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A comparative life cycle analysis of glass windows : Assiut University Hospital Clinic as a case study

Original Article

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Abstract

This study aims to analyze the environmental impact of different glass types of a clinic in Assiut University Hospital. The life cycle assessment (LCA) approach evaluates energy usage and its related environmental effects. This study will assess the environmental impacts of four types of window glass manufacturing, which are (1) flat glass, (2) fiber glass, (3) solar glass, and (4) waste glass. The Building Information Modeling (BIM) approach has been used to collect the building construction quantities, facilitating this task. The LCA has been used to calculate energy consumption and environmental emissions. As the main finding of this study, the fiber glass has the worst-case scenario with (1.02 Pt), in contrast with the waste glass (recycled glass) with (0.58 Pt), by the mid-point method result. Also, the global warming potential and non-renewable energy impacts have recorded the highest impact values for the fiber glass with 2939.49 $KgCO_2$ eq.and 46914.97 MJprimary, respectively. Finally, the human health (end-point) method has the most significant share of the adverse environmental impacts for the four glass types studied. The study has proposed that the life cycle cost and the durability and endurance tests must be examined to ensure that waste glass (recycled) is the best option from all points of view

1. INTRODUCTION

The glass windows significantly affect the energy loss in the building[1]. There are many high-performance glazing options for making windows that are energy efficient, including low-e and reflective coatings, sun control films, surface treatments, and laminated glass with a high-performance interlayer[2]. Otherwise, using new material is the most crucialtopic in recent publications to find the most sustainable choices and green alternatives. The environmental impact burdens are the sustainability metrics addressed in this article analytically using the life cycle assessment (LCA) approach.

Most of the research papers in the field of environmental impact have concentrated on the effect of various types of glass on energy consumption and indoor climate in different kinds of buildings. However, few studies have analyzed the correlation between indoor climate and life cycle environmental load. While earlier research has looked at the impact of various glass window types on yearly energy use and air conditioning systems in buildings[3], they have not considered how much energy is used in the manufacture, shipping, and recycling of materials, which varies depending on the type of glass used. Further incorporation of the environmental emissions from various life cycle stages is also necessary. Thus, from a life cycle viewpoint, it is crucial to understand the overall energy consumption and environmental emissions of buildings with various types of glass. This study focuses on a typical office building in Assiut, Egypt. The objective is to quantify the distinction in the life cycle environmental performance of different hypothetical scenarios for glass types. The study aims to identify the most suitable glass type for other window materials of a typical office building.

All processes throughout the whole lifetime of glass windows have been classified, as shown in Figure 1, to calculate the LCA of glass windows. The extraction of raw materials is the first stage, such assand, soda, limestone, clarifying agents, coloring, and glistening glass. Then, these materials are conveyed to the factories to start the manufacturing process of glass material.

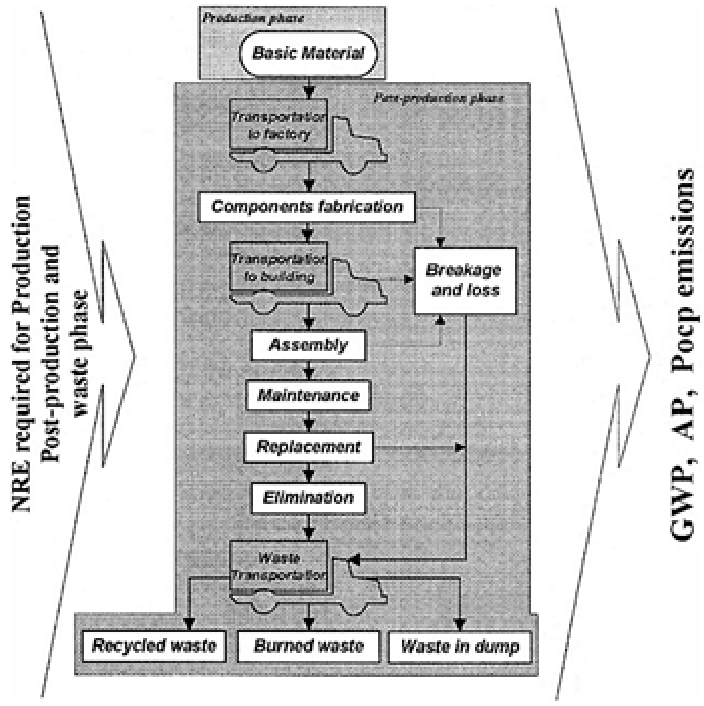


Fig. 1: Life cycle assessment methodology for the glass windows[4]

This paper will focus on four types of glass windows, which are (1) flat glass, (2) fiber glass, (3) solar glass, and (4) waste glass. These types have been selected based on these studies[1-23]. Briefly, next the author will illustrate the manufacturing process of these types. The flat glass production process can be divided into five universal steps[24]:(1) Raw materials batching, (2) Raw materials melting in the furnace, (3) Drawing the molten glass onto the tin bath, (4) Cooling of the molten glass, and (5) Quality checks, automatic cutting, and storage.Secondly, glass fiber was the first reinforcement used in modern polymeric composites[25]. A three-stage furnace combines the raw materials, melts them, extrudes the molten glass via a bushing in the forehearth, cools the filaments with water, and then adds a chemical size to create glass fiber. After that, the filaments are collected and coiled into a package. The five fundamental processes of this manufacturing are batching, melting, coating, and drying/packaging[10]. The third type is solar glass; photovoltaic modules use solar glass as an additional weatherproofing layer. glass also functions as the substrate in thin-film technology, upon which photovoltaic material and other chemicals are placed. Mirrors that focus sunlight are likewise made of glass, while new methods that do not utilize glass are developing. Figure 2 displays the different uses of solar glass.

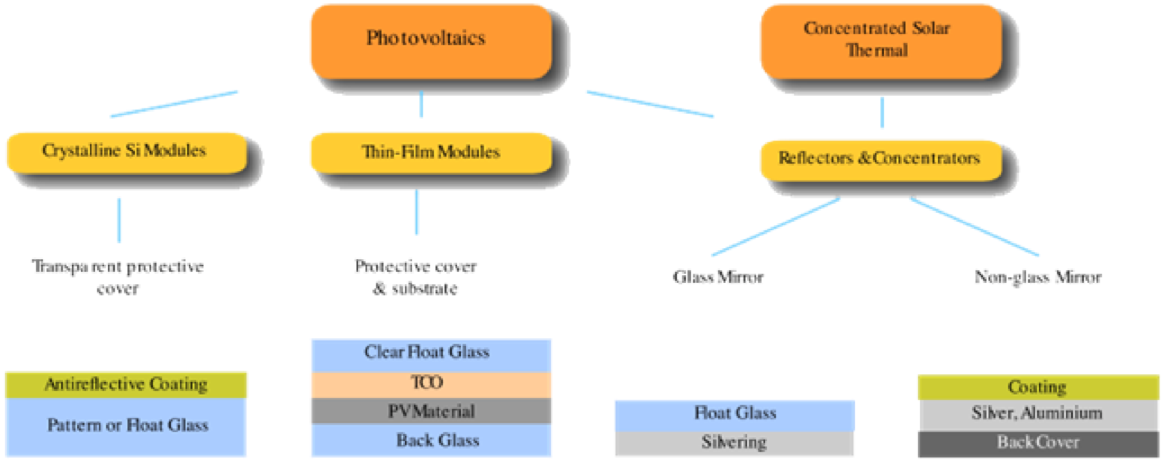


Fig. 2: Various uses of the solar glass

The fourth type is the waste glass; the recycling process goes through many steps, (1) collection and transportation, (2) sorting, (3) breaking, (4) screening, (5) bed drier fluidization, (6) Primary Screening and Pulverization, (7) Secondary Screening, (8) the cullet. The final step in recycling glass is sending what is now calleda"cullet"to create new goods. At this point, the cullet (broken glass) might range from pebble-sized to sand-sized. This recycled glass is utilized for new glass containers and things like fiberglass, ceramics, filtration systems, and abrasives[26].

2. LITERATURE REVIEW

The life cycle of various building materials has been assessed using the LCA appr; however, the building's glass windows systemhas not been evaluated from the environmental point of view.A comparative LCA of a window system has been performed by Weir and Muneer[6]. Also,carbon dioxide emissions have been investigated to assess the environmental impacts of different glass types. However, this article focused on the gases that are used in the manufacturing of glass types. The authors in this article havefocused only on one of the inputs of the LCA stages. Therefore, different papers have assessed all stages of a window's life cycle, such as Citherlet *et al.* [4]. Four determinants have been subjected to assessment (1) window types, (2) building types, (3) facade orientation, and (4) climates zones.This study's key finding is that energy use increases throughout the production process for high-performance windows, from raw material extraction to product fabrication. However, their life cycle energy was lower than a standard window system.Also, this article has revealed that high-performance windows consume more lighting energy.On the other hand, Abeysundra *et al.*[5] study has focused on wood and aluminum window frame types. Due to the energy-intensive manufacturing method used to produce aluminum, the aluminum frame contributed the most negatively to the environment.

Stephane Citherlet *et al.*[4] have studied the advanced glazing systems to help the stakeholdersaccurately designate the environmental impact of advanced windows using the LCA approach. The non-renewable energy consumption has been calculated for all scenarios.The main finding of this study was, despite the advanced windows having a marginally higher environmental impact through their life cycle, they still have good energy benefitsthat they provide during the operational phase.

Corbière-Nicollier *et al.*[17] evaluated the environmental performance of China reed fiber, which is used to strengthen plastics instead of glass fiber and to identify criticalecological criteria.On the other hand, Gong *et al.*[12] have performed a life cycle assessment for two types of solution-processed solar glass modules with low CO_2 emission factor. Rosa *et al.*[14] have used the LCA approach to investigate whether using hemp mats in place of some glass fibers could increase the eco-efficiency of composite materials made of glass fiber. Pulselli *et al.*[20], based on the LCA methodology, the entire life cycle of crystal glass was divided into four primary phases: the procurement of raw materials, the production of crystal glass, the use of the finished product, and the final disposal.

Cetiner *et al.*[8], in comparison to single-skin glass facades, this article has examined if double-skin glass facades are more energy and cost-efficient in moderate climates like Istanbul. A strategy is suggested to find the most effective options for this aim. Monticelli *et al.*[11] have compared the environmental effects of three lightweight textile facade systems with the two most popular translucent systems currently available (U-Glass and Polycarbonate).

Many research disciplines have widely adopted the LCA study and environmental performance, while others have combined the LCA and BIM. One case study was for a different type of glass, another was for a comparison of different types of glass, and a few were for the specified materials. In order to examine the environmental effects of four different types of glasses and assist stakeholders in making the most environmentally friendly choice, this study has created a novel framework combining LCA and BIM for a proposed building.

3. MATERIALS AND METHODS

This study will subject a proposed building in Assiut, Egypt, to the LCA and BIM techniques. Evaluation of the LCA of several window glass types has been done. The information dataset about the building construction components will be compiled using the BIM. This paper will concentrate on the cradle-to-gate scope for the glass manufacturing process as a designated system boundary. The paradigm for integration analysis between LCA and BIM is shown in Figure 3.

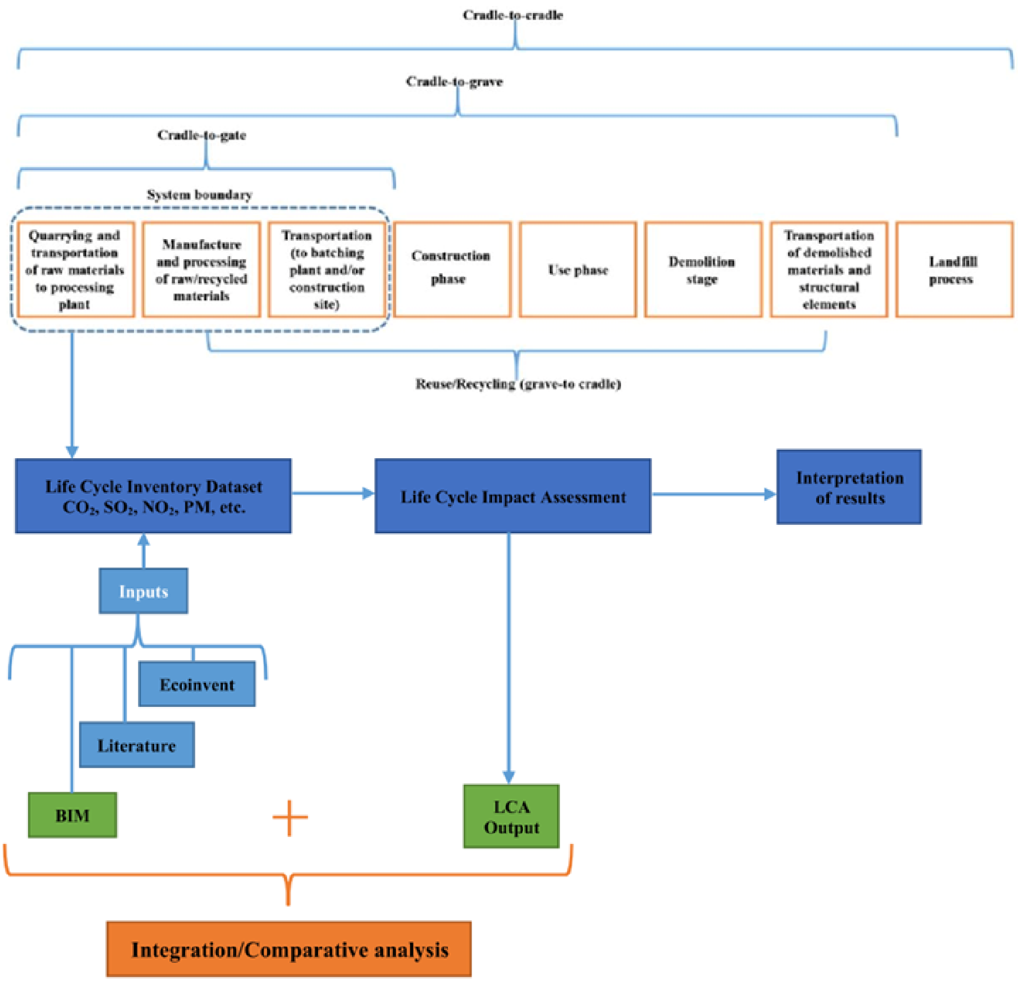


Fig. 3: Framework of the integration analysis

3.1. Environmental Impact Assessment approach

The LCA was implemented according to the ISO standards on LCA and to the main steps described in ISO norm 14041. The life cycle inventory (LCI) database is the most crucial stage in the LCA process. The environmental load factors' data, energy, greenhouse gases, and principal pollution emissions (air, soil, and water) are enclosed in the LCI models of building energy systems. The International Standards Organization (ISO) has defined the most acknowledged standards with many series[27-30], as shown in Figure 4.

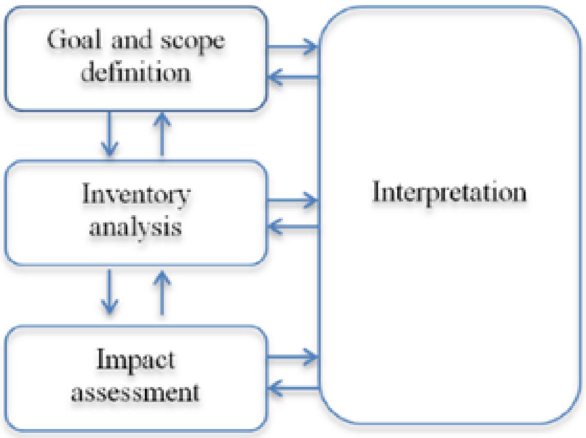


Fig. 4: LCA framework defined by ISO[31]

There are two types of environmental loads (1) direct environmental load on the use phase of building and (2) indirect environmental load on the phase of energy recovery, energyproduction, transportation, and building materials production. These are the life cycle factors which are the combinations between both loads[4], presented in Figure 5. The calculations between the different inputs and outputs in the life cycle of a building are very complicated. Specific software is needed to perform the LCA process.

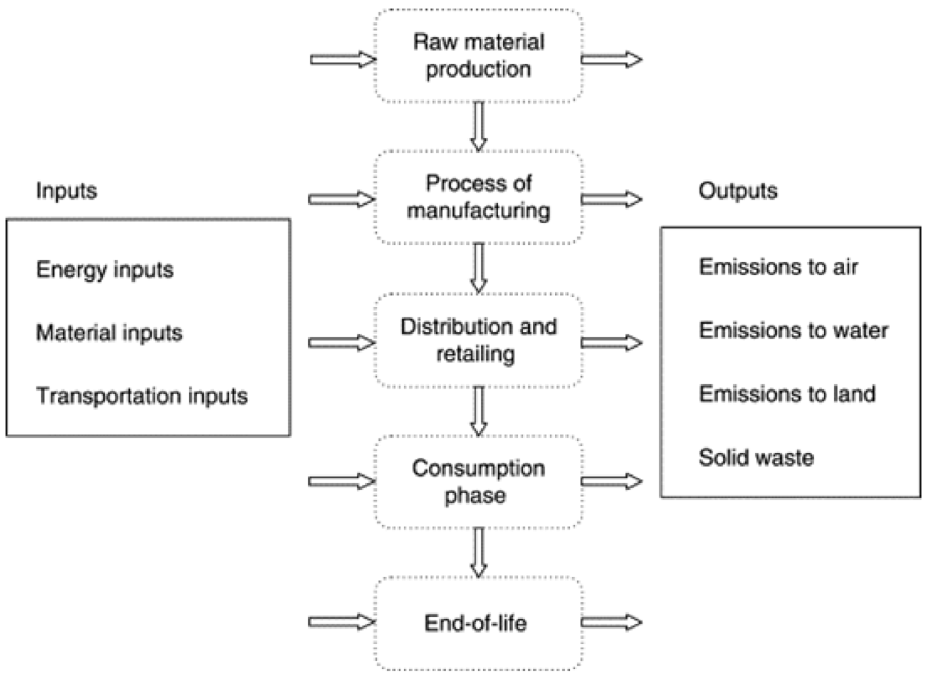


Fig. 5: nputs and outputs data of the LCA process

Due to a thorough comparison, as reported by Ali *et al.*[32] and Al-Ghamdi[33], the two studies have noted that the PReSimaPro is the most prominent LCA tool. As a result, all open-license Ecoinvent databases have been used with the PReSimaPro version 9.5 academic license, as illustrated in Figure 6.

Fig. 6: Faculty license of SimaPro V9.5

3.2. Building Information Modeling

LCA is one method that can be used to estimate energy use and environmental emissions. They can be computed using the LCA tool[34]. The most effective option for gathering the building construction quantities is Building Information Modeling (BIM), which makes this process easier. The environmental costs of material manufacturing can be significantly assessed by combining LCA with BIM. Numerous earlier research used this inclusion; SenemSeyis and Shu Su *et al.*[35,36] condensed all of them. This comprehensive strategy will be employed in this study. The LCA will provide an analysis of the environmental effects of scenarios. In addition, the BIM will provide information on building materials for the LCA's input. Autodesk Revit is the BIM program that is most widely used. The 2020 student-licensed version, as presented, will be used for this study Figure 7.

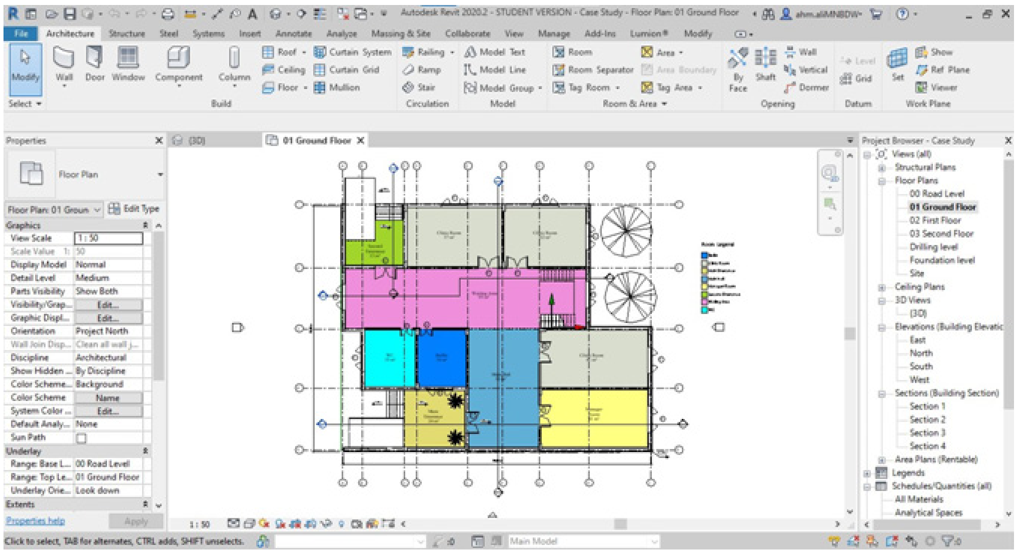


Fig. 7: Autodesk Revit user interface version 2020 licensed version

3.3. Case study analysis

The case study for a number of the author's research papers is the Assiut University Hospital Clinic (AUHC), such as[34,37,38]. The proposed clinic is located on the Assiut University campus (AU).Figure 8highlights the google earth of the AU campus. Also, Figure 9 shows the proposed location of the new clinic. TheRevit software uses the BIM methodology to set the geographical area. With coordinators 27.1838397979736 and 31.1667556762695, the longitude and latitude are defined,respectively. Figure 10 documents a sample of BIM model drawings, including the ground floor plan, section, and perspective.

Fig. 8: Assiut University Campus in Assiut City, Egypt

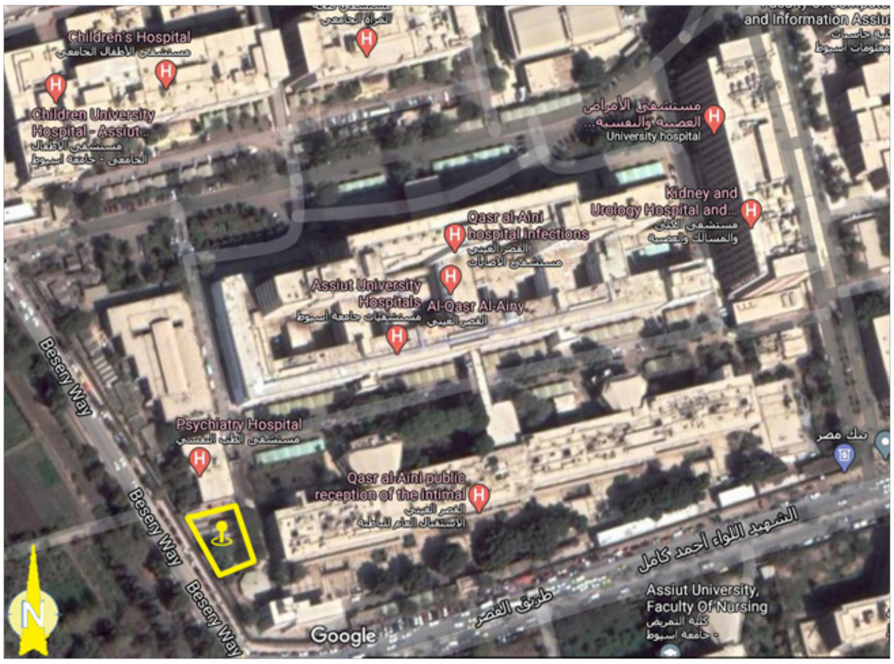
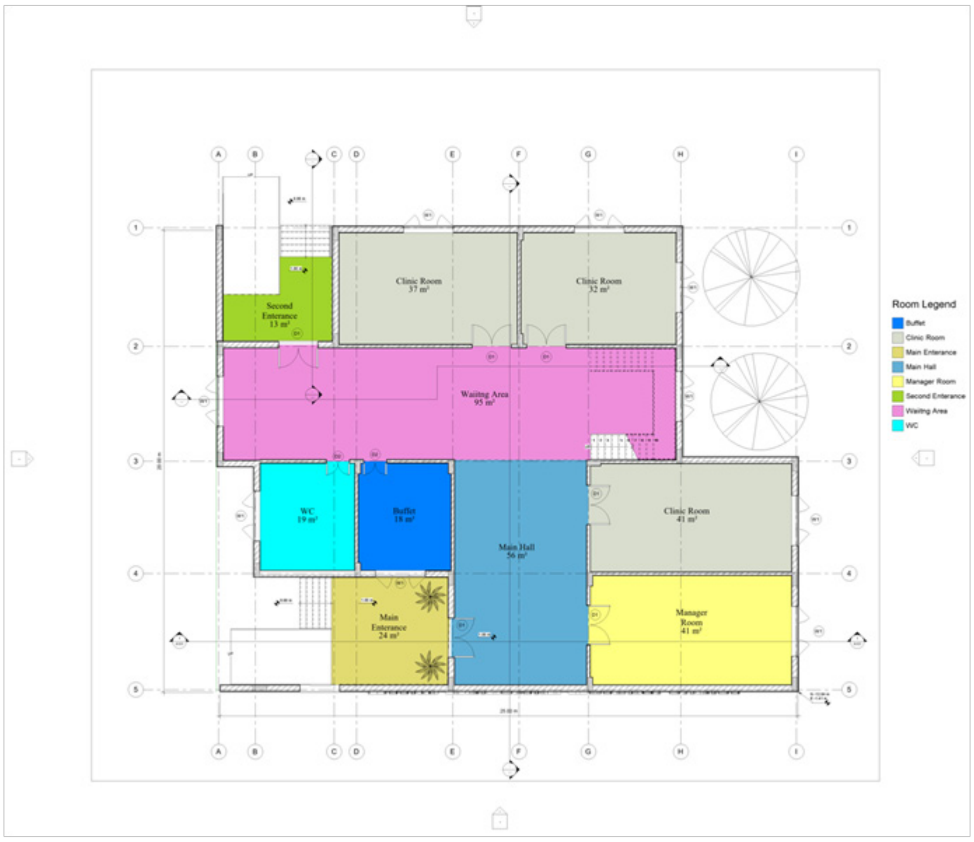
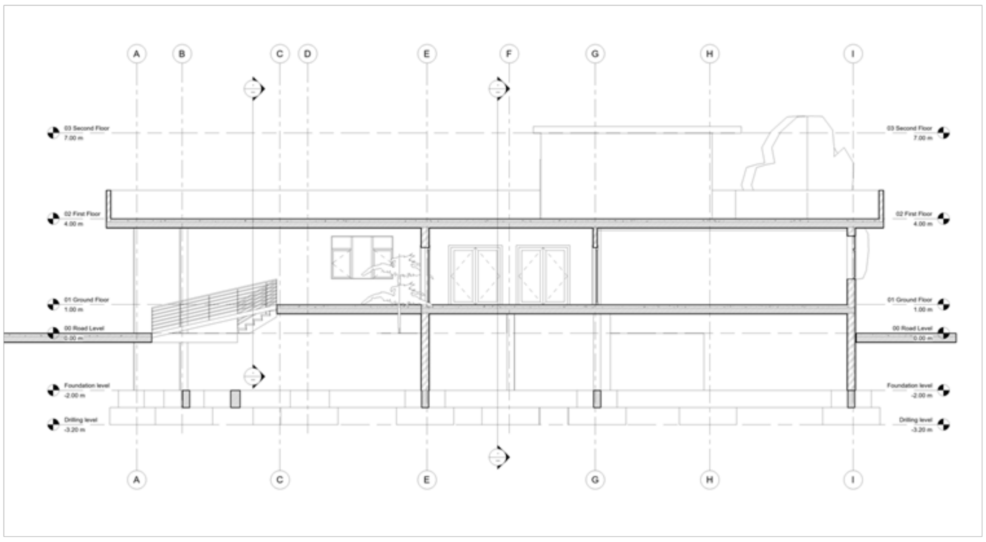


Fig. 9: New clinic location



a) Clinic ground floor plan



b) Clinic section drawing

c) Clinic perspective

Fig. 10: Clinic BIM model

3.4. Comparative LCA of glass types

This study will analyze and assess the environmental impacts of four types of window glass, which are (1) flat glass, (2) fiber glass, (3) solar glass, and (4) waste glass. Firstly, the network flows of the glass manufacturing process have been built inSimaPro, as shown in Figure 12.All four glass types have been constructed in SimaPro, as presented in Figure 11.

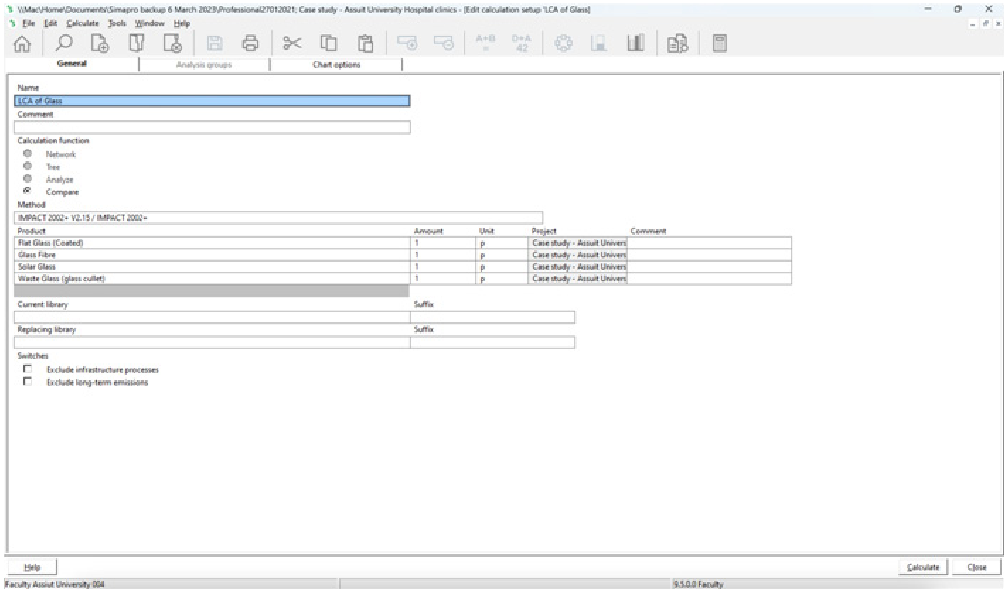
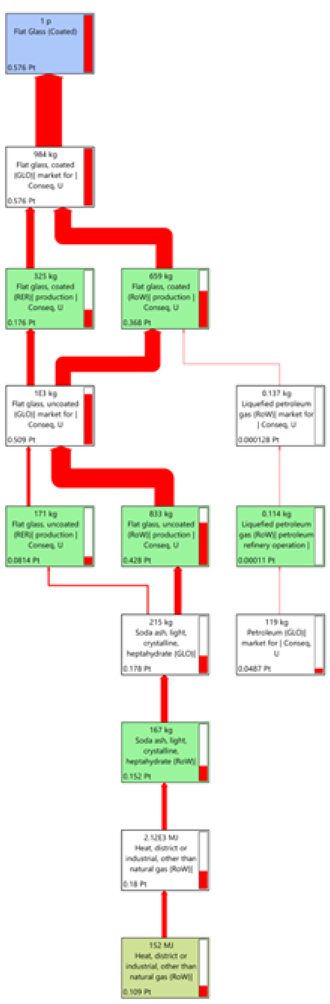
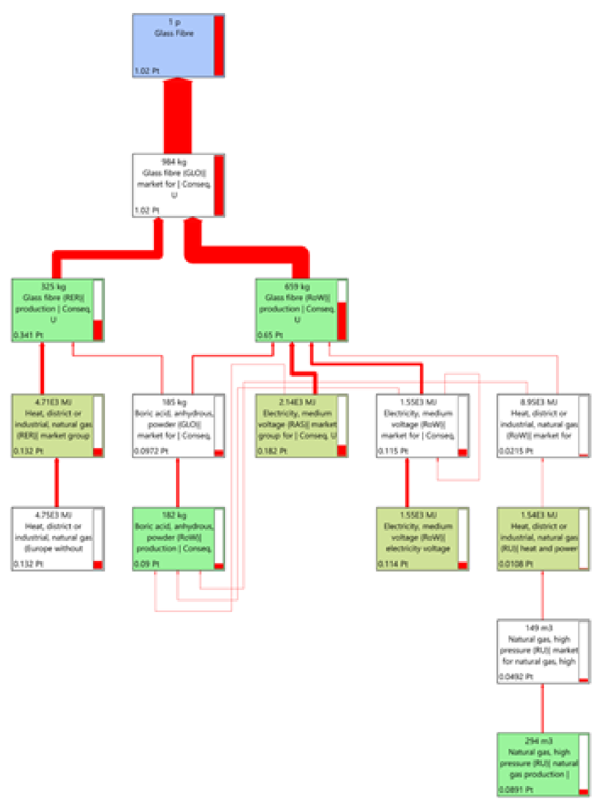


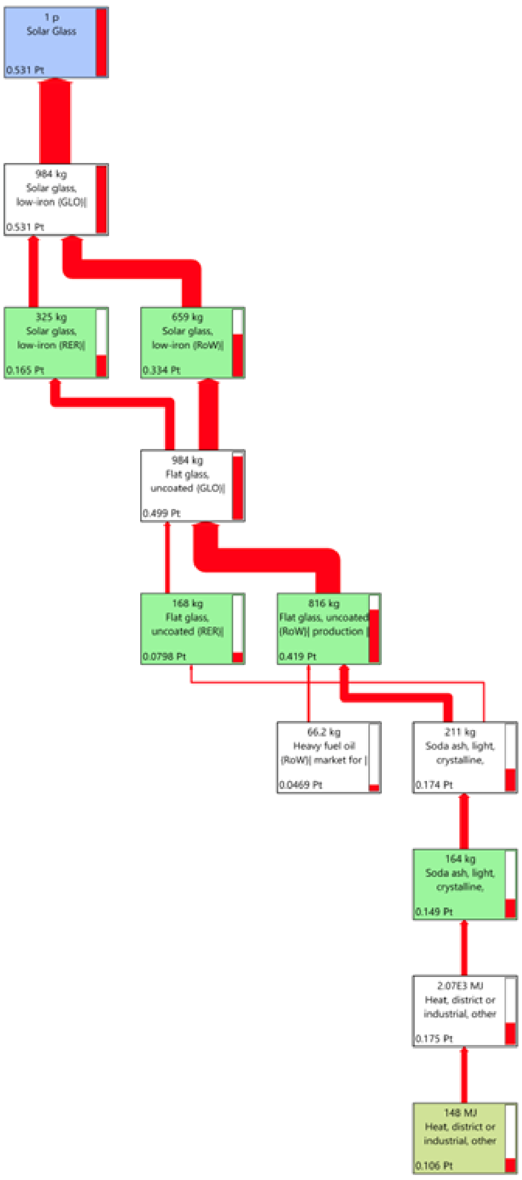
Fig. 11: Comparative LCA of four glass types in SimaPro



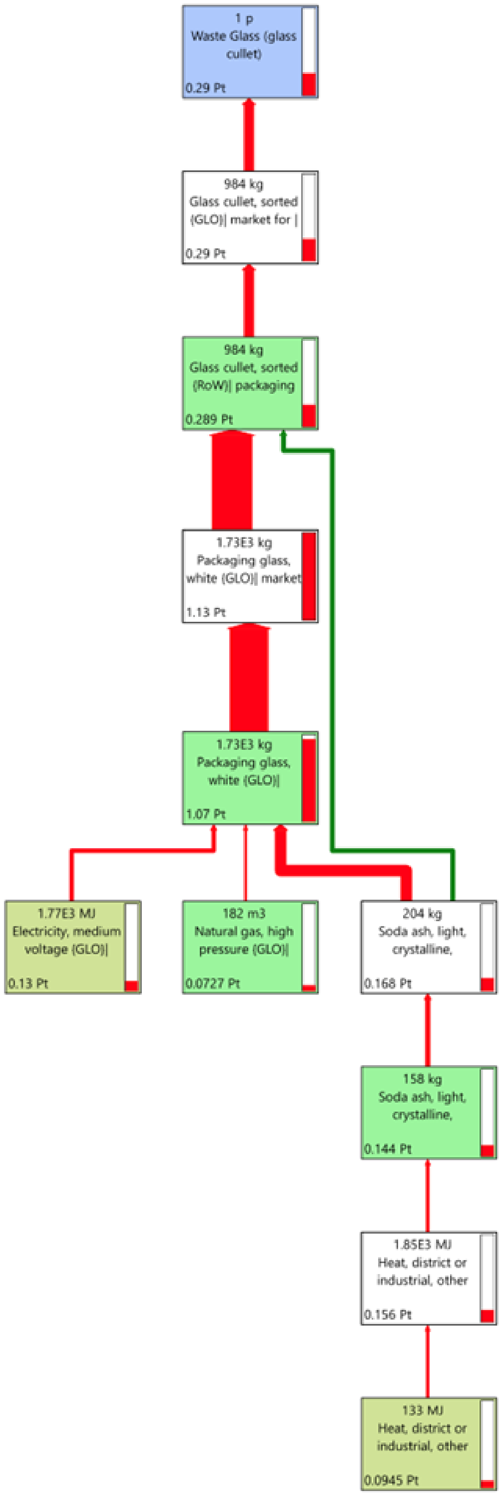
a) Flat Glass



b) Fiber Glass



c) Solar Glass



d) Waste Glass

Fig. 12: Network flows of the four glass types

4. THEORY/CALCULATION

4.1. Goal and Scope Definition

The function of the glass is to be installed in the building windows, so the functional unit chosen to represent the system was defined as 1 m2 of glass types. The LCA process of any product has three major stages, (1) the building materials production phase, (2) the building operation phase, and (3) the end-of-life phase. Each phase includes producing, transportation, distributing, and so on. The system boundary of this study can be highlighted in Figure 13. This research focuses only on the cradle-to-gate stage, which is glass manufacturing only, to help the stakeholders choose eco-friendly and green materials.

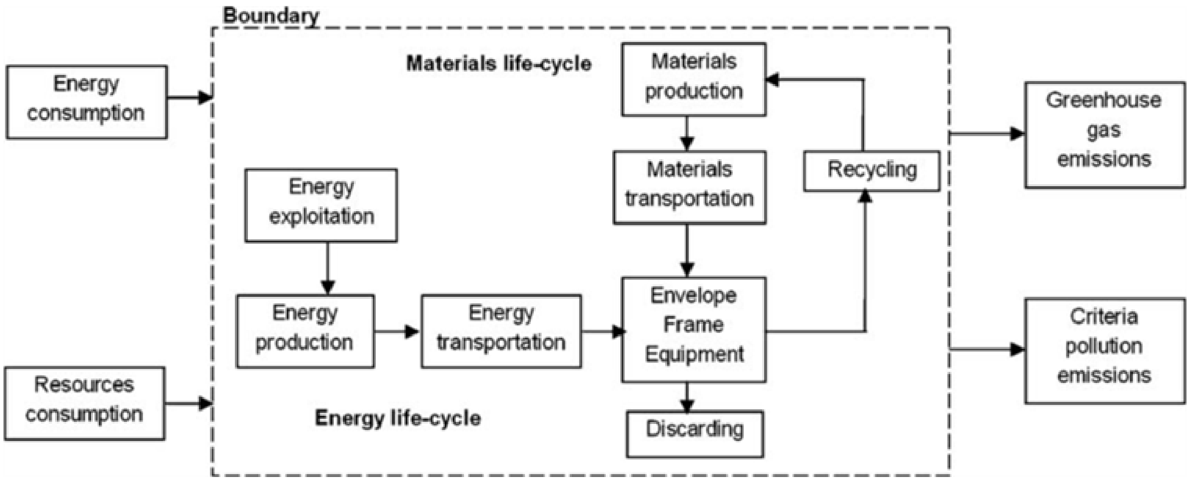


Fig. 13: Boundary of LCA in building energy system.

4.2. Life cycle Inventory database

Section 4.1 describes the first stage of the LCA approach (based on ISO 14041).The Revit software calculates the building material quantities, as shown in Table 1.

Due to the lack of LCA applications and LCI in Egypt, this study has depended on some assumptions from the literature review to complete the data of input materials. Martínez-Rocamora *et al.*[39] compared many LCA application studies; few dealt with construction material manufacturing. The main finding of this study is that the Ecoinvent Database is the most complete LCA database. This study relies on the Ecoinvent V3, the latest database version, as presented in Figure 14.This study has relied on the Ecoinvent V3 dataset[40]. The global market and the global industries of glass materials were carefully chosen from the Ecoinvent (SimaPro-based) database to be closer to Egypt's manufacturing processes

Table 1: Material quantities from the BIM model

Name	Area (m^2)	Volume (m^3)
Brick	861	164.16
Concrete	4382	0.88
Steel	---	17.00
Mortar	3089	29.70
Tiles	1556	62.29
Glass	132	0.41
Plaster	3358	32.31
Wood/Aluminum (window frames)	88	1.20

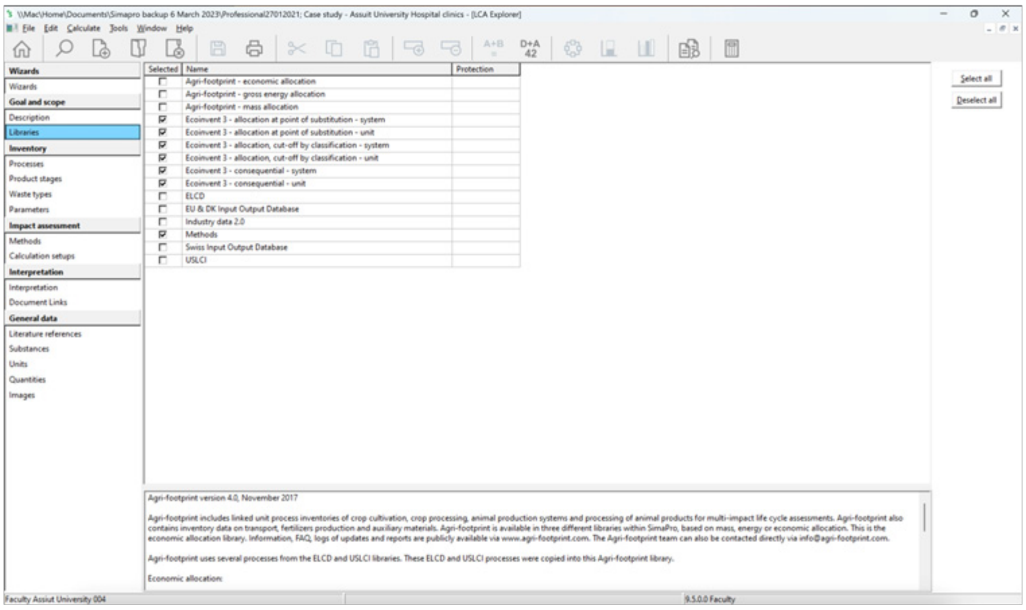


Fig. 14: The LCI database used in SimaPro

4.3. Life cycle impact assessment (LCIA)

The LCIA phase, the third stage of the ISO standard, differentiates the environmental impacts among the four glass types.This paper will use the mid-point and end-pointmethods to calculate the environmental impacts. This study will use the IMPACT 2002+ method, as listed in Table 2, to investigate the environmental impacts based on the literature review[32,33,41,42].

Table 2: IMPACT 2002+ characterization version Q2.2[43]

[Source]	Midpoint category	Midpoint reference substance	Damage category (end-Point)	Damage unit	Normalized damage unit
[a]	Human toxicity (carcinogens + non-carcinogens)	kg Chloroethylene into air-eq	Human health	DALY	Point
[b]	Respiratory (inorganics)	kg PM2.5 into air-eq	Human health		
[b]	Ionizing radiations	Bq Carbon-14 into air-eq	Human health		
[b]	Ozone layer depletion	kg CFC-11 into air-eq	Human health		
[b]	Photochemical oxidation (= Respiratory (organics) for human health)	kg Ethylene into air-eq	Human health		
			Ecosystem quality	n/a	n/a
[a]	Aquatic ecotoxicity	kg Triethylene glycol into water-eq	Ecosystem quality	PDF·m^2·y	Point
[a]	Terrestrial ecotoxicity	kg Triethylene glycol into soil-eq	Ecosystem quality		
[b]	Terrestrial acidification/ nutrification	kg SO_2 into air-eq	Ecosystem quality		
[c]	Aquatic acidification	kg SO_2 into air-eq	Ecosystem quality		
[c]	Aquatic eutrophication	kg $PO^4{}_3$- into water -eq	Ecosystem quality		
[b]	Land occupation	m2 Organic arable land-eq · y	Ecosystem quality		
	Water turbines	Inventory in m^3	Ecosystem quality		
[IPCC]	Global warming	kg CO_2 into air-eq	Climate change (life support system)	kg CO_2 into air-eq	Point
[d]	Non-renewable energy	MJ or kg Crude oil-Eq (860 kg/m^3)	Resources	MJ	Point
[b]	Mineral extraction	MJ or kg Iron-eq (in ore)	Resources		
	Water withdrawal	Inventory in m^3	n/a		
	Water consumption	Inventory in m^3	Human health		
			Ecosystem quality		
			Resources		

[a] IMPACT 2002, [b] Eco-indicator 99, [c] CML 2002, [d] Ecoinvent, [IPCC] (IPCC AR5 Report), and [USEPA] (EPA)
daly disability-adjusted life years, *PDF* potentially disappeared fraction of species, *-eq* equivalents, *y* year

5. RESULTS AND INTERPRETATION

This section will present the LCA results by two methods; single score and weighting per impact category.

5.1. Single score per impact category

As Figure 15 shown, the fiber glass has the worst-case scenario, in contrast with waste glass (recycled glass) which has fewer adverse environmental impacts among the four glass types, which corresponds toAkhshik *et al.*[10,25]. The single score presents the mid-point environmental results by points (Pt) to facilitate the comparison among all types. The fiber glass has the most significant share with (1.02Pt), then the flat glass (0.58Pt), then the solar glass (0.53Pt), and finally the waste glass (0.29Pt).

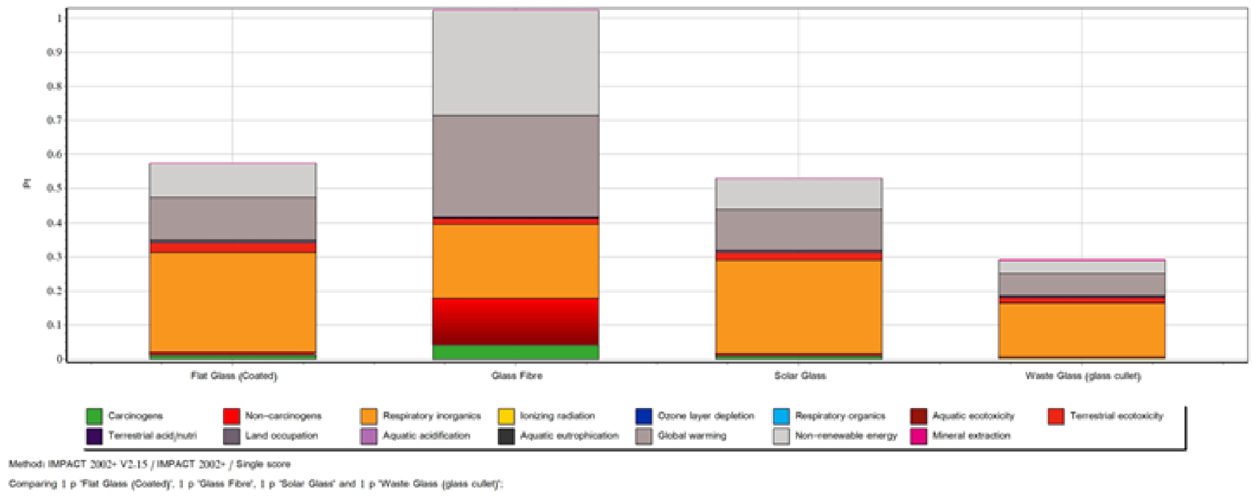


Fig. 15: Single Score results per glass material type with mid-point method

As for end-point methods, the results are shown in Figure 16. The ecosystem quality has a neglected impact among the four glass types. However, human health, climate change, and resource depletion have considerable adverse consequences. The order of the environmental implications of the glass type is similar to the mid-point result, which is that the fiber glass is the first rank.

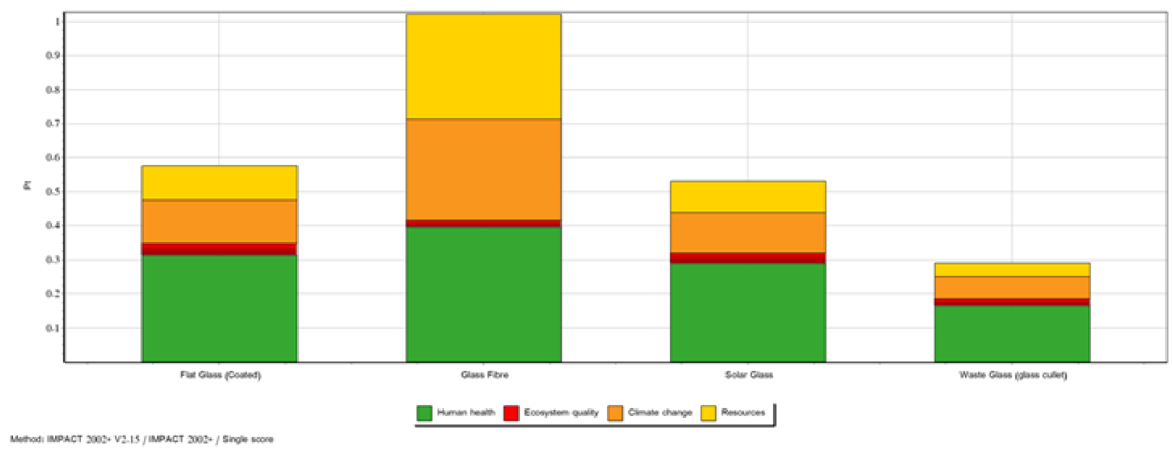


Fig. 16: Single Score results per glass material type with end-point method

5.2. Weighting per impact category

Figure 17 presents the weighting method results per the impact category (mid-point method). The global warming potential and non-renewable energy impacts have the most significant numbers for all glass types. The fiber glass is in the first rank with 2939.49 Kg CO_2 eq. Moreover, the waste glass records 660.30 Kg CO_2 eq. Also, the non-renewable energy impact, the fiber glass is 46914.97 MJ primary,and the waste glass is 5908.53 MJ primary. As well as the respiratory inorganics impact has an adverse impact on the environment in the glass industry. Flatglass has the most significant number, then solar glass, fiber glass, and finally the waste glass with 2.97, 2.76, 2.20, and 1.60 Kg $PM_{2.5}$ eq respectively. The three impacts highlighted previously are the significant impacts in the glass industry. Other environmental impacts such as (carcinogens, con-carcinogens, ionizing radiation, ozone layer depletion, respiratory organics, aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acid/nutria, land occupation, aquatic acidification, aquatic eutrophication, and mineral extraction) have neglectable environment impacts.

Figure 18 presents the weighting results for the end-point result according to the overall impacts. Human health, climate change, and resource depletion have recorded the most massive figures, consistent with Corbière-Nicollier *et al.*[17].

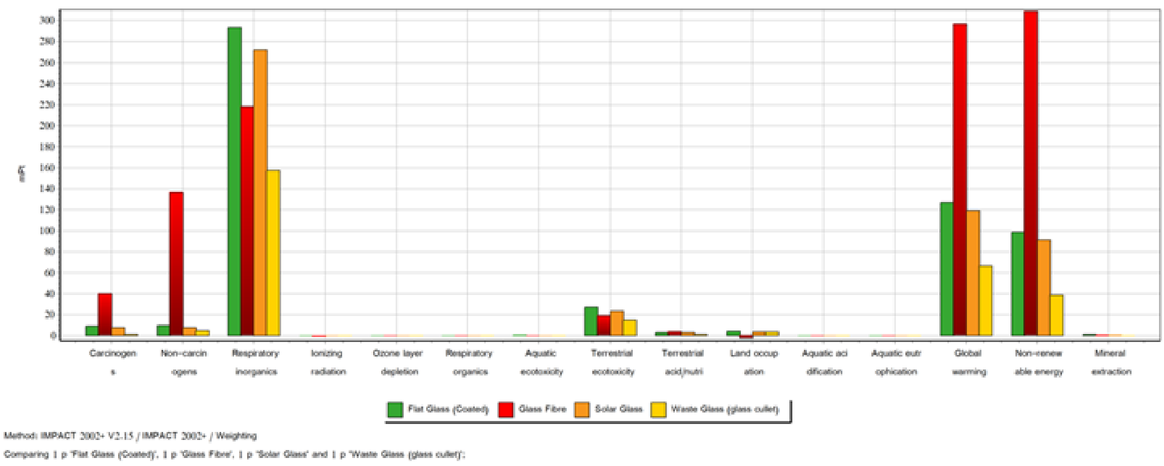


Fig. 17: Weighting results per environmental impact category with mid-point method

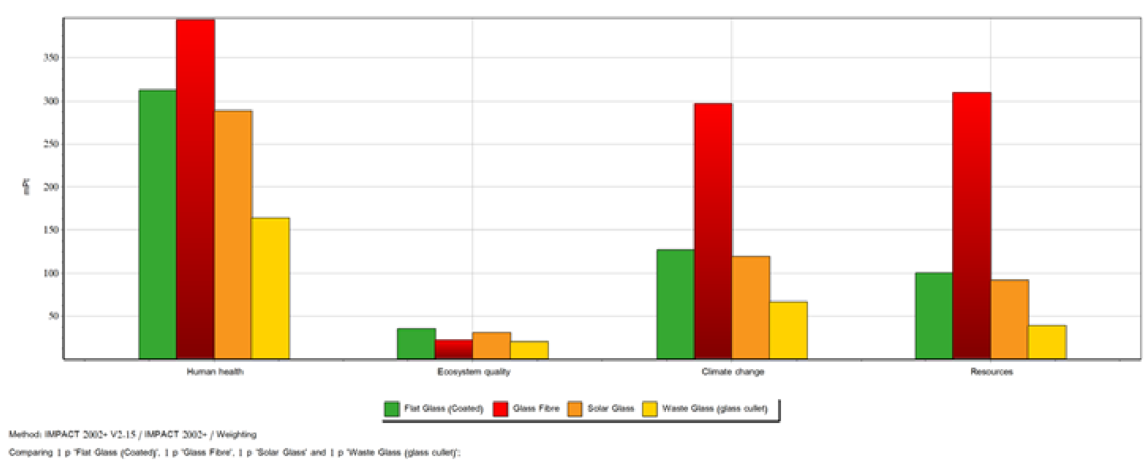


Fig. 18: Weighting results per environmental impact category with the end-point method

6. DISCUSSION

The present study aimed to systematically assess and evaluate the environmental impacts of four glass types, which are (1) flat glass, (2) fiber glass, (3) solar glass, and (4) waste glass. Using the LCA and BIM methodologies, the assessment has been implemented. Regarding the LCA results, the fiber glass has an adverse impact on the environment. To interpret this, Akhshik *et al.*[10] have highlighted that this type uses a three-stage furnace to combine the raw materials, and the fiber glass composition includes chemical materials.

In contrast, waste glass (recycled) needs less fuel and electricity in its production, as it is mentioned by Bostanci and Blengini *et al.*[44,45]. The flat glass ranks second since its manufacturing has a furnace process. However, it is still lower than the fiber glass, as cited by Rodrigues *et al.*[24, 46].Ultimately, the presence of photovoltaic material and certain chemicals in solar glass production still has destructive environmental impacts, in confirm by Stamford *et al.*[47].

Due to some of the glass production needs furnace process, the kilns emit more CO_2. The global warming potential has recorded the worst impact, as reported by Bolt and Jia Wein *et al.*[48,49]. As well, as the incineration process needs energy (MJ)to work, non-renewable energy impact has been recorded as the second rank of the environmental effects, as mentioned by Borghi *et al.*[50]. Some LCIA techniques have embraced Disability Adjusted Life Years (DALY) as a measure of human health environmental impact to incorporate varied-points into linked to damages to human health, as it is mentioned by Dastjerdi *et al.*, Li *et al*., Shi *et al.* and Hu *et al.*[51-54]. That is why human health has recorded the highest adverse impacts due to the high environmental effects (global warming potential and non-renewable energy).

7. STUDY LIMITATIONS AND FUTURE WORK

The present study considers the glass types involving the material manufacturing aspects. This study demonstrates the life cycle environmental impact of buildings with fourglass types. From the view of LCA, fiber glass has adverse environmental effects among the other glass types.

Future LCA studies should contain the environmental impacts accompanying the glass types' fabrication, installation, maintenance, replacement, and dismantling to allow for a complete environmental impact assessment. Since most studies have focused on thermal comfort by studying the building types, orientations, and site location determinants, the LCA approach should occur in future studies. As well as the building type, many publications have used the residential building as case studies, neglecting the office building.

A life cycle cost analysis should be measured to guarantee that the waste glass (recycled)is economically compared with the other types. Also, durability and endurance tests should be applied for the studied glass types to prove the best choice. Future studies should involve a comparative cost analysis for raw materials, manufacturing, product fabrication, transportation, and installation. Contractors and published papers can help researchers to collect these data. Ultimately, the operational use phasesstudy should be focused on future work relatively.

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