that among the construction materials, stone production with the single score of 64 and steel production with the single score of 27 have the highest environmental impacts. Besides, a LCA has been done for comparing environmental impacts of the steel structure buildings versus the concrete ones, resulting in an inferior level for steel buildings.

Keywords: LCA, SimaPro, Carbon Footprint, Housing, SimaPro

Introduction

Half a century ago, the average buildings' life span was previously 30 years in Iran, which is the same as the life of US buildings (Rahaei and Ghaemi, 2012). Currently, the average useful age has been decreased to 25 for Iranian buildings, while it has been increased to 120 years for the US ones. According to the statistics, this age is up to 300 years in some developed countries. Experts believe that the construction industry must evolve in the 21st century, arguing that a building should be evaluated by a group of specialists such as biologists, environmental experts, scientists, architects and engineers (Rahaei and Ghaemi, 2012).

The growth and sustainable development of humans' activities are affected by the sustainability of environmental, economic and social systems. Nowadays, planning for and management of resource utilization are of the most important economic, environmental and social issues of humans. The environment and the necessity of its protection have become the

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focal point of attention for the individuals and national and international institutions (Elahizadeh and Abedi, 2018).

A sustainable city with a long survival time is defined via the economical usage of the resources, avoiding excessive waste production, waste recycling, waste to energy (Majidi and Kamalan, 2017) and employing useful policies towards a green city (Taghvaei and Safarabadi, 2014).

Greenhouse gases emission has caused lots of environmental adverse impacts such as global warming (Shariatmadari et al., 2007). Among them, methane has about 21 times more golabl warming impact rather than CO_2 (Kamalan, 2016). In addition, the consequences of environmental pollution vary by the location and circumstances. The construction and its associated industries have been recognized as one of over consuming and polluting industries in the world. (Rahaei and Ghaemi, 2012).

The pollutions due to heating and cooling systems are more than that of vehicles. The manufacturing of building materials consumes a lot of energy and exploits non-renewable environmental resources. The current civilization traits that bring pollution and environmental degradation can be seen anywhere (Acgih, 2001). It is notable that all emissions have charges their own cost to the society (Motlagh et al., 2005).

According to the aforementioned arguments it can be said that primary and accurate decisions can transform the sustainable design procedure into a very useful and economical one. Life Cycle Assessment (LCA) provides a scientific approach that accurately investigates different life stages of a product or service resulting in improvement of the environmental characteristics (Bueno and Fabricio, 2018). Schlegl et al. (2019) in a research on the evaluation of CO2 emissions of construction and the utilized materials for residential buildings in Germany, concluded that environmental assessment at the planning phase of construction can result in decreasing the resource consumption and environmental impacts during the whole life cycle (Schlegl et al., 2019).

The current issues of the construction sector need to be solved by some solutions that reduce the resource consumption and subsequent environmental impacts. Life Cycle Assessment is a tool that is widely used for evaluating the environmental impacts of the construction sector (Soust-Verdaguer et al., 2017).

Alamdari et al. (2018) evaluated seven different building materials for the construction. The results indicate that the wooden panel and steel are the best choices due to their lower greenhouse gas emissions in comparison to other structures, improved structural defects and better load-bearing capacity. Raeis Samiei (2018) did an LCA research on the impacts of generating recycled pellets. The functional unit is one kilogram of recycled pellets used in concrete and batard mortar. (Asl et al., 2019)

This research's achievement is recognizing four main indexes for life cycle analysis of green materials and also realizing some criteria for decreasing the cost of green construction and the optimization of buildings' energy consumption which finally will result in the ranking of the indexes and criteria. Sheshbolouki et al. (2019), using quantitative and qualitative analyses, realized and evaluated the interactions' impacts and the possible opportunities of incorporation of a few techniques together, Building Information Modelling (BIM) technology, Integrated Project Delivery (IPD) method and Lean Construction (LC) technique, on the construction projects.

Mohammadi et al. (2019) examined the usefulness and capability of the LCA and BIM integration for a real project and showed that columns, bars and the group of side components (such as the cement that is used in non-structural element) have the biggest impact on the three midpoint effects of ozone layer depletion, global warming potential and fossil fuel resources and the effective latent energy has a bigger share in the global warming potential.

Taherian et al. (2018) conducted an environmental modeling project using SimaPro software to examine mixing one cubic meter of different types of concretes naming micro silica, geopolymeric, micro-nano bubble, nano silica and regular concrete. The results showed that the global warming potential for geopolymeric concrete is less than the others and is 26 per cent less in comparison to the regular one. In addition, the global warming potential for micro silica, nano silica and micro-nano bubble are 56%, 17% and 38% greater than that of the regular concrete, respectively. The biggest impact is of the micro silica concrete while the regular one is recognized as the most environmentally friendly concrete.

Chen et al. (2010), examined three types of block joists, concrete, clay and polystyrene. The chosen sustainable development criteria were environmental, political, economic and social ones. In addition, the AHP method was used for data analysis and impact assessment.

Henricson (2010), in partnership with the Energy and Environment Department of the Chalmers University of Technology, conducted a research project named Green Construction on the environmental assessment of residential buildings in Gutenberg. The goal of this research was increasing the environmental performance of the residential buildings and providing a base with measurable criteria for the evaluation of development plans.

Zare et al. (2015) has approach provided a balance between the sustainable development goals and the decision-makers' requirements in the construction industry through utilizing a developed optimization. This approach considered an armed concrete frame under some gravitational and side-load bearings then designed the concrete frame considering the ASCE2010-based formability constraints and calculated the steel consumption in concrete profiles for the sake of decreasing the CO2 emission.

Li et al. (2019) conducted life cycle cost calculations as well as some quantitative analysis on CO_2 emission for a case study of armed concrete structure in China to decrease the energy-related emissions. The results showed that the greenhouse gas emissions in the operation and maintenance phase are 30% higher than that of the construction phase and even 300% higher for hospital buildings while the emissions in the demolition phase are relatively small comprising only 3 to 12 per cent of the life cycle emissions. Considering the type of the building, life cycle CO_2 emission for hospital buildings is up to 3390 kg/m3, so much greater than that of different types of the concrete structure.

Schlegl et al. (2019) recommended a base criterion based on the buildings' life cycle datasets in Germany. In the primary stage, a synchronized dataset of a large number of examined buildings was created. In the second stage, the data were analyzed in terms of compatibility based on the data format, structure and the detail level.

Recently, a study has been carried out to investigate the LCA difference between steel and concrete structure for a two floor building indicating higher pollution impact factors of the concrete frame (Oladazimi et al., 2020). Also, residential building construction in Parand, Iran (Asadollahfardi et al., 2015) as well as Egypt (Ahemd et al., 2015) have been fully investigated in terms of LCA concluded some strategies to lessen the environmental impact of building constructions. Sharma has shown that construction phase emits more than half of GHG lonely. It also consumes the highest portion of energy (Sharma et al., 2011).

The current research has done a life cycle analysis on a five-floor residential building in Tehran from the production of materials to the recycling of the waste materials after the building's demolition to examine the environmental impacts.

Materials and Methods

Life Cycle Assessment

In recent decades the performance and efficiency of the systems and their economic affordability and social affairs were of the important parameters for choosing the best option but after a while and the occurrence of some environmental consequences such as global warming, air pollution, acid rain, the contamination of surface and groundwater, soil erosion and desertification, decline of non-renewable resources and endangering the human beings' health, the decision-makers were attracted to the environmental issues. This research utilizes one of the environmental assessment methods, life cycle assessment which has been widely used since 1990 by the researchers in the most countries around the globe and succeeded to change the viewpoint of decision-makers toward the systems and processes. Life cycle assessment is an analyzing tool that is successful and promising despite the lack of a unique and particular method requiring several assumptions and parameters and it returns reliable and effective results and depicts the detrimental impacts of systems, procedures and human activities in a more clear way. The tool is capable of evaluating the impacts on the whole procedure. the tool not only considers the principal procedure, but also the whole substructures, primary materials and resources, the required energy for processes, waste production, losses, emissions and the produced materials and energy (Attarian and Mokhtari, 2014). The general framework of the life cycle assessment that is based on the 14040 ISO Standard has been depicted in figure 1.

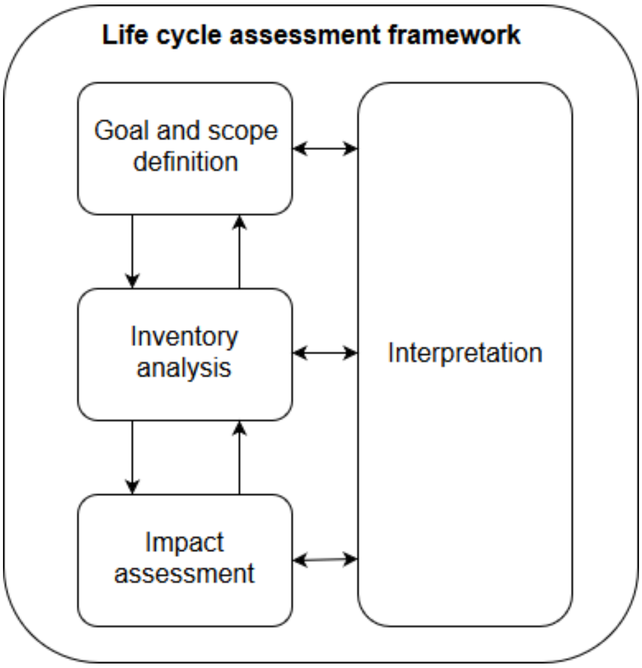


Figure 1. The life cycle assessment general framework (Travessin and Braghini, 2013)

LCA can help decision-makers to select a product or service with the least environmental impact. This information can be used in association with other factors such as the cost and the performance. The LCA information determines the transformation of the environmental impacts from a medium to the other and from a stage of the life cycle to the other thus helps to prevent the transformation of environmental issues from one stage to the other. The capability of tracking the environmental impacts helps decision-makers and managers to realize the environmental features of a product or service (Mohammadi et al., 2018). Using the LCA method, the analysts can:

- Develop a systematic evaluation of a product's environmental impacts
- Evaluate the environmental impacts of a product, service or process
- Help the agreement of stakeholders for the planned project

- Quantitative the impact to the air, water and soil in each stage of the life cycle
- Evaluate the human-based and ecological impacts of material consumption and environmental emission in the local, regional and global society
- Recognize and compare the human-based and ecological impacts of two or multiple products
- Recognize the impacts on one or multiple media

This research utilized the life cycle assessment, SimaPro software and IMPACT 2002+ method to analyze the environmental impacts of using construction materials. In this method, the impact of each input has been divided into fifteen midpoint effects such as carcinogenic effect, ozone layer depletion, freshwater aquatic ecotoxicity, land occupation, etc. and four endpoint effects named resources, human health, ecosystem quality and climate change.

The first stage of the research identifies the regular activities in the construction of a building along with calculating the required materials and energy in different stages and processes of the construction. SimaPro software was later used to analyze the structured data.

The life cycle assessment method is utilized for realizing the important consequences of potential environmental impacts. In this stage, a large volume of various input data and information have been provided by the inventory stage, are categorized for accelerating the process of the information analysis. ISO standards provide four stages for categorizing the inventory data (Zbicinski et al., 2006).

- Mandatory stages: Categorization and Characterization
- Optional stages: Normalization and Weighing

Impact Categorization

In this stage, the flow of inventory inputs and outputs are categorized representing the impact groups. (For example, the N2O, CH4 and CO2 inventories which result in global warming are identified as the climate change impacts subcategory) (Zbicinski et al, 2006).

Characterization

In this stage, quantitative evaluation of the life cycle emissions is done for examining their environmental impacts. So the released emission of one impact group is multiplied by a characterization factor representing the share of the element or compound in the related impact group. For example, in the climate change group, the characterization factor for CO2 is 1 while that is 11 for CH4, meaning that releasing one kilogram of CH4 is equivalent to releasing 11 kilograms of CO2 (Goedkoop et al, 2009). In conclusion, all the emission flows related to a group are converted into a common unit being capable to be summed up. Finally, a list of environmental impacts called “environmental profile” is prepared (Zbicinski et al, 2006).

Normalization

Each characterization group is based on different units such as CFC-11eq, SO2eq and CO2eq. As a result, a direct comparison between the groups is not possible. In the normalization phase, each group value is divided into a reference value, making available the comparison of different impact group (Zbicinski et al, 2006). A usual reference value is the average annual environmental loading of a country or continent divided by the population of the region. However, the value can be selected arbitrarily (Goedkoop et al, 2009). Normalization demonstrates the share of environmental loading of each impact group (such as global warming or acidification) in the product’s life cycle.

Weighing

In the comparative analysis, the most important goal is to identify the most environmentally friendly product. If a product qualifies in some categories and not in some others, it is impossible to select the best choice. In this case, the relative importance of the impacts is considered. The quantity and share of the weighing factors are evaluated by a large number of experts, so it is a place of dispute in the scientific community (Zbicinski et al., 2006).

Interpretation

Interpretation is a method that systematically recognizes, quantitates, evaluates and verifies the provided information by the life cycle's inventory and impact assessment stages. ISO 14043 standard defines two goals for this stage:

- Clear analysis and interpretation of the results, explaining the constraints, providing some advice based on the previous stages.
- Providing a comprehensive and apprehensible statement of the life cycle results

The LCA method still has a lot of weaknesses. Two major sources of uncertainty in this method are the quality of data and the modeling method of LCA. The data usually comes from various resources. They are estimated and assumed and in some cases, they are theoretically calculated. The LCA modeling method consists of goals, system boundaries, allocation rules and characterization models for a long term of period. If the assumptions have changed, the life cycle calculations repeat again and the results are compared to each other and the hot spots are recognized (Zbicinski et al., 2006).

An introduction to SimaPro software

SimaPro is economic software that has been developed by Perry Consultant Company in the Netherlands. The software provides some professional tools for collection and evaluation of the environmental performance of products, processes and services. The software's datasets comprise a large collection of clear and quality data of ordinary products and processes. Some of the datasets are Ecoinvent (Switzerland), US input and output database, Denmark's input and output database, Industrial databases, Buwal 250, LCA Food, the US Franklin LCA database, IDEMAT 200, Agri-footprint, archived data etc. The Ecoinvent is a multipurpose database of 2700 processes. SimaPro does the production system's calculations using the inverse matrix. For the same purpose, it utilizes some highly efficient algorithms enabling it to perform thousands of process calculations for a single product. SimaPro had been the best LCA software throughout the past 25 years. The software had been reliable for a large number of industries and scientists and it is used in more than 80 countries. (Spriensma, 2004)

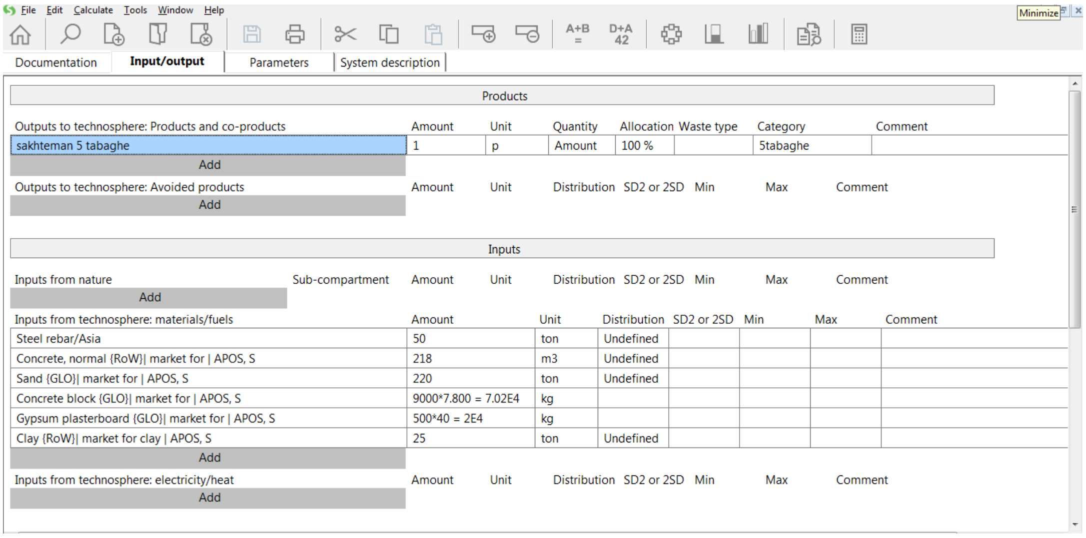
Results and Discussion

The boundary of the system in the current research is from the production of building's materials to the construction of the building and the functional unit is a five-floor residential building in Tehran. The data collection method has been an interview with the construction agents and library resources. The input data are listed in table 1.

SimaPro has been utilized to calculate LCA of the sample building, Figure 2 shows the input material window as a sample.

Table 1. Input data based on field survey and literature review

No.	The type of material	Quantity	Unit
1	Bar	50	Tonne
2	Concrete	120	m^3
3	Foundation concrete	50	m^3
4	Columns concrete	48	m^3
5	Sand	220	Tonne
6	Cement block	70	Tonne
7	Plaster	20	Tonne
8	Clay	25	Tonne
9	Unolite	960	Kg
10	UPVC Window	19.5	m^2
11	Pumice	45	Tonne
12	Stone (façade and staircase)	56	Tonne
13	Ceramic	3200	Kg
14	Cement	50	Tonne
15	Welding	55	Hours
16	Water	25	Tonne
17	Dye	170	Kg
18	Copper wire	550	Kg
19	Electricity	1100	kWh
20	Diesel fuel	11,100,000	kCal



Products

Outputs to technosphere: Products and co-products	Amount	Unit	Quantity	Allocation	Waste type	Category	Comment
sakhteman 5 tabaghe	1	p	Amount	100 %		5tabaghe	

Outputs to technosphere: Avoided products	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment

Inputs

Inputs from nature	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment

Inputs from technosphere: materials/fuels	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Steel rebar/Asia	50	ton	Undefined				
Concrete, normal {RoW}| market for | APOS, S	218	m3	Undefined				
Sand {GLO}| market for | APOS, S	220	ton	Undefined				
Concrete block {GLO}| market for | APOS, S	9000*7.800 = 7.02E4	kg					
Gypsum plasterboard {GLO}| market for | APOS, S	500*40 = 2E4	kg					
Clay {RoW}| market for clay | APOS, S	25	ton	Undefined				

Inputs from technosphere: electricity/heat	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment

Figure 2. Input material window of SimaPro

The interpretation of the results

In this stage, the life cycle assessment results of the five-floor residential building is discussed. The impacts of each input inventory on the mid and endpoint effects are illustrated in figures 3 and 4.

As it seems, the most environmental impact of CO_2 emission is related to bars with the value of 9.89×10^4 and “cut and polished natural stone”, “concrete” and “Portland cement” are in the subsequent levels. The calculations have indicated that the least CO_2 emission is of “potable water” with the value of 14.1 and “clay”, “pumice” and “electricity” with the value of 258, 381 and 781 are in the next levels, respectively. In addition, the cumulative value of carcinogenic effect for construction materials in the characterization factor equals to 1940 kg C_2H_3Cleq. The major share is for the natural stone with the value of 458 and regular concrete, and bar are in the next level with the value of 296, 78 and 53, in the same order.

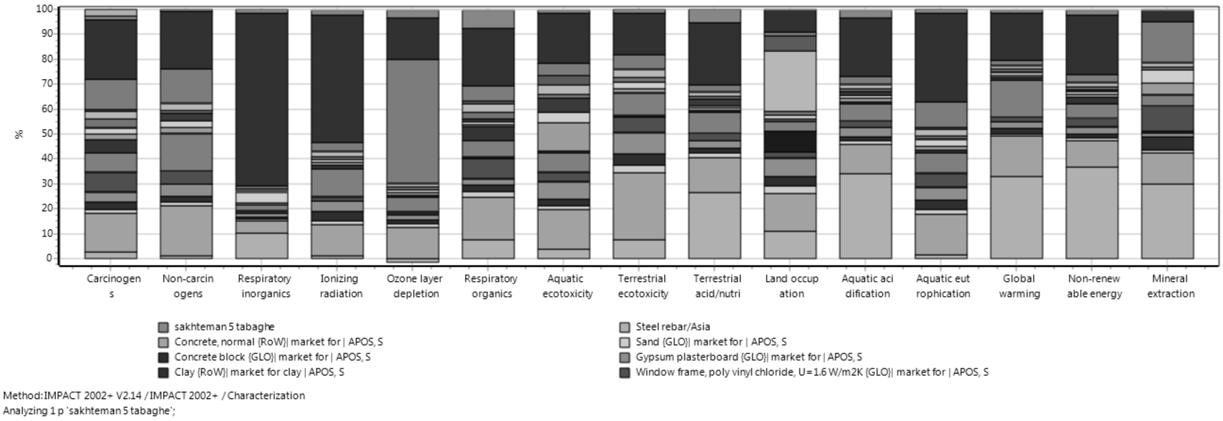


Figure 3. Midpoint impact effects of different building materials used in a residential building

Results demonstrate that cement has the maximum share of about 42% of ozone layer depletion, while loader operation has got the least share about nil from 0.0239 CFC-11 eq of total cumulative value. The freshwater ecotoxicity potential due to the construction materials indicated that the cumulative value in the characterization stage is 11,900,000 kg TEG water that the most contribution is for the regular concrete equal to 1,978,736 kg TEG. The least contribution is for potable water equal to 33,255 kg TEG.

The land occupation impact equivalent to the surface of land that is occupied by the building is usually less than that of the actual occupation surface of the construction. The results indicated that the land occupation impact of the construction materials is 5,200 m2org.arable that the most contribution is of the wooden entrance doors with the value of 1260 and concrete and bars are in the second and third level, with the value of 798 and 572, respectively. The least land occupation impact value is for the electricity equal to 104 and clay equal to 1,936.

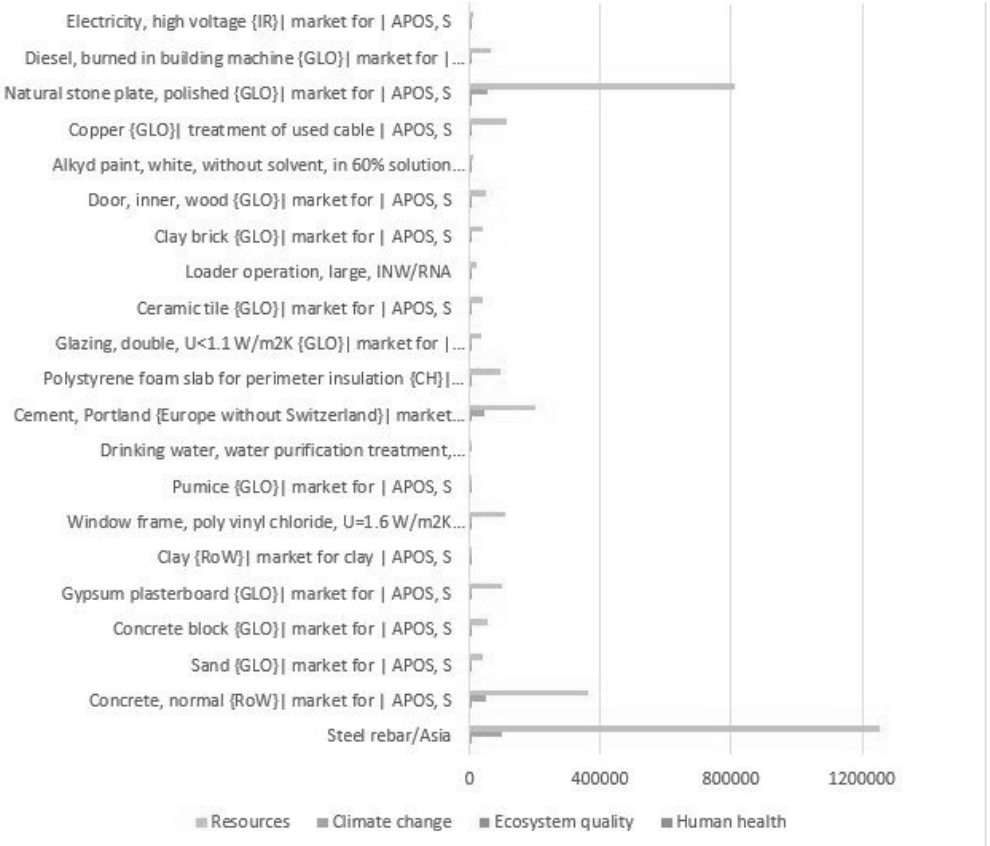


Figure 4. Endpoint impact effects of all materials used in a residential building

The analysis on the results of human health impact indicates that stone results in the highest impact equal to 0.366. The second and third highest impacts are for concrete and the bars equal to 0.028 and 0.054. In addition, the least human health impact is for the consumed water equal to 3.51×10^{-6} followed by electricity equal to 0.00049. The unit of human health impact is DALY representing the Disability Adjusted Life Years.

The other endpoint effect is related to the quality of the ecosystem and its unit is PDF×m^2×YR. The results indicate that the highest cumulative ecosystem quality impact is due to regular cement equal to 3.81×10^4 followed by extraction, cutting and polishing of natural stone and Portland cement with the values of 8.75×10^4 and 6.43×10^3. The least ecosystem impact is for potable water, electricity and clay with the values of 0.207, 49.06 and 136.41.

Among the selected impact indicators, the results of climate change indicator are highly important because it states the CO_2 emission directly. Regarding the high importance of climate change in this method, the indicator has been regarded both as a midpoint effect and an endpoint effect. Steel bars have gained the highest CO_2 equivalent emitters level among the building materials, which it rate stands at about 10^5 $KgCO_2eq$. Then, natural stone and concert have the next levels with the values of $5.6*10^4$ and $4.9*10^4$ $KgCO_2eq$, respectively. It is notable that potable water and clay have the least impact on climate change at the rate of 14 and 258 in the same order.

The results show that the highest impact to the resources is for bars with the value of 1.2×10^6 followed by the natural stone and Portland cement both with the value of 8.09×10^5. The least impact is for the potable water and electricity with the value of 59.57 and 1334.38.

Figure 5 indicates the normalized and weighted (with a common weighing factor) results. It can be seen that the highest impact of the building's construction process is the respiratory effect with the weight of 73.33. Also, this building has impact on climate change and non-renewable energy with about 30 and 22 normalized weights, respectively.

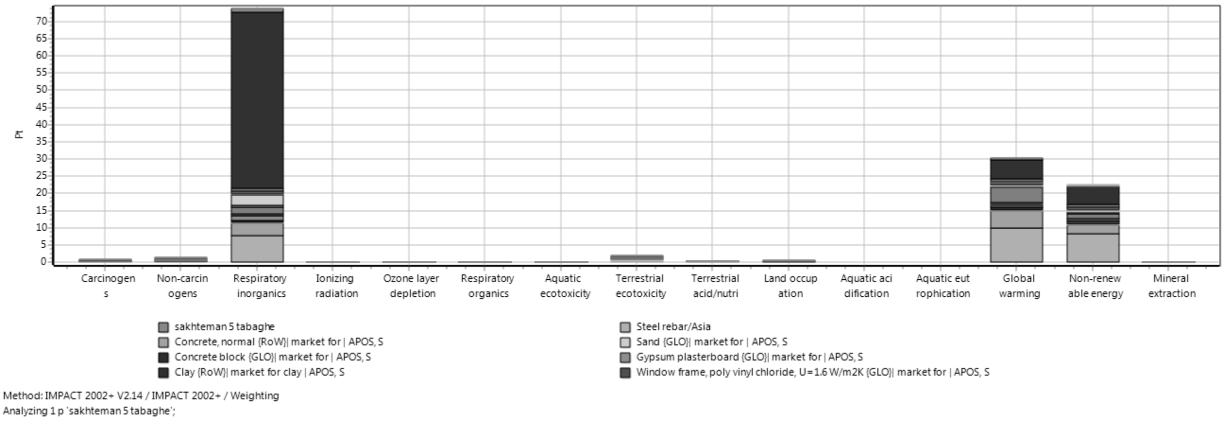


Figure 5. 15 different midpoint effects' score in terms of the system's inputs

The comparison of different building materials effects as single score in building LCA

There is a possibility to convert the environmental impact and input order in SimaPro to investigate the impact of each building material on human health, ecosystem quality, climate change, and resources. Figure 6 is obtained through this capability of the software.

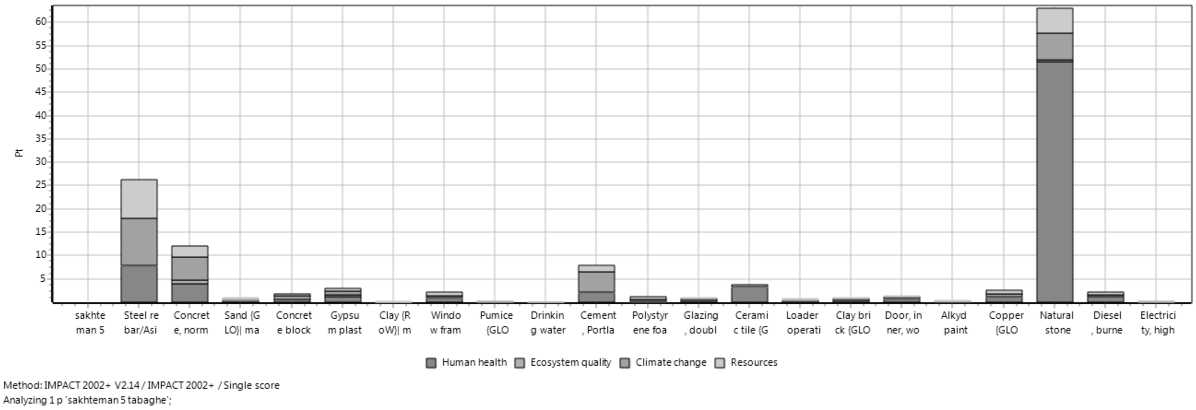


Figure 6. Building's LCA single

The highest impact is related to the impact of natural stone on human health with the score of more than 50. Also, natural stone has totally an impact of 68 on the environment in LCA. However, steel bar has the greatest adverse impact on climate change and resources with values of 20 and 15, respectively. Besides, concrete, natural stone and cement has almost the same impact on climate change at less than 10 level.

Steel bar, concrete and cement have the next ranks below natural stone regarding the impact on the environment in LCA investigations with the level of about 26, 14 and 8 in the same order.

The comparison of endpoint LCA effects of steel and concrete structure

For the comparison of endpoint effects for the two types of steel and concrete structure buildings, the results achieved by the impact assessment stage have been evaluated. The results indicate that human health effect for both of the structures is almost the same equal to 0.538 but regarding the ecosystem quality impact, the steel structure building with the impact score of 3.69×10^4 has a better position in comparison with the impact score of a concrete building with the value of 3.81×10^4. However, the evaluation of climate change indicator shows that steel structure buildings with the impact score of 3.82×10^5 have a more negative effect than the concrete buildings with the impact score of 2.99×10^5. Also, the resource impact indicates that steel buildings with the impact score of 4.31×10^6 have a higher adverse impact on the resource in comparison to the concrete buildings with the impact score of 3.42×10^6.

Conclusion

The current research was performed for life cycle analysis of materials and the construction and operation of concrete buildings in Tehran. So the needed data of consumed materials and energy and the operations of a five-floor concrete building in Tehran were collected then were analyzed by SimaPro software and the results were thoroughly evaluated. The main findings of this research can be summarized as:

- Steel bars has the highest share of CO_2 emission among other building materials with the share of 33%. The next main CO_2 emitters are natural stone and concrete at the rate of 18.5 and 16.3 percents, respectively.
- Copper and cement have the most negative impact on ozone layer depletion.
- Natural stone (23.7%), concrete (15.3%), and steel bar (2.7%) are the most carcinogens.

- Concert is the most important source of aquatic ecotoxicity with the rate of about 16% among other building materials.
- Natural stone, concrete and steel bar have got respectively the most negative impact on human health. While, their order regarding resources will be steel bar, natural stone and cement.
- Three building materials which have the most adverse impact on ecosystem quality are concrete, natural stone and cement.

Since a considerable share of CO_2 production in the studied building is due to concrete and cement, it is recommended that the cement is lessened through utilizing some filler materials such as fly-ash, red-mud, etc. In addition, since the cut natural stone has a large environmental impact in comparison to other materials, it is recommended to use composite, nano-composite, polymers and other materials instead. After a careful study of the environmental impacts of ore mines, preparing some regulations and instructions related to the production limits of such materials both for national use and also importing to other countries is highly recommended.

This research also analyzed the endpoint impacts (ecosystem quality, human health, resources and climate change) of concrete and steel structure buildings. It has been observed that the steel structure building has an inferior environmental position in comparison to the concrete structure one so that steel structure has 27% more adverse impact on the environment than concrete structure, for a same building. It can be due to the iron ore extraction, melting, transformation, rolling and welding processes.

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