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Life cycle assessment of a residential building in Egypt: A case study

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The present study discussed the significant environmental impacts of a residential building located in New Cairo, Egypt. This covered all life cycle steps from cradle to cradle with a projected 60-year life span: (i) an inventory of all the construction materials were analysed, covering the building structure as well as the energy consumption; (ii) three types of functional units were defined; (iii) the two top building materials were examined, and a sensitivity analysis was conducted to investigate the impact associated with the choice of building materials. The result shows that two life cycle phases concerning, manufacturing and operation, were more significant in all of the impact categories. It also shows that building structure and flooring result in most of the environmental loads. In terms of the sensitivity analysis, it was found the structural concrete had the largest impact, dominating all selected impact categories except ODP. Finally, limitations and challenges are discussed to explore better design decisions for selecting buildings' structural systems in future studies.

Keywords: Environmental impact assessment, Life cycle analysis, Residential building, Tally plugin.

1. Introduction

In 2018, United Nations Environment Programme reported that the buildings worldwide are responsible for 40% of the world's total energy use, 25% of global water, 40% of global resources and they emit about one-third of greenhouse gases emissions, thus witnessed a prioritization to reduce the environmental impact on the built environment [1]. Saving energy in buildings has various benefits including reducing costs, increasing the security of supply and saving the environment [2]. Buildings account for 19 % of energy-related CO_2 emissions, 32 % of global energy use and 57 % of world electricity consumption, according to the report of the Intergovernmental Panel on Climate Change. Thus, buildings are one of the most significant infrastructures in modern society in terms of their energy consumption. The residential and commercial buildings contributed towards 41.1% to total primary energy consumption, because of their operation to primary energy use, 74% to electricity consumption, and 40% to CO_2 emissions [3]. Also, it is found that for the greenhouse emissions related to buildings, 40–95% of these emissions are caused by the operational energy use, with the remainder being caused by the construction and demolition processes. Yet, buildings also offer the greatest potential in developing countries to achieve significant reduction of emissions of GHGs. In addition, the consumption of energy in buildings can be reduced by proven and commercially available technologies about30 to 80 percent [1].

Any change in the structural system plays a role in the environmental impact assessment. Hence, this study aims at studying the environmental impact of concrete structural systems in residential buildings. Accordingly, the method adopted is; 1) compiling an inventory for the building's structural system and its energy consumption, 2) estimating environmental loads in several impact categories through life cycle stages, construction elements and conducting a sensitivity analysis of the two main construction materials within the building's life cycle.

2. Reviewing previous literature

It presents a recent review of the literature on Science Direct database covering the period 2000-2020. This literature review provides an overview of the Life Cycle Analysis and its application in the building industry.

2.1 Life cycle assessment framework

Life cycle assessment (LCA) is a technique for evaluating the environmental aspects and potential impacts associated with a product's life cycle from acquisition raw material to final disposal [4]. It yields reliable assessment results which practitioners may reply on for the decision-making process on both the building and urban levels [5]–[7]. The Life Cycle Assessment includes four phases: the goal and scope definition, life cycle inventory (LCI), impact assessment, and interpretation of results.

The goal and scope definition represents the functional unit, system boundaries, and the quality criteria for the inventory data. The life cycle inventory analysis (LCIA) is analyzing the inputs and outputs for a product are compiled and quantified for its life cycle. Finally, in respect of the defined objective and scope, the life cycle interpretation phase contains results of either the inventory analysis or the impact assessment (or both). Previous studies have followed the environmental impact categories characterization scheme reported by the 'Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts' (TRACI) 2.1, developed by the United States Environmental Protection Agency (US EPA) to quantify environmental impact risk associated with emissions [8]–[10].

There have been various studies on complete LCAs as Ramesh, Prakash, and Shukla (2010) reviewed the life cycle energy analyses of 73 cases across 13 countries. It was found that the life cycle energy demand of office buildings varies from 45 GJ to 99 GJ per gross floor area over 50 years with 10-20% for embodied energy and 80-90% for operational energy. Also, Itard (2009) presented the results of an energy flow investigation, based on LCA considerations, on the relative values of embodied and operational energy of dwellings and dwelling renovation. The result after comparing the primary operational energy use and the new-built variants with the primary energy embodied in the variant itself showed that the embodied energy (EE) in renovation variants is very low, opposite to the EE in "low energy" new-built that can amount up to 60 years of operational energy use. Furthermore, the cumulative energy demand (CED) and the global warming potential (GWP) have examined by Bawden and Williams (2015), for a portfolio of 10 low, mid and high-rise multi family residences. The CED is increasing from 30, 34, to 39 GJ/m^2 for low, mid and high-rise multi-family residences, respectively and GWP is found to increase from 1.8, 2.2, to 2.5 CO_2eq/m^2, respectively. As well as another study by Gong et al. (2012) who compared the total life cycle energy and greenhouse gases (GHG) emissions of three multi-family residences of similar size but varying in commonly used framing materials (wood, steel and concrete). The ratios of energy consumption of concrete framework construction (CFC), light gauge steel framework construction (SFC) and wood framework construction (WFC) to that of the life cycle in the embodied materials phase are 13%, 23%, and 27%, respectively, and the ratios in the operation phase are 87%, 76%, and 71%, respectively.
The study also showed through the life cycle, the energy consumption of CFC is almost the same as that of SFC, and each of them is about 30% higher than that of WFC. Moreover, Lu et al. (2017) compared quantitative measurement for the environmental impact of using (engineered wood, concrete and steel) along 1m section of a structural beam in a continuous beam system with 6 m spans. The GWP of concrete had the greatest environmental burden (17.43 kg CO_2-eq), mainly due to significant transportation, fossil fuel consumption as well as the use of energy-intensive materials during the manufacturing process. The steel has reached (12.83kg CO_2-eq), so it has better environmental performance due to its lighter weight, which led to a reduction in the energy and material consumption, as well as transportation while the engineered wood beam had much better performance on GWP of (5.22kg CO_2-eq). Furthermore, Xia, Ding, and Xiao (2020) reviewed the reuse and recycling strategies for the design for deconstruction (DfD) and recycled aggregate concrete (RAC). The results were when applying only one strategy; the maximal impact indicator reductions induced by DfD are 1.8–2.8 times compared to that by RAC. When applying two strategies simultaneously, the benefit of either DfD or RAC shall decline compared to that of the corresponding strategy applied alone, but the overall benefits shall increase. The study also showed that using fully reusable structure with 100% (RCA) replacement of the conventional design will achieve the maximal environmental benefits, with percentage, 15.0% and 13.3% reductions for GWP and ADP, respectively

It is noted that the previously referenced studies describe various environmental loads and energy consumption for residential and commercial buildings worldwide, nevertheless, there is a lack of studies in Egypt. Hence, this study applies LCA for a residential building in New Cairo, Egypt.

3. Methodology

The research method follows three consecutive stages; 1) designing a solid slab structural systems and compiling an inventory of materials for an LCA, 2) developing 3D modelling for the structural building design and 3) integrating Revit 3D modelling and Tally environmental impact Plug-in, to define materials in the Tally plug-in for measuring the Life Cycle Categories according to TRACI 2.1 characterization scheme in the construction stage.

3.1 *Developing a Revit Structural 3D-Model*

This 3D model allows for the visualization and coordination of building components into an early design process that will dictate changes and modifications to the actual process of construction. This aims at obtaining an accurate estimate of material quantities for all structural elements in the building to be able to use the environmental impact assessment plug-in. The concrete solid slab 3D structural system model applied, and its plan view shown in figures (1&2).

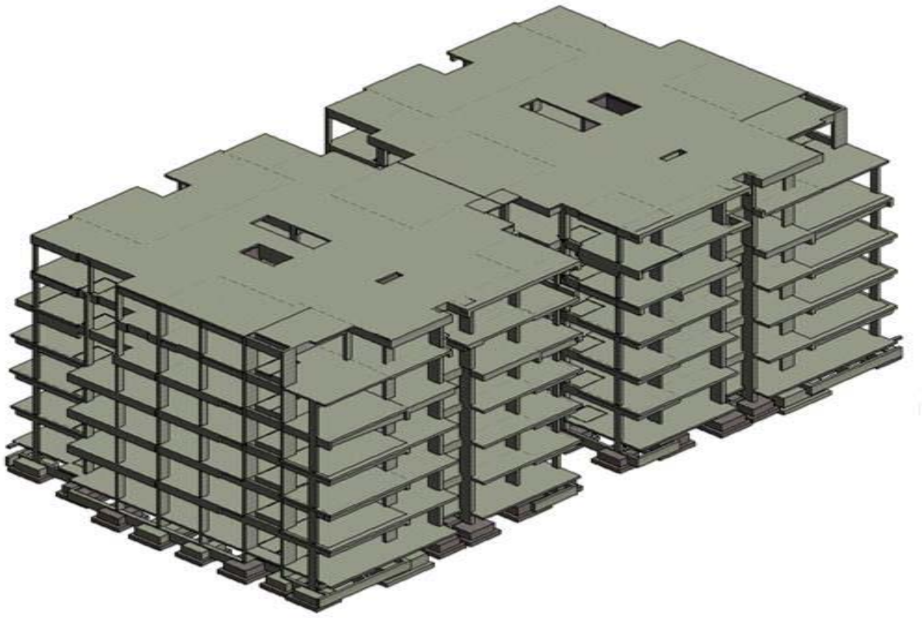

Figure 1. 3D view of the Concrete Structural Building

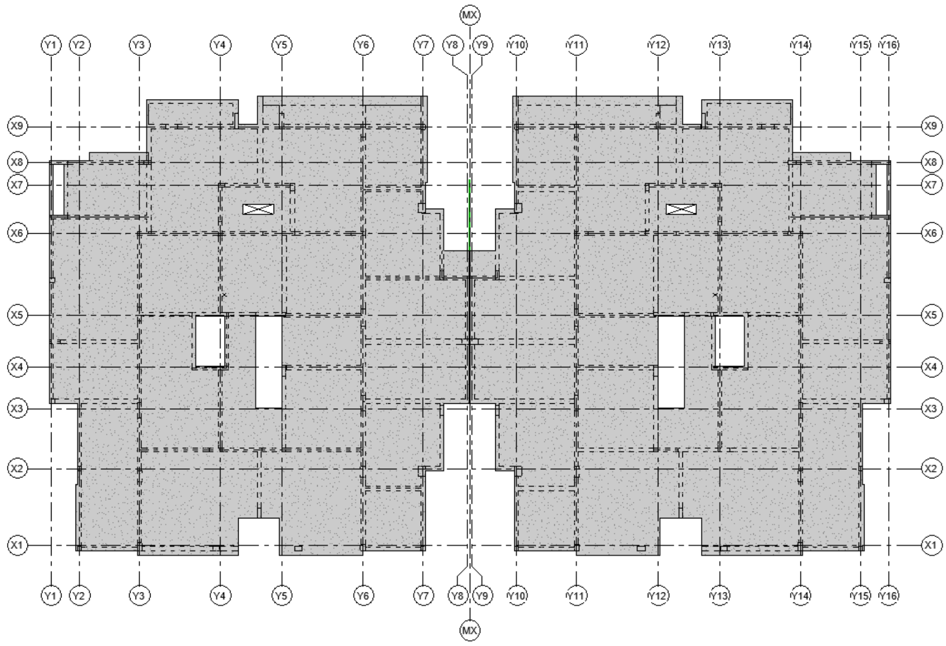

Figure 2. Plan view for the Concrete Structural Building

3.2 Tally Environmental impact assessment

The Tally plugin is integrated with Revit 3D structure model to allow the user to assign materials from its environmental product database to the BIM software; so, the user can view and follow the embodied environmental impact results based on the material selection decision-making process.

In this study, the system boundary in Tally plugin was defined as the process beginning from resource extraction and manufacturing of building products, to site preparation and the construction process, then moving to the operating energy and maintenance phase, the building demolition process and ending with recycling or reusing materials. Table (1) shows the system boundary defined for this study. To evaluate the goal and scope of LCA for residential buildings, it is essential to determine the functional unit. In building research there are several functional units for LCA. In this study, the functional equivalent is introduced as the square meter size of residential areas with a 60-year life span according to the Athena Sustainable Materials Institute (2016). In regard to the purpose of the building and the functions that it serves; the functional unit can be broken down into:

- Total impacts through building life cycle
- Total impacts per construction elements
- Total impacts per construction materials

Table 1. Life-Cycle Stages as defined by EN 15978, source [16]

<table>
<tr><td colspan="16">Building life cycle</td><td>Supplementary information (Module)</td></tr>
<tr><td colspan="3" rowspan="2">Product / Manufacture Stage [A1-A3]</td><td colspan="2" rowspan="2">Construction Process Stage [A4-A5]</td><td colspan="7">Use stage [B1-B7]</td><td colspan="4" rowspan="2">End-of-life Stage [C1-C4]</td><td rowspan="2">Benefits and load beyond the system boundary</td></tr>
<tr><td colspan="5">Building Fabric</td><td colspan="2">Operation of the Building</td></tr>
<tr><td>A1</td><td>A2</td><td>A3</td><td>A4</td><td>A5</td><td>B1</td><td>B2</td><td>B3</td><td>B4</td><td>B5</td><td>B6</td><td>B7</td><td>C1</td><td>C2</td><td>C3</td><td>C4</td><td>D</td></tr>
<tr><td>Raw materials supply</td><td>Transport</td><td>Manufacturing</td><td>Transport</td><td>Construction</td><td>Use</td><td>Maintenance</td><td>Repair</td><td>Replacement</td><td>Refurbishment</td><td>Operational energy use</td><td>Operational water use</td><td>Demolition</td><td>Transport (to disposal)</td><td>Waste processing</td><td>Disposal</td><td>Reuse
Recycling
Energy recovery</td></tr>
<tr><td colspan="3">Cradle-to-Gate</td><td colspan="13">Gate-to-Grave</td><td rowspan="2"></td></tr>
<tr><td colspan="16">Cradle-to-Grave</td></tr>
<tr><td colspan="17">Cradle-to-Cradle</td></tr>
</table>

In the life cycle impact assessment stage, seven impact categories have been selected: Acidification Potential (AP) (kg SO_2eq), Eutrophication Potential (EP) (kg Neq), Global Warming Potential (GWP) (kg CO_2eq), Ozone Depletion Potential (ODP) (kg CFC-11eq), Smog Formation Potential (SFP) (kg O_3eq), Primary Energy Demand (PED) (MJ), Non-Renewable Energy Demand (NRED) (MJ) and Renewable Energy Demand (RED) (MJ).

It is noted that the following life cycle processes are excluded from this study:

- The transportation to factory and transportation to disposal.
- Personnel- related activities (accessories, furniture, office supplies).
- Energy and water use related to company management and sales activities, which may be located either within the factory site or at another location.

3.3 *Description of the case study building*

The case study is a residential building in New Cairo. It consists of a ground and 5 floors with clear height for each floor equals 2.70 m. The building is under construction, the statically system was solid slab concrete structural system with various thickness (12-25 cm), the beams and columns were with several cross sections. The isolated and combined footing were linked by grade beams. the external view of the building shown in Figure (3). The case-study building has a total gross area 8676.25 m^2. Each floor level has 8 apartments with 3 bedrooms per apartment, two living-room areas, four bathrooms, a kitchen and a balcony (terrace) across the private garden of the building. In addition, the information on residential energy consumption was provided by Electrical Egyptian code, including the consumption of electricity 10 Kilo-volt ampere KVA for luxurious residential. The total consumption of electricity approximate was 281,880 annual kilowatt-hour kWh. On-site construction using 2 generators with capacity 100 (KVA) for each, so the total electricity uses 1,800 (KWh). These two data were taken into Tally plugin as factors of energy usage.

Figure 3. Front view of the case study.

3.3.1 Description of the construction materials

3.3.1.1 Reinforced Concrete

The concrete structural system was designed based on The Egyptian Code for Design and Executing Reinforced Concrete Structures. A bill of Materials report was produced by the Revit structure quantities takeoff sheet. The largest amounts of materials used in concrete solid slab structural system were concrete and steel reinforcement rod in floor elements 1,456.22 m^3 and 179,719.9 kg, respectively. Further information regarding the quantities of each material is shown in Table (2).

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Table 2.Material quantities for each element in the Solid slab concrete structural system model.

The reference unit	Concrete solid slab structural system Elements		Quantitative (m^3) or (kg)
Materials required	Structural concrete, 3001-4000 psi, 0-19% fly ash and/or slag	Rectangular-Footing + Combined footing	770.98 m^3
		Combined footing Plain concrete	75.34 m^3
		Rectangular-Column	305.53 m^3
		Rectangular Beam & smells	541.43 m^3
		Floors	1456.22 m^3
		Core	73.98 m^3
		Shear walls	49.44 m^3
	Steel, reinforcing rod	Rectangular-Footing + Combined footing	22448.1 kg
		Rectangular-Column	76,991.70 kg
		Rectangular Beam	136,435.3kg
		Floors	179719.9 kg
		Core	5442.4 kg
		Shear walls	3637.6 kg

The LCI data on concrete is sourced in accordance with GaBi databases and modelling principles. Reinforced concrete grade in the project is with cubic characteristics strength of 25 N/mm^2. Ordinary Portland cement (Type I) has been used in the project. Cement is designed in accordance with the Egyptian Standard Specifications (ESS) 373, ESS. 541. Reinforcing bars satisfy the E.S.S 262-1974 for grades 24/35 & 36/52. Also, Table (3) provides a list of the building characteristics and the scope boundaries for each material in different stages of the LCA for solid slab concrete structural systems.

Table 3. The data describing scope boundaries for Concrete structural system

Material Name	Cast-in-place concrete, structural concrete, 3001-4000 psi	Steel, reinforcing rod
Description	Structural concrete, 3001-4000 psi, 0-19% fly ash and/or slag. Mix design matches the National Ready-Mix Concrete Association (NRMCA) Industry-wide Environmental Product Declaration (EPD).	Common unfinished tempered steel rod suitable for structural reinforcement (rebar)
Used in	All structural elements as (Foundation, Floors, Columns…etc.)	All structural elements as (Foundation, Floors, Columns…etc.)
Life Cycle Inventory	16% Cement, 7% Batch water 44% Coarse aggregate, 33% Fine aggregate	100% Steel rebar
Product Scope	Cradle to gate, excludes mortar Anchors, ties, and metal accessories outside of scope (<1% mass)	Cradle to gate
Transportation Distance	By truck: 24 km	By truck: 24 km
End-of-Life Scope	55% Recycled into coarse aggregate 45% Landfilled (inert material)	70% Recovered 30% Landfilled (inert material)
Module D Scope	Avoided burden credit for coarse aggregate, includes grinding energy	Product has a 16.4% scrap input while the remainder is processed and credited as avoided burden.
Service life	60 Years	60 Years

4. Results

A comprehensive LCA was carried out for a residential building in New Cairo, Egypt. The study included the entire life cycle of the building, including the manufacturing, construction, operating energy, maintenance, end-of-life and module D phases.

4.1 The results per building life cycle

The results show that the highest environmental impacts during the building's life cycle occurred during the operating energy phase, was approximately 62%–98% (except for the ODP), while product stage was approximately 16%-34% (except for the ODP was 70%), end of life was approximately 1%-4%. The construction phase and the last life cycle phase, module D, clearly had a lesser impact, less than 0.3% to -2%, respectively in all of the studied categories. This ratio corresponds with the study carried by Zhang et al. (2014) which computed the environmental impact of a residential building located in Vancouver, Canada. The study indicated that two life cycle phases had the greatest impact, these were; manufacturing and operation, with approximately 7%-51% and 30%-90%, respectively, while the end of life stage caused less than 1% impact in all of the studied categories.
The GWP in operation stage for this case study, was 7.05 E106 kgCO_2 eq, so the GWP was 1.19 per square meter. These results are consistent with the results of Bawden and Williams (2015) who examined the total life cycle energy, and GWP for a portfolio of 10 difference family residences. The GWP is found to increase from 1.8, 2.2, to 2.5 CO_2eq/m^2 for low, mid-rise and high-rise buildings, respectively. The proportion of the embodied energy and operation energy in the case study was 10-17% and 80-90%, respectively. This is similar to Ramesh, Prakash, and Shukla (2010) and (Wang, Yu, and Pan (2018) who analyzed the life cycle energy with 50 years and found that it was 10-20% for embodied energy and 80-90% for operational energy. The result of the environmental impacts of the model is shown in Fig. (4).

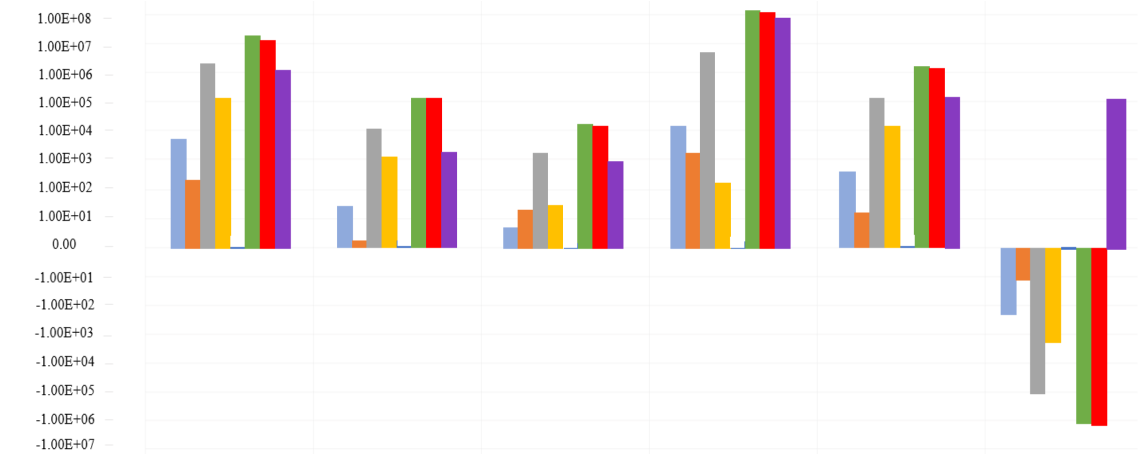
4.2 The results per construction elements

The 3D Revit model includes floors, walls and the structural system (foundations, columns and beams). The results of environmental impact comparing these elements are shown in Figure. (5). This shows that the structural elements of the building dominate the high values of all environmental impact; with 3.71E+03 (kg SO_2eq), 2.09E+02 (kg Neq), 1.09E+06 (kg CO_2eq), 6.59E+04 (kg O_3eq) and 1.14E-3 (kg CFC-11eq). The Primary Energy Demand presented 1.14E+07 (MJ); of which the non- renewable energy is responsible for 1.06E+07 (MJ) and renewable energy with 7.83E+05 (MJ). The structural elements were responsible for approximately 7%-24% more than of other elements as walls and floors, with a total mass of 3.93E+06. Furthermore, These results are consistent because an assembly that uses more materials would, therefore, have more environmental impacts than other assemblies as stated by Zhang et al. (2014) who found that walls which have a huge quantity, thus they have a total GWP of approximately 30,948 kg CO_2 eq and a total fossil-fuel consumption (FFC) of about 434,571 MJ, which is the highest of the assemblies.

4.3 The results per construction materials

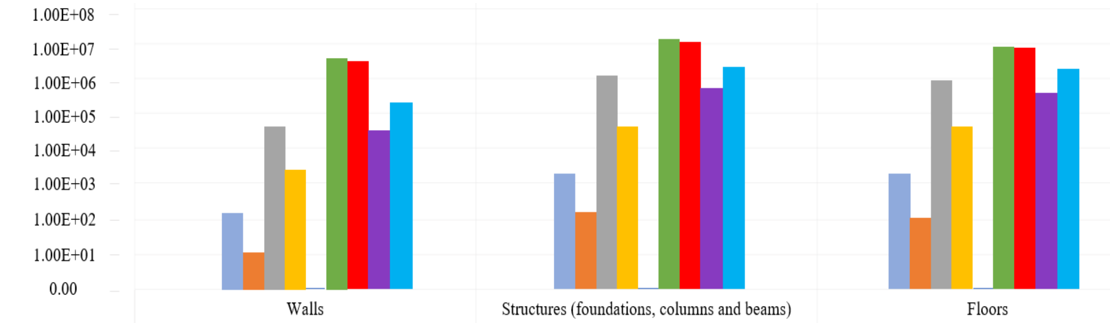
Then a sensitivity analysis is performed to help stakeholders decide which material has the greatest impact on the environmental performance of a building. Using the analysis results shown in Fig. (6), designers could choose to reduce the amount of these materials in the building or find substitutes that have fewer environmental impacts.
This shows that the reinforcement concrete has the highest contribution for all environmental categories (except ODP) because of the amount of concrete with 7.2*106 kg, which it represents an increase of 17.2 over steel reinforcing rod quantity. That mainly due to significant transportation, fossil fuel consumption as well as the use of energy-intensive materials during the manufacturing

process that compatible with studied of Lu et al. (2017). The structural concrete has 4.04E+03 (kg SO2eq), 3.18E+02 (kg Neq), 1.51E+06 (kg CO2eq), 9.19E+04 (kgO3eq), 1.24E+07 (MJ) for non-renewable energy demand and 9.94E+05 (MJ) for renewable energy demand. The structure concrete represents an increase of 1.35, 3.69, 2.57, 2.65, 1.59, 1.98 over steel reinforcing rod for AP, EP, GWP, SEP, NREP and RED, respectively.



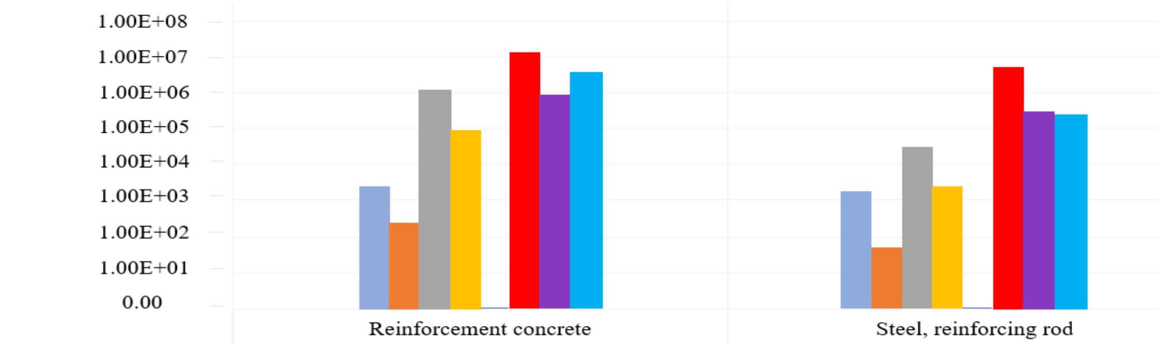
	Product	Transportation	Construction	Operational energy	End of life	Module D
AP	6.69E+03	4.68E+01	7.28E+00	1.76E+04	6.92E+02	-3.88E+02
EP	3.81E+02	3.81E+00	3.07E+01	1.84E+03	3.51E+01	-1.51E+01
GWP	2.15E+06	1.01E+04	1.54E+03	7.05E+06	1.50E+05	-2.17E+05
SEP	1.16E+05	1.55E+03	4.84E+01	2.10E+05	1.38E+04	-4.24E+03
ODP	3.64E-03	3.46E-10	7.96E-10	8.88E-06	2.75E-08	1.58E-03
PED	2.09E+07	1.47E+05	2.74E+04	1.81E+08	2.56E+06	-1.89E+06
NRED	1.97E+07	1.43E+05	1.82E+04	1.02E+08	2.40E+06	-2.01E+06
RED	1.20E+06	3.55E+03	9.21E+03	7.98E+07	1.69E+05	1.19E+05

Figure 4.Distribution of the environmental impacts of the building life cycle studied.



	Walls	Structures (foundations, columns and beams)	Floors
AP	2.21E+02	3.71E+03	3.11E+03
EP	1.41E+01	2.09E+02	1.81E+02
GWP	7.09E+04	1.09E+06	9.34E+05
SEP	4.29E+03	6.59E+04	5.64E+04
ODP	4.45E-05	1.14E-03	8.77E-04
PED	6.96E+05	1.14E+07	9.60E+06
NRED	6.47E+05	1.06E+07	8.94E+06
RED	4.92E+04	7.83E+05	6.64E+05
Total mass (kg)	2.90E+05	3.93E+06	3.48E+06

Figure 5. Distribution of the environmental impacts of different building components.



	Reinforcement concrete	Steel, reinforcing rod
AP	4.04E+03	3.00E+03
EP	3.18E+02	8.62E+01
GWP	1.51E+06	5.87E+05
SEP	9.19E+04	3.47E+04
ODP	2.71E-07	2.07E-03
NRED	1.24E+07	7.78E+06
RED	9.94E+05	5.02E+05
Total mass (kg)	7.28E+06	4.23E+05

Figure 6. Distribution of the environmental impacts of concrete structural systems materials

5. Conclusion

This study performed an LCA for a residential building in New Cairo, Egypt. This research evaluated and analyzed adverse environmental impacts through the building life cycle. The operating energy phase alone produced more than half of the total environmental impacts, with a share of approximately 60%-76% for concrete structural elements. Another significant life cycle phase was manufacturing, with a share of approximately 18 to 34% of total impacts. A breakdown of the building components indicated that the structure element (foundation, columns and beams) and floor element resulted in significant environmental impacts in the given impact categories. Moreover, according to the sensitivity analysis, the concrete was the most critical construction material; not only in terms of consumed quantities, but also in the associated environmental impact categories.

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