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Life Cycle Assessment and Sustainable Building Materials

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Abstract:

Trending to green and sustainable buildings became inevitable during the increasing crises of global current lack of resources and energy besides all forms of pollution. Architects play an important role in reducing the environmental impact of their buildings through a good understanding of the negative impact of construction process during full life cycle and how to reduce it. Selecting materials and products for a high performance building is not an easy task as there are a lot of considerations and criteria for comparing the available options. This paper focuses on Life Cycle Assessment (LCA) as a method to evaluate the environmental impact related to building materials at different stages and how to assess and compare it with alternatives based on its environmental efficiency. The paper also includes a practical study conducted by the researcher using LCA tool to assess and compare two optional designs of two residential buildings with different structure systems, reinforced concrete and load bearing walls, depending on their environmental impact to prove that applying LCA in early design phase can make a difference in building design and the selection of building materials.

Keywords: Sustainable Materials, Life Cycle Assessment, Materials Efficiency, Eco-efficient materials, Environmental impact of building materials

1. Introduction

Global estimations about the use of materials increased eight-fold in the last century and that current usage is almost 60 billion tons (Gt) of materials per year [1]. Globally, construction sector depletes 40% of natural materials, consumes 40% of the total primary energy and 15% of the world's fresh water resources, generates 25% of all wastes and emits 40–50% of GHG [2], and it is expected to continue growing rapidly. Worries about these rates and the negative impact resulting from the increasing use of materials and resources have recently started.

Building materials play an important role in enhancing the overall performance of a building and achieving the goal of sustainable construction. The selection of materials and products for high-performance green buildings has been a big challenge; as efficient choice of materials should meet the needs of current and future generations in addition to reducing the environmental impact on human health and ecosystem. The environmental impact of the construction process starts with the extraction of raw materials, then manufacturing, installation, operation (use) and maintenance till the end of building life (disposal/reuse/recycle) including transportation in every stage and all of that is called life cycle of a building. Thus construction is not an environmental friendly process due to resources depletion, energy consumption and different emissions that affect humans and ecosystem.

To reduce these environmental impacts, the design and selection of building materials should be based on scientific methodologies as they affect the comfort and health of building users and the environment in general. The selection should not only be based on the material performance but also the environmental impact.

Architect role in reducing the environmental impact of the building starts from the initial design phase where some factors should be put in mind and can be summed up as follows:

- Reduce the use of materials and resources as much as possible.
- Use the Life Cycle Assessment (LCA) to understand and evaluate the environmental impact of a building.
- Enhance the principles of Reuse and Recycle to close material loop.

Architects need methodology and tool to help them during design phase and provide them with environmental data about products and materials as well as assessment methods. Built environment assessment tools are currently classified as into two groups [3]:

1. Qualitatively based building rating systems.
2. Quantitative tools using a physical life cycle approach with quantitative input and output data.

Quantitative tools like LCA can be the most accurate as environmental data of building materials and products (primary energy, different types of emissions, water use……etc.) are available to the architect as well as appropriate impact assessment and weighting methods.

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2. Environmental Impact of Construction and Building Materials

The construction industry is one of the largest users of both renewable and non-renewable natural resources without concerning of the environmental impact associated with construction activities and its negative effects on resources, ecosystem and human health. In the meantime of current natural resources and energy crisis, sustainable design trend is the solution.

The selection and use of sustainable building materials play an important role in the design and construction of green building. The selection should not only focus on the performance, but also environmental aspects to understand all the negative effects related to materials selection and minimize it as much as possible.

The environmental impact of construction and building materials can cause damage to each of resources, ecosystems and human health as shown in (Fig.1).

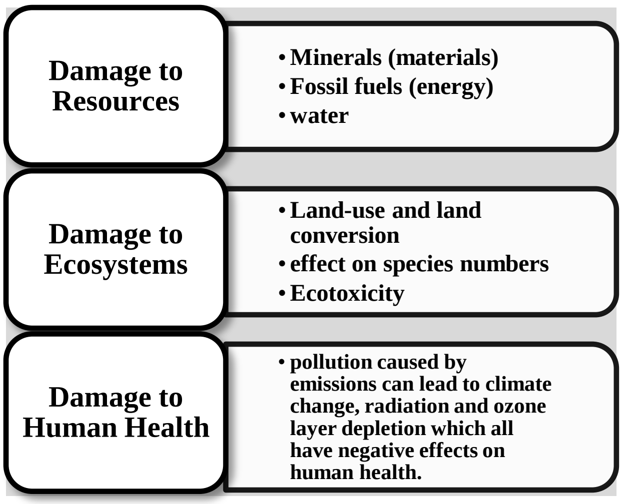


Figure 1: different damage types caused by construction process.

3. Sustainable Building Materials

Building products or materials have an extensive impact on the environment on every stage. The resourcing of materials, their manufacturing processes, Installation, transport requirements, use and final disposal (see Fig.2) can involve wide-reaching environmental and social damage, including global warming, pollution, depletion of natural resources, destruction of natural habitats, extinction of plant and animal species, waste production and health problems.

Green building materials are defined as: “those that use the Earth’s resources in an environmentally responsible way” [4].

Sustainable building materials: are materials related to resource and energy efficiency in the manufacturing process and that these materials should pollute less and have no negative impact on human health [5].

Choosing the right materials, products and components for a building is not an easy mission under any circumstances.

To make the right decision on selecting building materials, products or components, architect or decision maker should concern about the whole life cycle (see Fig.3).

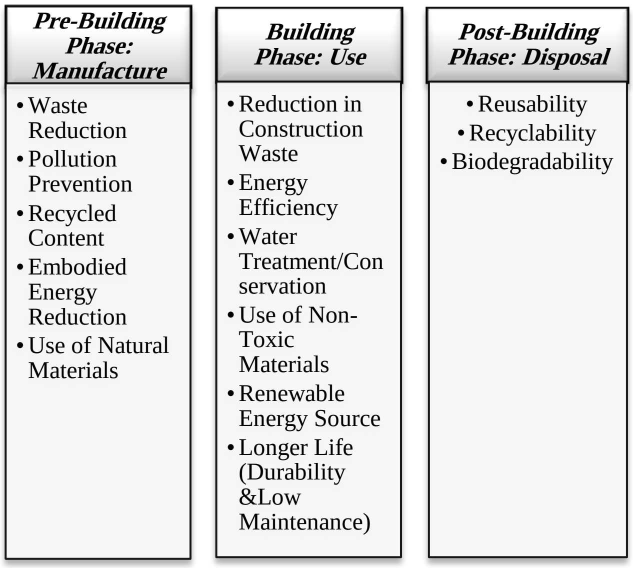


Figure 3: green features of sustainable building materials. [6]

Sustainable building materials are related to the following criteria [7]:

• Resource efficiency.

• Energy efficiency (including initial and recurrent embodied energy, and GHG emissions).

• Pollution prevention (including indoor air quality).

Selecting appropriate materials for a building is the key to good design. Methodologies and tools have been developed to optimize material selection depending on physical and mechanical properties, also by taking account of environmental considerations and focusing on achieving sustainability goals to minimize impacts on the environment.

Figure 2: The various stages of building materials.

4. Life Cycle Assessment (LCA)

As the architectural and construction industries walk forward to achieve sustainability, a lot of methods, tools and rating systems are being developed to help assess and reduce the environmental impact. The most appropriate and accepted method used to produce a whole assessment of the environmental impacts associated with a building and building materials is the LCA.

The primarily formalization of LCA standards in the ISO 14000 series was in 1997 through 2002 and the launch of the Life Cycle Initiative, a combined effort by United Nations Environment Programme (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC), was in 2002.

4.1.Definitions of Life Cycle Assessment (LCA)

According to International Standard ISO 14040 LCA is a *"compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle."* [8].

The Code of Practice by the Society of Environmental Toxicology and Chemistry (SETAC) describes LCA as *"process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and materials used and releases to the environment; and to identify and evaluate opportunities to affect environmental improvements. The assessment includes the entire life cycle of the product, process or activity, encompassing, extracting and processing raw materials; manufacturing, transportation and distribution; use, re-use, maintenance; recycling, and final disposal."*(see Fig.4) [9].

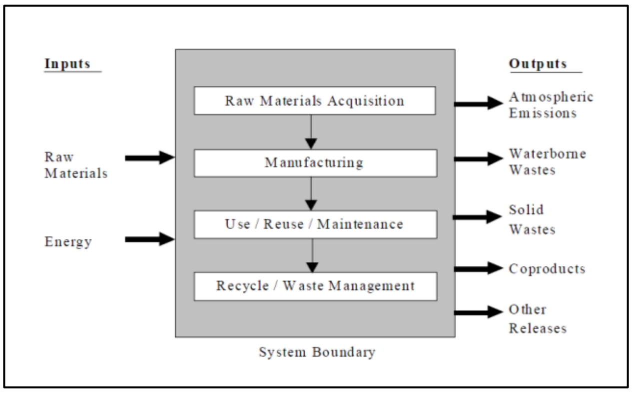
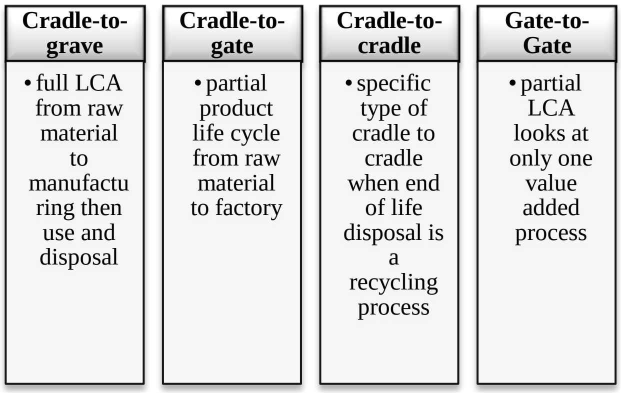


Figure 4: Life cycle stages. [10]

4.2.Variants of Life Cycle Assessment (LCA)

The scope of LCA can extend to various stages and processes in a product's life. Depending on the purpose of conducting the LCA, there are numbers of options to be considered. LCA methods implemented in the building construction industry can be one of the following [11]:



4.3.Four Steps to Make Life Cycle Assessment (LCA)

According to ISO 14040, LCA consists of four components or steps (see Fig.6):
Step 1: **Goal and Scope Definition**
Step 2: **Inventory Analysis**
Step 3: **Impact Assessment**
Step 4: **Interpretation**

4.3.1 Step 1: Goal and scope definition

Goal definition and scoping is the phase of the LCA process that defines the purpose, method, the type of analysis, impact categories to be evaluated, system boundary and set of data that needs to be collected are identified of including life cycle environmental impacts into the decision-making process [10].

4.3.2 Step 2: Inventory analysis

Inventory Analysis can be defined as the step which identify and quantify all the inputs (energy, raw materials, and water) and the outputs (air emissions, solid waste disposal, waste water discharges) also different types of land use for the entire life cycle of a product, process, or activity (see Fig.5) [12].

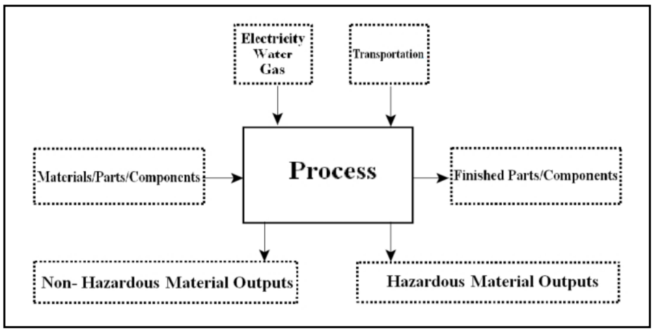


Figure 5: Flow diagram example for a process. [12]

4.3.3 Step3: Impact assessment

The Life Cycle Impact Assessment (LCIA) is the third phase of Life Cycle Assessment (LCA) process. The impact assessment translates the emissions from a product or process into impacts on eco-system, human health and also on resources. Besides, this helps in understanding the impact by its effect on human health, environment and resources.

4.3.4 Step 4: Interpretation

Life cycle interpretation is the last phase of the LCA process. In this phase the results are reported in the most informative way possible and evaluated.

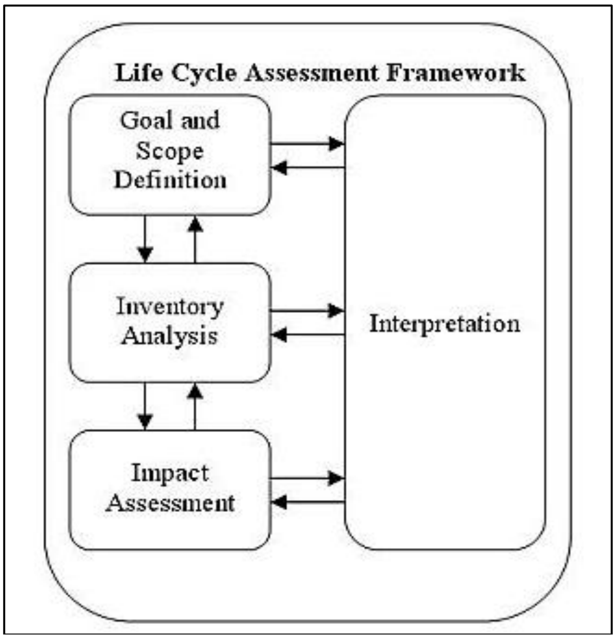


Figure 6: Life cycle assessment steps according to ISO 14040. [12]

4.4.LCA Impact Categories

The impact categories of LCA methodologies vary from system to system. Environmental impact categories are mappings from amounts of emissions to the environmental impacts that these emissions cause.

The impact categories have been established from nationally recognized standards established by agencies like the Environmental Protection Agency (EPA), Occupational Safety and Health Administration, and National Institutes of Health. Each category is an indicator of the contribution of a product to a specific environmental problem. These categories are defined by the Life Cycle Impact Assessment (LCIA) methods presented in Table 1.

Table 1: Commonly used Life Cycle Impact Categories. [13]

Impact Category
Global Warming Potential (GWP)
Ozone Depletion
Acidification Potential (AP)
Eutrophication
Photochemical Smog
Ecological Toxicity
Human Health
Resource Depletion
Fossil Fuel Depletion
Land Use
Water Use

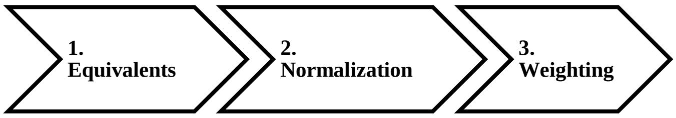
4.5.Life Cycle Impact Assessment (LCIA) Method

The Life Cycle Impact Assessment (LCIA) phase of an LCA is the evaluation of potential human health and environmental impacts of the environmental resources and releases. Impact assessment should address ecological and human health effects; it should also address resource depletion [13].

Several methods are used to convert the inventory analysis results into environmental impacts. Some commonly used methods are:

Eco-indicator 99	**EDIP 1997**	**IMPACT 2002+**	**TRACI**

The basic structure of impact assessment methods: [11]



4.5.1 Equivalents

A wide range of emissions may contribute to give one impact category. The summation of the different chemicals, multiplied by their equivalence values, leads to one Impact Category.

4.5.2 Normalization

Normalization is a technique for changing impact indicator values with differing units into a common unit. This is achieved by dividing the impact category value by a selected reference quantity [11].

4.5.3 Weighting

The weighting step is the evaluation step. Different impact categories can be compared based on their importance and their effect on environment and human health [14].

4.6.LCA Tools

An LCA tool can be defined as environmental modeling software that presents life cycle inventory (LCI) and perhaps life cycle impact assessment (LCIA) results through accurate analytical process that follows ISO standards and other accepted LCA guidelines (see Fig.7) [15].

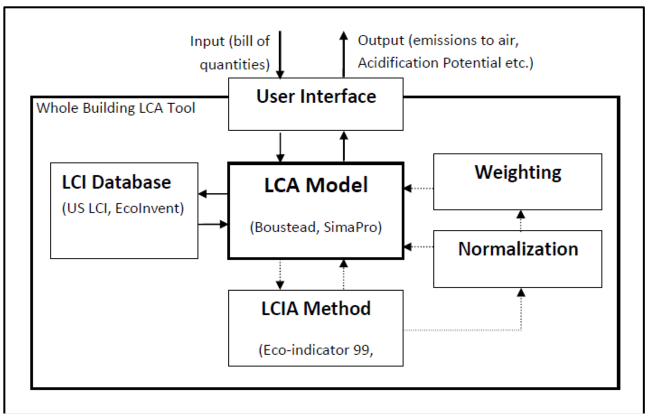


Figure 7: Typical whole-building LCA tool. [11]

List of some commonly used LCA tools:

Tool for LCA practitioner	Tool for general users (Architects)
SimaPro - GaBi - Boustead - LCAit EQUER	BEES - ATHENA® Impact Estimator ATHENA® EcoCalculator - EIO-LCA Eco-Quantum – LiSA - Envest

Building Information Modeling (BIM) can reduce the time consumed in conducting an LCA and streamline the process for architects by enabling the calculation of environmental impacts resulting from the choice of materials.

5. Practical Application Using the LCA Method to Assess and Compare Building Materials

The Practical application includes a study conducted by the researcher using LCA (SimaPro) tool to assess and compare two optional designs depending on their environmental impact.

5.1.LCA Tool Used for the Study (Simapro)

SimaPro is the LCA software. Known for its professionalism, flexibility and openness, SimaPro is the world's most widely used life cycle assessment software for achieving trusted results.

Impact Categories:

- Carcinogens
- Respiratory organics
- Respiratory inorganics
- Climate change
- Radiation
- Ozone layer
- Ecotoxicity
- Acidification/Eutrophication
- Land use
- Minerals
- Fossil fuels

Software version: SimaPro 7.3.3

Database: SimaPro includes databases with a broad international scope, including the well-known international **ecoinvent** database. All datasets are harmonized regarding structure, nomenclature and fit well with the impact assessment methods.

Impact assessment methods: Impact assessment is an important step to measure the environmental impacts in LCA. SimaPro offers a selection of methods, the method applied in the study is **(Eco-indicator 99)**

The ECO-INDICATOR 99 Methodology [16]**:**

Eco-indicator 99 is a method which uses the damage-oriented approach. Traditionally in LCA the emissions and resource extractions are expressed as 10 or more different Impact Categories. It is not easy to weight the impact categories but the method weight the different types of damage that are caused by these impact categories, as it limit the number of items that are assessed.

Assessing seriousness of three damage categories:

1. Damage to **Human Health**,
2. Damage to **Ecosystem Quality**,
3. Damage to **Resources**.

In order to calculate the Eco-indicator score, three steps are needed (See fig.8) :

1. (step1) Inventory of all relevant emissions, resource extractions and land-use in all processes that form the life cycle.
2. (step2) Calculation of the damages these flows cause to **Human Health**, **Ecosystem** Quality and **Resources**
3. (step3) Weighting of these three damage categories.

In order to be able to use the weights for the three damage categories a series of complex damage models had to be developed (See fig.8).

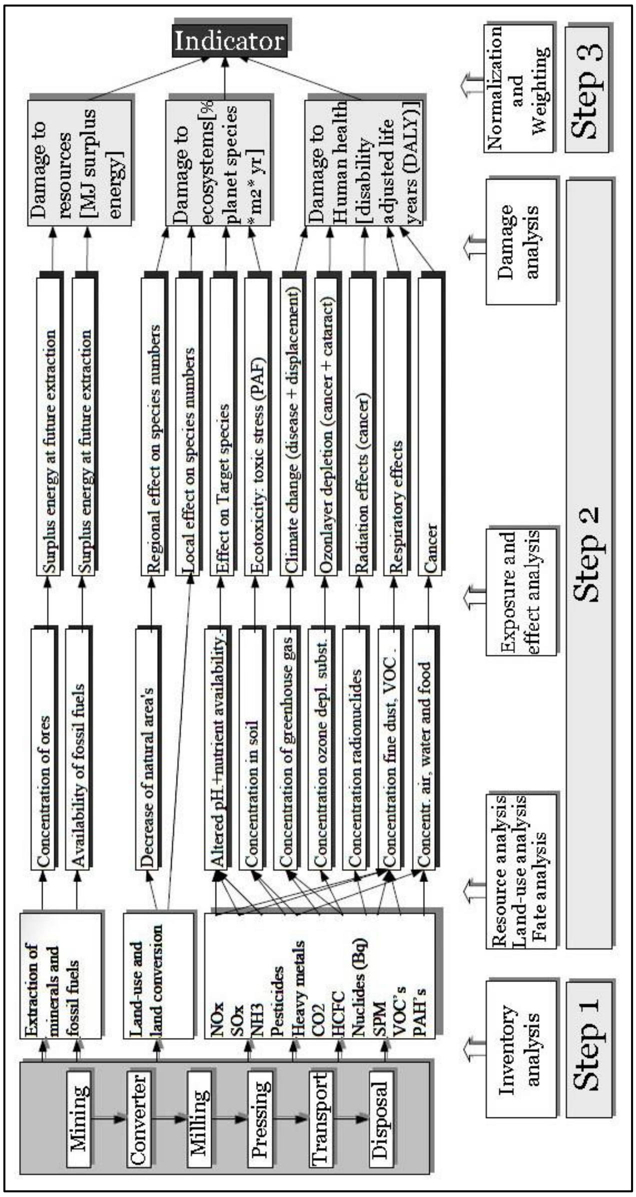


Figure 8 : Detailed representation of the damage model.

5.2.Comparing the Environmental Impact of Two Residential Buildings with Different Structure Systems at the Production Phase Using the (LCA) Software Tool Simapro

The study compares two models of a single family house with different structure systems , the first house is a reinforced concrete structural system (reinforced concrete columns and beams) and the second house is a load bearing walls structure system (masonry walls). Both houses are built on the same area of 185 m^2 of land and have the same layout, which is represented in fig.9, 10.

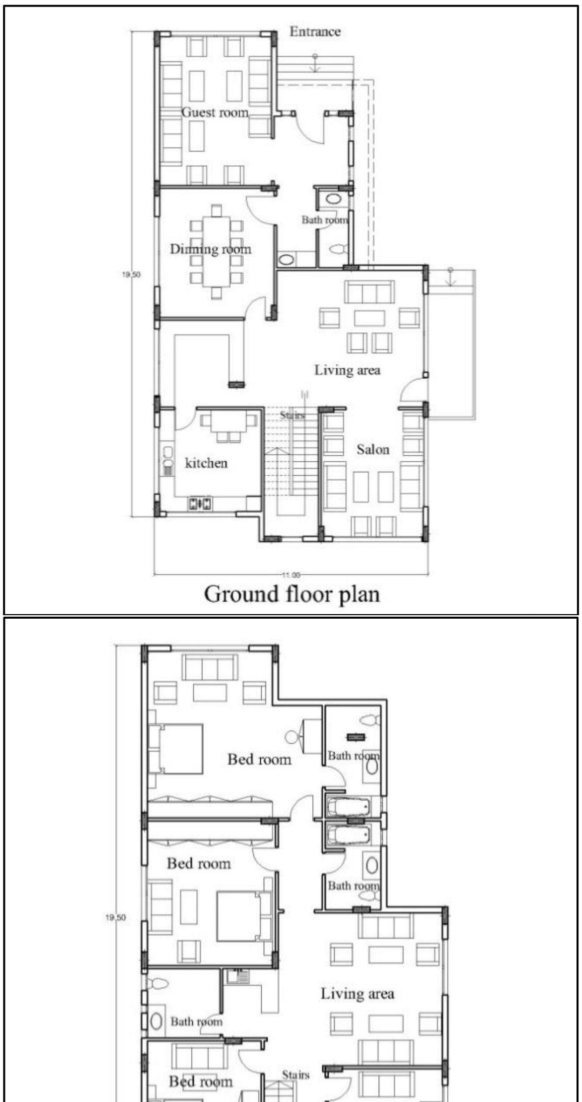


Figure 9: The reinforced concrete structural system house.

The first building is a two-floor house supported by reinforced concrete columns and beams and reinforced concrete floor slabs. The exterior walls thickness is 20cm and the interior walls thickness is 10cm for the two floors.

The second building is a two-floor house supported by a load bearing walls structure system. The architectural design of the second house is almost the same design as the first house except for little difference as the load bearing walls structural system is restricted and the two floors must be harmonious. The openings are narrower than the first building. The ground floor walls thickness is 40cm and the first floor walls thickness is 30cm.

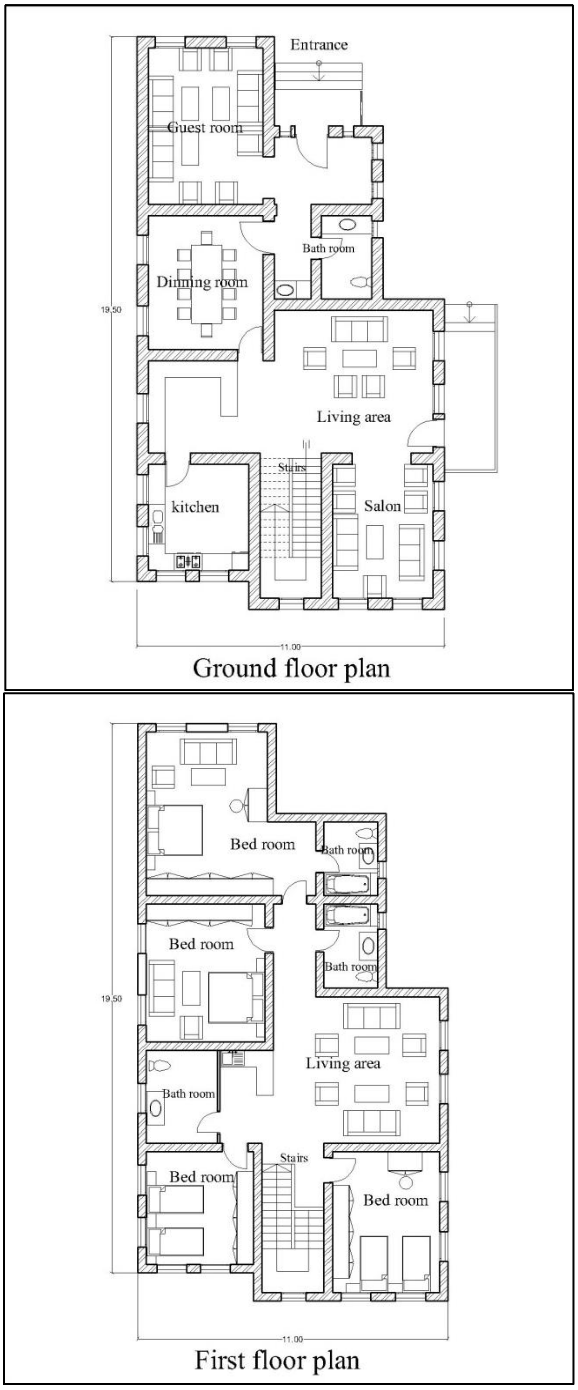
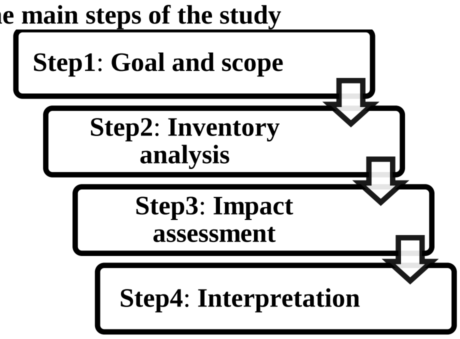


Figure 10: The load bearing walls structural system house.

The study focus on the different environmental impacts of the two model houses on the ecosystem, resources and human health during the manufacturing phase [**Cradle to gate study**].

The study is focusing on the structural components of the building only includes: walls, columns, beams, slabs and foundations in the production phase only.

The main steps of the study



5.2.1 Step1: Goal and scope

- **Aim of the study:** The goal of the study is to evaluate and compare the impact of two model houses with different structure systems on the environment.
 To compare the environmental impact of different building materials used in each structure systems model, every model house is composed of material quantities and components according to its structure system.

First house is reinforced concrete structural system house which consists of reinforced concrete columns, beams, slabs and the walls are clay bricks.

Second house is a load bearing walls structural system house which consists of masonry walls (clay bricks) and reinforced concrete slabs

The LCA study was conducted to evaluate two design options and select the most environmentally friendly one.

- **Depth of study:** The study includes the extraction of raw materials and the manufacturing stage only.
- **Questions:** Which structural system is more ecofriendly and has less effect on the environment at the production phase?
- **Function:** Low-rise residential buildings for single family housing.
- **Function unit:** Impacts have been calculated on a one building basis.
- **Building Lifespan:** A 75-100 years lifespan was estimated by the structural engineer.
- **System boundary:** Two floors residential family house.
 Life cycle of the building is divided into four phases: Materials extraction and manufacturing, then construction, use and maintenance, and end of life. The study includes only the first stage where the materials are extracted and manufactured [Cradle to gate].
- **Audience:** Public, decision makers, architects and other construction professions.

5.2.2 Step2: Inventory analysis

An inventory of inputs was prepared using the **Ecoinvent** database for the majority of the inventory data sets and material quantities from the structural design (see Table2, Fig.11 and Fig.12).

- **Data sources:** Ecoinvent international database v2.2 + structural design for material quantities–
- **Data quality:** Ecoinvent (very good) + structural design for material quantities (good)
- **Assumption:** - The two houses are the same area and height and almost the same design except for some editing that fits every structural system like the difference in wall thickness and very little changes in the architectural design.
- A brick wall is assumed to be 80 % brick and 20 % mortar by surface area.
- The two model buildings have different structural system but consist of the same materials with different quantities that fit every structural system.

Table 2: Materials quantities inventory according to the Structural design.

	Reinforced concrete structural system	**Load bearing walls structural system**	
Concrete	135.5	80	m3
Bricks	64000	240000	kg
Reinforcing steel	14000	7500	kg
Cement mortar	34592	129720	kg

The inventory flow diagram for every structural system:

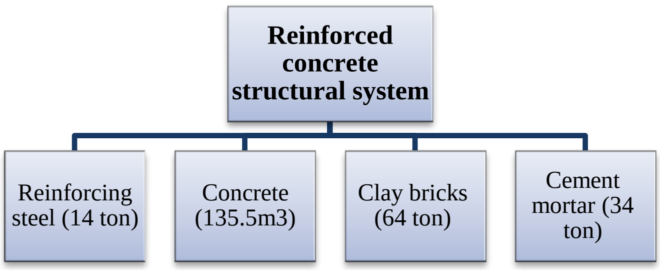


Figure 11: Flow diagram of the Reinforced concrete structural system.

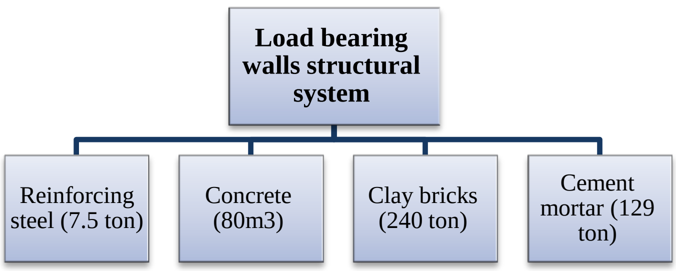


Figure 12: Flow diagram of the Load bearing walls structural system.

Assuming that both structural systems have the same material flows but with different distribution and quantities according to the structural design. The results of the study will determine which structural system has higher impact on the environment at the production phase.

5.2.3 Step3: Impact assessment results

- **Inventory Results**: Once the data was collected, the material flows were modeled using SimaPro 7.3.3 software. This software uses EcoInvent and other inventory databases for calculations.
- **Uncertainty sources:** The ecoivent database is an international database some data may not be the same for Egypt but it would make approximate close results for the study.

The results are explained in three stages:

First stage: Compare a uniform unit results of the four different materials used in construction in both structural systems to determine the different environmental impact categories for every material.

Second stage: **Analyze** both the reinforced concrete and the load bearing walls structural system impact on the environment in a network graphical image and by weighting.

Third stage: Compare the environmental impact of the two structural systems in a detailed study starting with characterization, normalization then weighting to determine which structural system has the higher impact on the environment in the manufacturing stage.

5.2.3.1 First Stage of the Results

The results of the comparison show that the reinforcing steel has the higher impact on the environment because of the high energy used in the manufacturing phase and the emissions during the production phase.

The bricks have the second higher impact on the environment due to the energy used for drying (firing process) (see Fig.13).

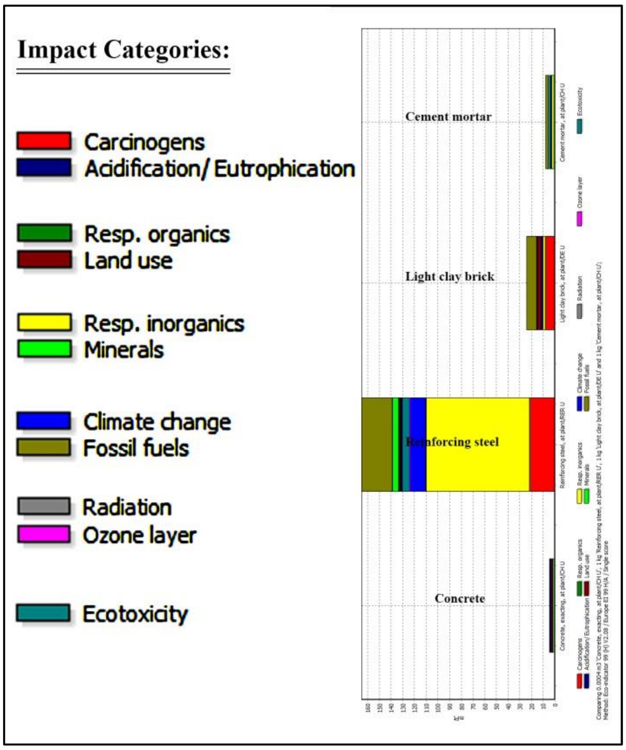


Figure 13: Comparison result of the four materials (Weighting).

5.2.3.2 Second stage of the results (analyzing the impact)

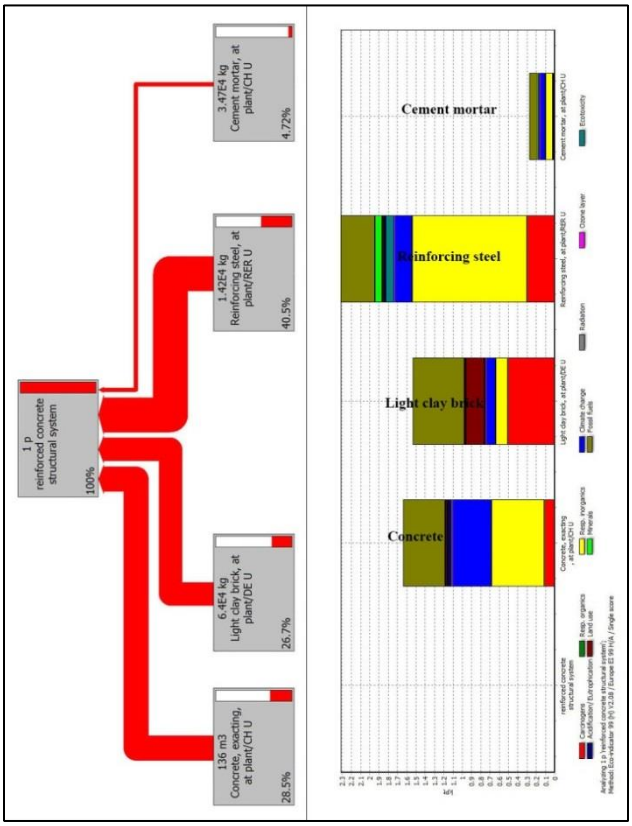


Figure 13: The reinforced concrete structural system analyze.

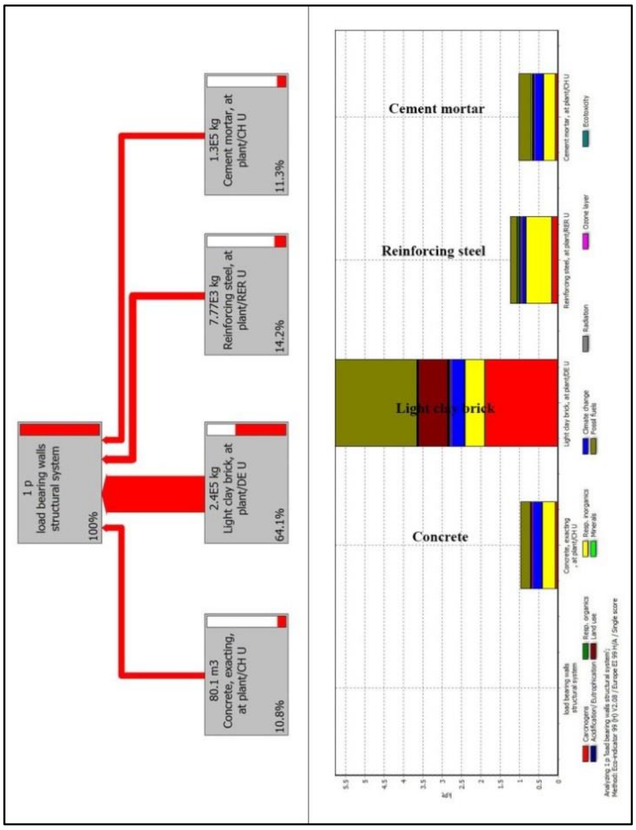


Figure 14: The load bearing walls structural system analyze.

The analysis results of the reinforced concrete structural system show that the production of the reinforcing steel used in the construction has the highest overall impact on the environment(see Fig.14).

The analyze results of the Load bearing walls structural system show that the production of the bricks used in the construction have the highest overall impact on the environment(see Fig.15).

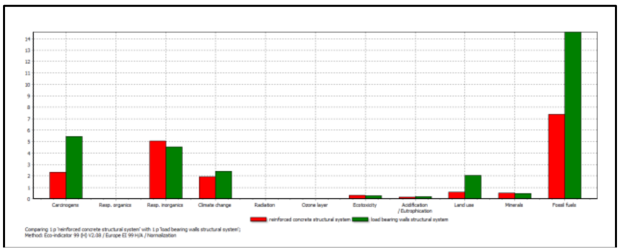
The network graphical image shows the distribution of the environmental impact represented in the links thickness.

5.2.3.3 Third stage of the results (The comparison*)*

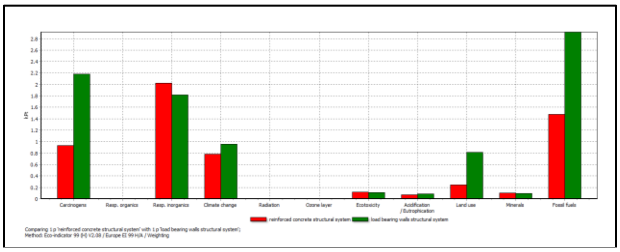
The third (final) stage of results compares the two structural systems and determines which structural system has less impact on the environment in the extraction and manufacturing stage.

Although the two structural systems consist of the same materials (concrete, reinforcing steel, light clay brick, and cement mortar), the quantities are different for each structural system and all this information was modeled in the SimaPro software.

Comparison results:
Normalization



Weighting



Reinforced concrete **load bearing walls**

5.2.4 Step4: Interpretation

The results show that the load bearing walls structural system has higher overall impact on the environment in the production phase (see Fig.16).

Impact categories analyze shows that Load bearing walls structural system has remarkable high impact for **carcinogens** and **fossil fuel** and this is due to the bricks drying and firing process. As burning of fuel (coal, oil, and natural gas) causes emissions like PAH's which has a bad effect on human health and causes cancer.

Conclusions: The load bearing walls structural system house has the higher impact on the environment at the production phase and this is because of the quantities of materials needed to construct a load bearing walls house is much more than the reinforced steel house.

Although the environmental impact of producing clay bricks is less than the environmental impact of producing reinforcing steel, the reinforcing steel structural system is more agile than the load bearing walls structural system. So the quantities of steel needed for constructing the first house is much less than the quantities of bricks needed for constructing the second house.

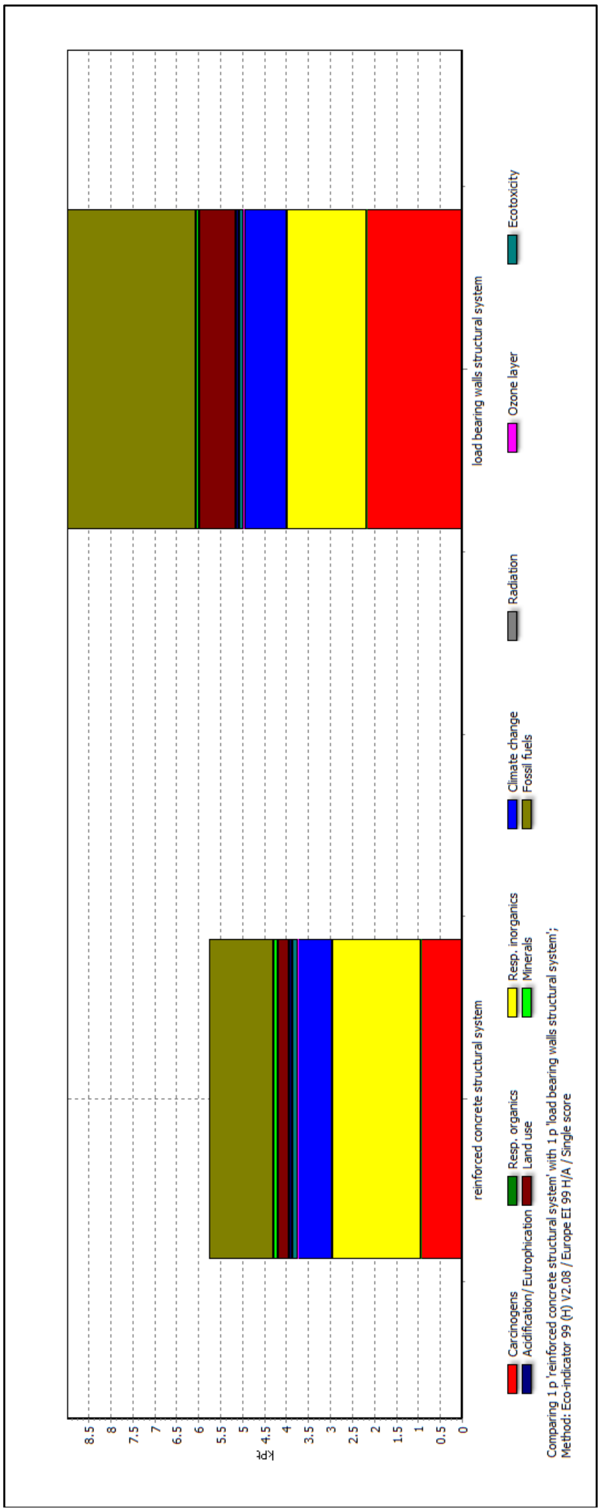


Figure 16: Final comparison result for the two structural systems (single score).[1]

[1] Single score is another way to present the weighing results.

Note: The accuracy of results in second and third stages depends on the accuracy of the structural calculations.

6. Conclusion

Understanding and applying Life Cycle Assessment (LCA) in construction sector can make a difference in building design and the selection of building materials. The goal of the study is to prove that by comparing two different structural systems of one building design through life cycle assessment method.

If the architect understands Life Cycle Assessment (LCA) implementation methodology well and has the appropriate tool it will be easy to compare optional building designs and choose the most environmentally preferable design with the least impact on environment, resources and human health.

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