World Academy of Science, Engineering and Technology
International Journal of Architectural and Environmental Engineering
Vol:9, No:9, 2015

Life Cycle Assessment as a Decision Making for Window Performance Comparison in Green Building Design

Ghada Elshafei, Abdelazim Negm

***Abstract*—**Life cycle assessment is a technique to assess the environmental aspects and potential impacts associated with a product, process, or service, by compiling an inventory of relevant energy and material inputs and environmental releases; evaluating the potential environmental impacts associated with identified inputs and releases; and interpreting the results to help you make a more informed decision. In this paper, the life cycle assessment of aluminum and beech wood as two commonly used materials in Egypt for window frames are heading, highlighting their benefits and weaknesses. Window frames of the two materials have been assessed on the basis of their production, energy consumption and environmental impacts. It has been found that the climate change of the windows made of aluminum and beech wood window, for a reference window (1.2m×1.2m), are 81.7 mPt and -52.5 mPt impacts respectively. Among the most important results are: fossil fuel consumption, potential contributions to the green building effect and quantities of solid waste tend to be minor for wood products compared to aluminum products; incineration of wood products can cause higher impacts of acidification and eutrophication than aluminum, whereas thermal energy can be recovered.

***Keywords*—**Aluminum window, beech wood window, green building, life cycle assessment, life cycle analysis, SimaPro software, window frame.

I. Introduction

THE concept of green building objects is to improve the environmental performance in all aspects of buildings. As buildings are a composition of numerous materials and subassemblies, tools have been developed to better inform environmentally preferable decisions [1].

Windows play a significant role in buildings, it accounts for 10-25% [2] of a building's exposed surface and available in a wide range of designs and frame materials. The primary contribution of windows to buildings is to incorporate daylight and to maintain the interior environment at desirable comfort conditions. An important aspect of windows is their environmental impact – energy consumption, natural resources depletion and environmental burden associated with their manufacture [3].

Ghada ElShafei is with the Department of Environmental Engineering, Egypt-Japan University of Science and Technology E-JUST, New Borg El-Arab, Alexandria, Egypt, (corresponding author, phone: +20-1116683799; E-mail: Ghada.Elshafei@ejust.edu.eg).
Abdelazim Negm is with the Department of Environmental Engineering, Egypt-Japan University of Science and Technology E-JUST, New Borg El-Arab, Alexandria, Egypt (e-mail: negm@ejust.edu.eg).

Selecting the most appropriate materials for any application depends on the consideration of a range of technical and economic factors including, for example, functionality, durability and cost. A further and increasingly important factor for material specifiers, in a world where sustainable development is a key issue, is the associated environmental performance of material applications from the perspective of manufacturing and product performance [4]. Among the tools available to evaluate environmental performance, life cycle assessment (LCA) provides a holistic approach to evaluate environmental performance by considering the potential impacts from all stages of manufacture, product use and end-of-life stages. This is referred to as the cradle-to-grave approach [5].

Salazar J. [1] applied the life cycle assessment on three window types commonly available in North America: PVC, fiberglass, and wood covered with an aluminum cladding. The LCA was based on the production of the three windows by a single representative manufacturer of each type. The damage modeling results indicated that the life cycle impacts are dominated by the combustion of non-renewable energy resources. Burning fuels cause increased emissions of respiratory inorganics, terrestrial acidification/nitrification impacts, and global warming. The PVC window's life cycle used the most nonrenewable energy and caused the most damage due to that window's shorter service life, 18 years vs. 25 years for fiberglass and aluminum clad wood. The use of cladding materials other than aluminum also prevented the disposal of aluminum into municipal landfills which reduced the aquatic Eco toxicity of the wood window's life cycle. Other potential improvements to the impacts of the three windows' life cycles include improving energy efficiency, particularly during secondary manufacturing.

Asif M. et al. [3] addressed the life cycle assessment of the materials used for window frames of aluminum, PVC and timber window for a reference window (1.2m×1.2m). They concluded that Aluminum frames cause the highest burden to the environment because of the dangerous pollutants release and high energy consumption during aluminum production. PVC contributes large amounts of poisonous pollutants throughout its life cycle while timber window frames have the least environmental burdens. All frame materials deteriorate to various degrees by environmental impacts. PVC is sensitive towards heat and UV radiation. Timber if not frequently treated, can easily be affected by the environment. Aluminum, if not protected well by coatings, gets damaged under corrosive conditions especially in coastal and industrial areas.

Richter et al. [6] cover the same materials assessed by [3] but also include steel, stainless steel and nonferrous windows. Considering the whole life cycle including the compensation of heat losses; heating system, mass-based allocation of co-production processes is applied throughout the wood chain; recycling material is modelled with the cut-off procedure.

Kreissig et al. [7] compare aluminum, wood, wood-aluminum and PVC windows due to different system boundaries. They made a direct comparison of these window types. They included the study [6] in their comparison, because it was based on functionally equivalent product systems and considers the frame and the glazing. This combination allows the evaluation of environmental effects of the whole construction including its thermal properties. The latter is important because the compensation of heat losses is a major contributor to the environmental profiles of the windows, [8].

Jungmeier G. [9] applied the LCA for forestry wood, biofuel and wooden products. The results of the inventory assessment for this standard version of the solid wood window are greenhouse potential and acidification. The highly negative global warming potential of the wood frames results mainly from the renewable CO_2 that is embodied onto the wood residues that are produced along the window production. According to the allocation rule, the wood residues were treated as waste, so all upstream interventions including the CO_2 up-take were not allocated to them, although 90% of the final window frame is incinerated in the disposal processes.

Elizabeth Minne et al. [10] selected a basic single-pane window as a baseline to compare to two basic double-pane windows and four energy-efficient windows in a single-family home. Seventeen United States cities were investigated to represent 17 climate regions. When projecting the impacts of retrofitting a large number of homes, it was found that metro Atlanta could reduce CO_2 emissions by about a half a million metric tons of CO_2 annually with any of the energy efficient window choices.

The main target of this study is to make a decision about what is the best material for windows used in green building according to which one of them effects on the thermal comfort of the interior space referenced to environmental impact, human health and climate change comparison results. Therefore, a comparative analysis study using LCA for window frame materials; from aluminum and beech wood with dimensions of 1.2m*1.2m is made. A Life Cycle Assessment (LCA) approach has been adopted to evaluate these frame materials regarding their production taking into account the affiliated energy and environmental impacts using SimaPro software ver. 8.0.4.30. This study also provides the environmental impacts of painting/coatings on aluminum and beech wood, disposal of windows. The transportation values are similar for the two materials, aluminum and beech wood window in this comparative study due to their effects on the environmental impacts in LCA study. The paper also gives a critical review of a several kinds of materials performance of the windows examined.

II. Methodology

Fig. 1 shows the logical relationship of the four LCA components as presented in the ISO 14040 “Principles and Framework” of LCA. The directional arrows indicate the continuous need to modify the assessment, and backtracking to previous stages, based on the interpretation of the findings at each stage [11]. Following ISO 14041 a step-wise procedure for system boundary setting and allocation are outlined without system expansion in the LCA of the two types of window that are commonly available in Egypt: beech wood and aluminum is based on the production of the two windows by a single representative manufacturer of each type. Average transportation distances (200 km is assumed as the same in the two materials to get the effect of the two different materials on green building design and specified as tkm and in the distance to recycle or reuse assumed as 10 km), commodity systems, maintenance, and service life estimations are used to complete the life cycle inventory model. Fig. 2 shows the framework for the present study.

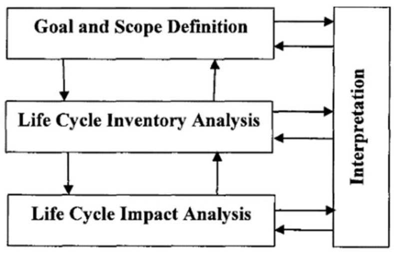

Fig. 1 Life Cycle Assessment Framework (ISO 14040, 1997) [11]

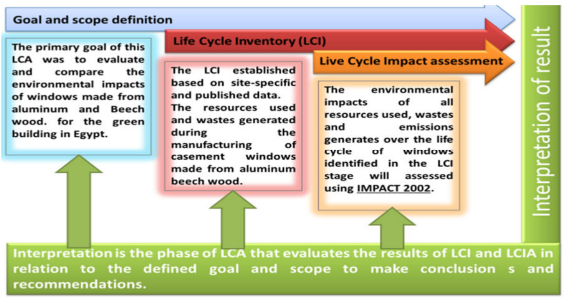

Fig. 2 Life cycle assessment framework for aluminum and beech wood windows

III. Window Frame Material

This research is based on calculation make on two different materials for frame window aluminum (Jumbo sectors 2mm) and beech wood window. The reference window is (1.2m×1.2m), so the aluminum window weights 4.0992 kg and the beech wood window volume is 12000 cm^3. The two materials process as follows:

A. Aluminum

Aluminum windows are light, durable and highly heat conductive made of hollow extruded profiles. Aluminum is produced from its abundantly available ore, bauxite. After that, it is going through a group of processes to get the aluminum sheets then the product is manufactured [12]. Fig. 3 shows the stages that the aluminum goes through from its extraction till the end of life which is expressed in the cradle to gate phase. While in Fig. 4 the assembly of aluminum window network is shown.

Primary, aluminum production requires a great deal of energy (225MJ/kg) [13] and it generates huge amounts of environmentally dangerous pollutants like carbon dioxide, acidic Sulphur dioxide, along and dust. Aluminum can be recycled repeatedly with virtually no deterioration in quality. Recycling aluminum requires only about 7% of the energy needed for primary aluminum production from its ore [14], and the energy required to melt 1 kg of aluminum is in average 13 kWh [15].

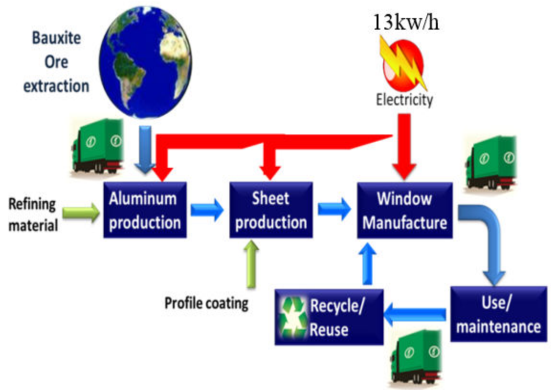

Fig. 3 Life cycle stages of an aluminum window

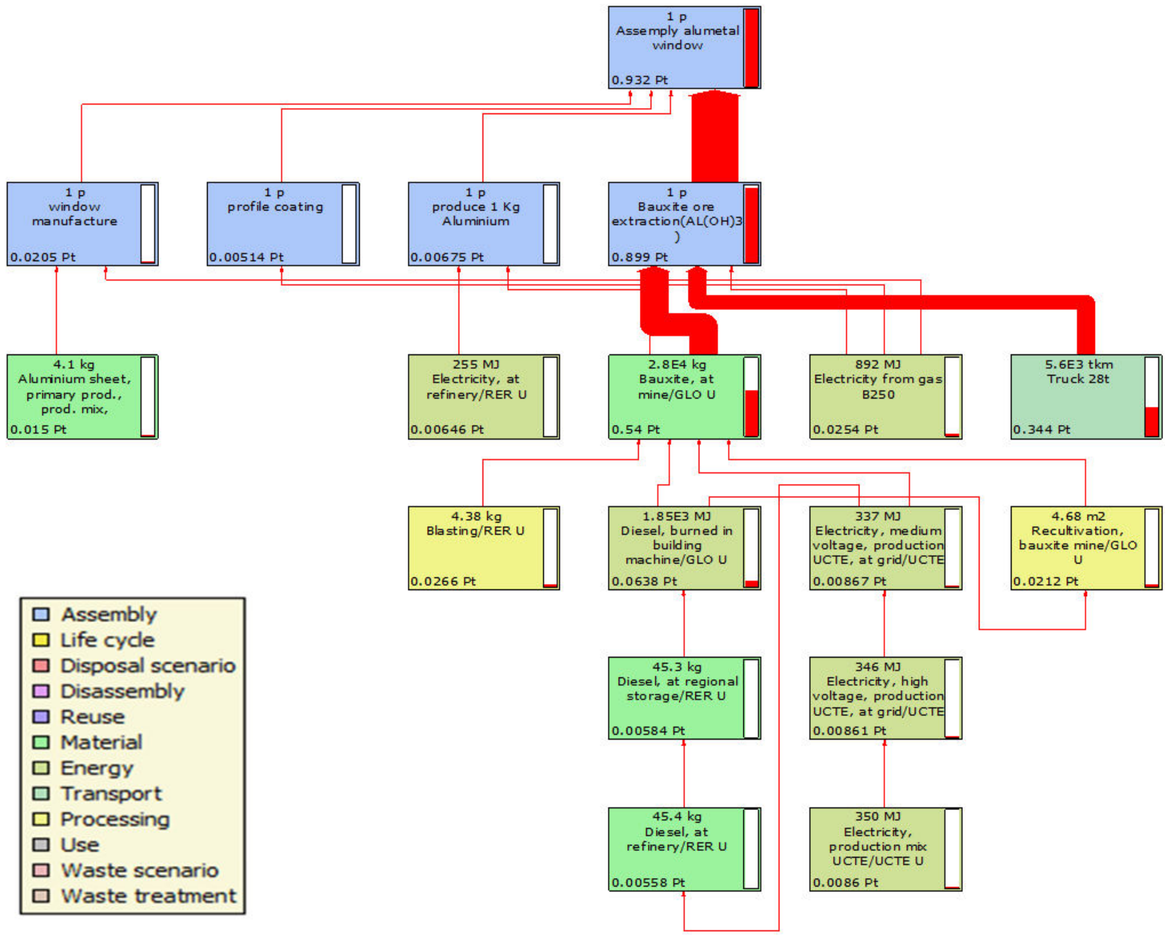

Fig. 4 The flowchart of assembly aluminum window

B. Beech Wood

Wood is a renewable material that can be used for wood products and energy production [16]. Beech wood can be defined as a renewable material with a very low embodied energy compared to aluminum [3]. Wood window is the traditional window frame material, because of its availability, ease of processing and the lowest thermal conductivity amongst frame materials [17]. Wood can be affected by moisture, which can make it warp or twist, so it have to be painted or stained and must be maintained every few years [3]. Fig. 5 shows the life cycle of beech wood window.

LCA of wood products usually consists of three main phases: (production, use, and end of life) [16]. The production phase that has a large input and has three basic parts for modelling the beech wood window:

1. Cutting a tree and sawing planks in sawmill are studied in order to describe their environmental impact, and for the steel parts that exist in sawmill will be used from the existing data in SimaPro Eco invent database.
2. Describing the end of life for the beech wood shed, as in our example assuming that 40% of the wood will be burned, 60% is landfilled [18].
3. Developing the specifications of the shed and the life cycle, so the electricity used in sawmill will be added. Fig. 6 shows the beech wood window network.

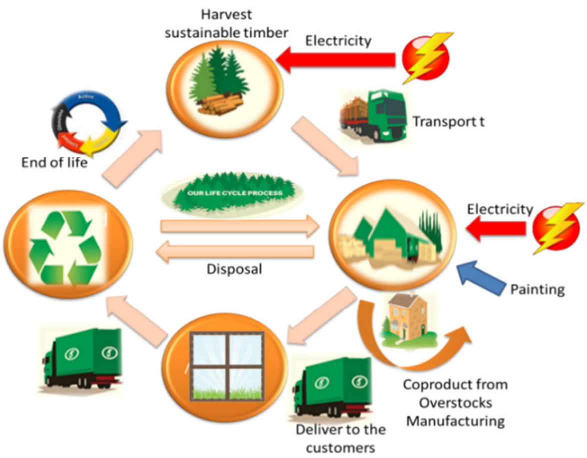

Fig. 5 Life cycle stages of a beech wood window

The data requirements of the beech wood window approach depend on the goal and scope of this study, this leads, to the functionally as the following:

- LCA particle boards: 1 m^3 particle board+ y kWh electricity + z kWh heat.
- LCA wooden products: 1 wooden product+ y kWh electricity + z kWh heat.
- LCA bioenergy for heat and electricity: y kWh electricity+ z kWh heat.
- LCA sawmill: 1 m^3 wood board + y kWh electricity + z kWh heat (if co-products from sawmill are only used for energy) [16].

A. Goal and Scope

The main objectives of this work are to evaluate and compare the impacts caused by the production of each window type using LCA through their entire life cycles. Also, recognize the significant contributors to impacts from these two materials in green building design. The formal of the functional unit is declared in the following points:

- Materials: Aluminum and beech wood window.
- Size: 1.2m x 1.2m.
- Style: casement.
- Frame profile: standard frame profile for Egypt manufacturer.
- Length of service: 75 years.
- Maintenance: sealed unit replacement.
- Operable: operable.

The LCA work included all life cycle from raw material extraction to product manufacturing, installation, maintenance and disposal at the end of life. Figs. 7 and 8 show the process diagrams of aluminum and beech wood windows respectively. Transportation was considered for all materials up to the point of installation. The system boundaries are established such that, the transportation values are similar for the two materials, aluminum and beech wood window to eliminate their significant environmental impacts in the present comparative study.

B. Life Cycle Inventory

The collected inventories of the two materials are grouped into impact categories and scaled based on IMPACT 2002+ v2.12 characterization and damage factors. The flows of resources used and emissions in the product system are calculated for each process included in the product system definition. This is called the life cycle inventory (LCI) [1]. The impacts on the environment are then calculated based on the LCI for the product system and factors relating to their flows to indices the environmental degradation, which called characterization factors. Table I presented the LCI input data for the two types of materials (aluminum and beech wood).

C. Life Cycle Impact Assessment

Life cycle assessment is a quantitative technique for evaluating the resources used and associated environmental burdens of a product from "cradle to grave", and emissions identified in the life cycle inventory. ISO 14042 (2000) specifies that all the resource used, health consequences, and ecological consequences are grouped into impact categories to which an impact indicator is calculated [21]. It considers all life stages of a product from resource extraction and manufacturing to secondary manufacturing, use, maintenance and end of life.

This is achieved by scaling inventory values by their relative influence and reporting in common terms, greenhouse gas emissions as CO_2 equivalents for example. These emission equivalence categories are referred to as midpoint impact categories while further modeling may be completed to calculate their effects on human health, ecological quality, and resource use damage categories. Life cycle impacts may be either reported directly, normalized to show the relative scale, or weighted based on estimates of valuation functions [1].

1. Impact 2002+ Method

The environmental impacts of all resources used, wastes and emissions generated over the life cycle of windows identified in the life cycle inventory stage are assessed using IMPACT 2002+. The impact categories can generally be classified as affecting human health, ecosystem quality, resource use, and global warming. The global warming and resource use are grouped together under the heading name of carrying capacity because these categories affects directly on the earth's ability to support human populations [9].

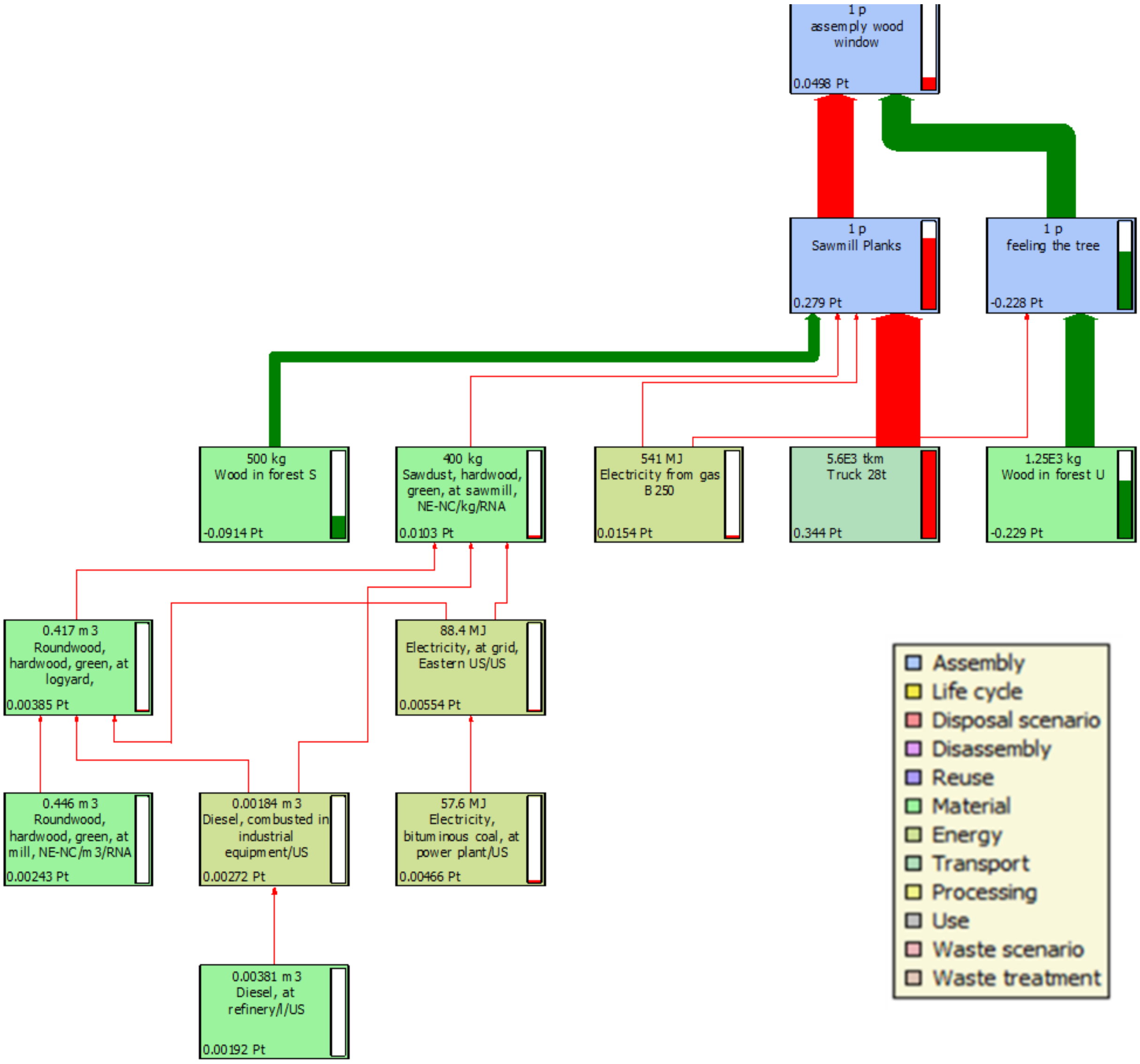

Fig. 6 The flowchart of assembly beech wood window

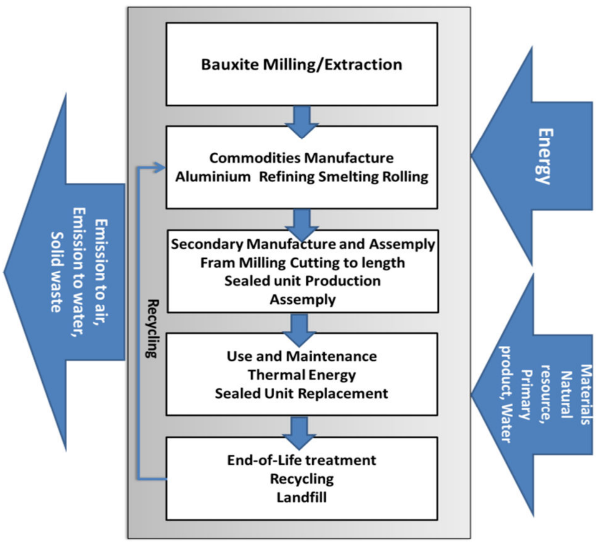

Fig. 7 System boundary for aluminum window [19]

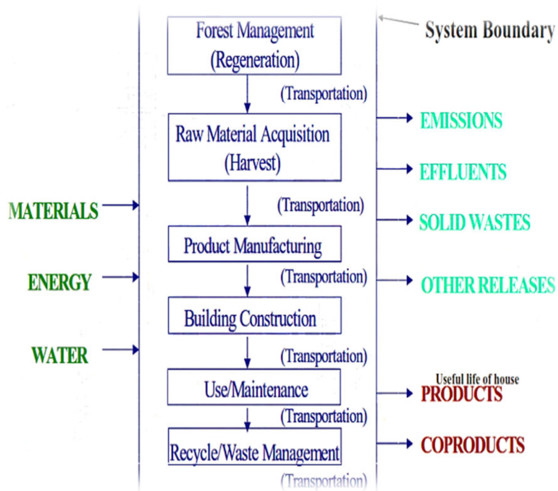

Fig. 8 System boundary for beech wood window [20]

TABLE I
INPUT DATA FOR ALUMINUM AND BEECH WOOD

	Input	Amount	Reference
Aluminum			
Bauxite ore extraction	-Bauxite, at mine/GLO U	28 ton	[3]
	-Electricity from gas B250	140 kWh	[12]
	-Truck 28t	5600 tkm	Assumed
Produce 1 kg aluminum	-Process water, ion exchange, production mix, at plant, from surface water RER S	9500 kg	[3]
	-NaOH ETH U	0.215 kg	
	-Lime I	0.086 ton	
	-Bauxite, at mine/GLO U	4.750 kg	
	-Carbon monoxide, CO, at plant/RER U	0.400 kg	
	-Aluminum fluoride, at plant/RER U	0.018 kg	
	-Cryolite, at plant/RER U	0.007 kg	
	-Electricity, at refinery/RER U	255 Mj	[12]
Produce 1 kg aluminum from aluminum scrap	-Aluminum scrap, post-consumer, prepared for melting {RoW}| treatment of aluminum scrap, post-consumer, by collecting, sorting, cleaning, pressing | Alloc Rec, U	1.180 kg	[3]
	-Electricity from gas B250	15.75 Mj	[12]
Profile coating	-Coating powder, at plant/RER S	0.061488 g	[2]
	-Electricity from gas B250	50 kWh	[12]
Window manufacture	-Aluminum sheet, primary prod., prod. mix, aluminum semi-finished sheet product RER S	4.0992 kg	[2]
	-Transport, single unit truck, diesel powered/US	0.040992 kgkm	Assumed
	-Electricity from gas B250	53.2896 kWh	[12]
	Beech wood		
feeling the tree	-Wood in forest U	1.25 ton	[22]
	- Chain sawing I	3 min	
	-Electricity from gas B250	0.386116 kWh	
Sawmill Planks	-Wood in forest S	500 kg	[22]
	-Sawdust, hardwood, green, at sawmill, NE-NC/kg/RNA	400 kg	
	-Pine log with bark, reforested managed forest, production mix entry to saw mill, 44% water content DE S	100 kg	
	-Electricity from gas B250	150 kWh	
	-Truck 28t	5600 tkm	Assumed
Shedfor product window	-Wood board ETH S	6.12 kg	[22]
	-Steel low alloy ETH U	2 kg	
	-Transport, single unit truck, diesel powered/tkm/RNA	0.0612 tkm	Assumed
	-Automotive painting, electro coating, per m2/RNA	0.0240061 5 m^2	[20]

2. Midpoint Results

The midpoint category results are represented in terms of equivalence to a reference substance commonly associated with that impact [21]. However, the midpoint values give a little insight as to the effects of the product system beyond the relative intra category impacts towards the three areas of protection [18]. By multiplying the midpoint results by a second group of characterization factors that relate the midpoint category to a damage effect, the relative significance of each towards total effects on human health, ecological quality, and the earth's carrying capacity may be understood [1]. The following describes the units that used to calculate damage effects across midpoint categories:

- Human Health: Disability Adjusted Life Years (DALY) is the decrease in life expectancy and healthy years due to disability. Where the aluminum present the disability for 0.36 Pt, and the wood disability is 0.14 Pt. so, the aluminum has a bad effect on human health.
- Ecosystem Quality: Potentially disappeared fraction (species) over a given area and a length of time relates ecosystem damage directly to the degradation of species populations. Where the wood has a good effect on ecosystem than the aluminum.
- Carrying Capacity—Resource Use (MJ): The energy value relates to the expected future increase in energy requirements to recover that resource. The wood manufacturing utilizes the resources in a good manner than the aluminum manufacturing.
- Carrying Capacity—Global Warming (kg CO_2): The global warming in terms of the midpoint equivalence is affected due to the manufacturing of wood or aluminum. It's cleared that wood has a good impact on warming than in aluminum case. Fig. 9 provides a graphical representation Cradle to grave Midpoint Impact totals for aluminum and beech wood.

3. Damage Results

The life cycle impacts are disaggregated into the different stages in the lives of the two window types. The major life stages include the resource extraction and manufacture of the finished product, use and maintenance, and end of life treatment. The damage impact of the two window types are shown in Fig. 10, from the figure it's cleared that the effect of damage on human health is better than its effect in case of wood, where the damage effect of wood is 43% and the aluminum is 100%. In case of ecosystem its cleared that the impact of damage in aluminum is decreased to 75% where in wood frame is increased to 100%, and the interpreted of these changes in damage impact is due to the cutting of trees that convert CO_2 to O_2 and according to this the ecosystem is defected in a high percentage for aluminum, and according to this impact the beech wood has a good impact on climate change in opposite to aluminum, and in resources the rate of consumption of wood as a natural resource is higher than aluminum.

4. Cradle to Gate Findings

The primary goal of this LCA was to compare the life cycles of the two frame materials. For this reason, the cradle to gate window manufacture was disaggregated to show the influence of the primary frame material, for the wood and aluminum windows, sealed unit, all other materials, secondary manufacturing energy, and transportation of materials to the manufacturer.

The cradle to gate results provides several significant insights. First, the wood use less energy and cause less acidification/nitrification, and emissions of respiratory inorganics, and greenhouse gas than the aluminum materials alone. The aluminum causes the total frame impacts to be greatest for these materials. This is particularly noticeable for the wood window frame, in which a majority of frame impacts are caused by the aluminum.

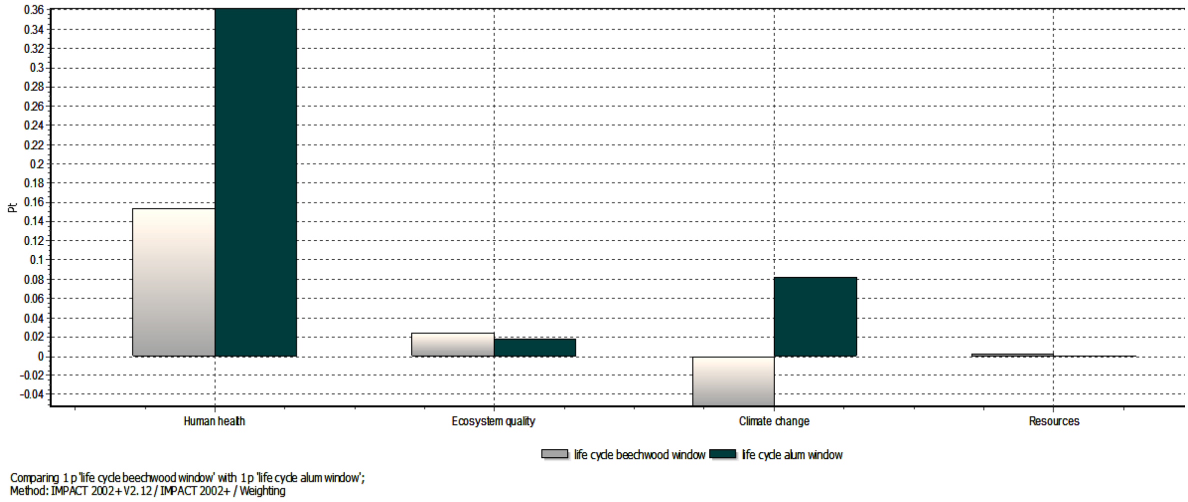

Fig. 9 Cradle to grave midpoint impact for aluminum and beech wood windows

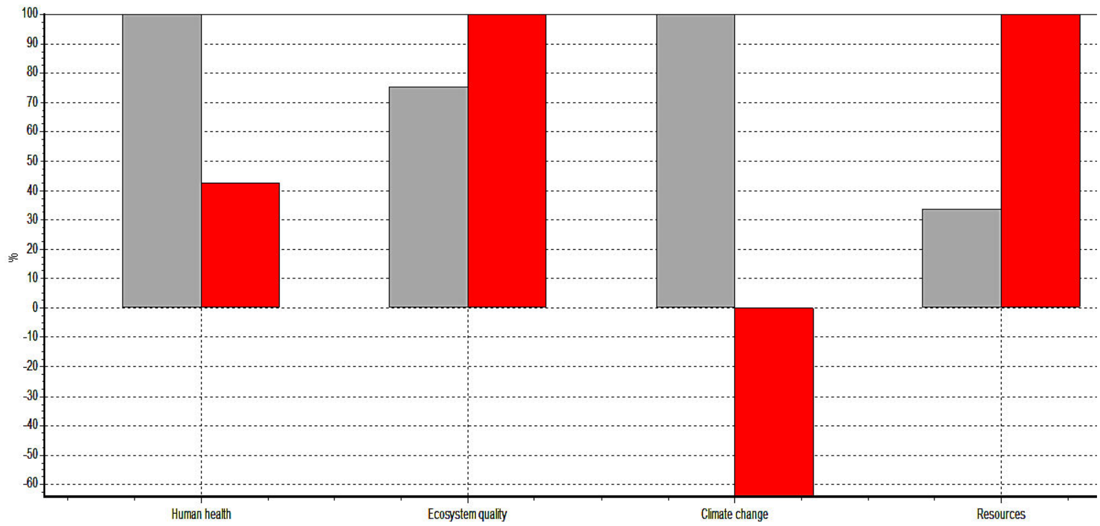

Fig. 10 Damage results for different life stages of aluminum and beech wood windows

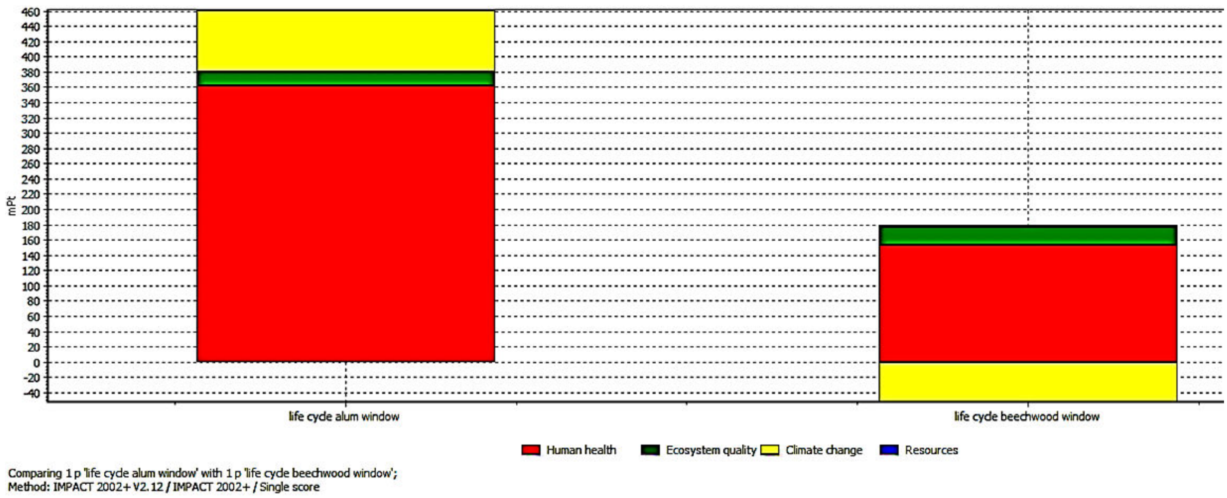

Fig. 11 Single score of aluminum and beech wood windows

IV. Analyzing the Results

Life cycle assessments of windows have generally been used for two purposes; the first one is comparing window frame materials and it determines their relative contribution to impacts. The second is the performance of windows based on the choice of material, proper maintenance and cleaning is another important factor in durability and service life of windows. Aluminum window needs low maintenance however beech wood window needs high maintenance but easy to repair. Fig. 11, the single score results for the two types of windows are presented to declare their impact on human health, ecosystem quality, climate change, and resources. It's cleared that the aluminum has a negative impact on human health with large points, but for the wood windows, it has a negative effect with little points. Also, their impact on climate change cleared that the aluminum has a negative effect but inversely, the wood has a positive effect.

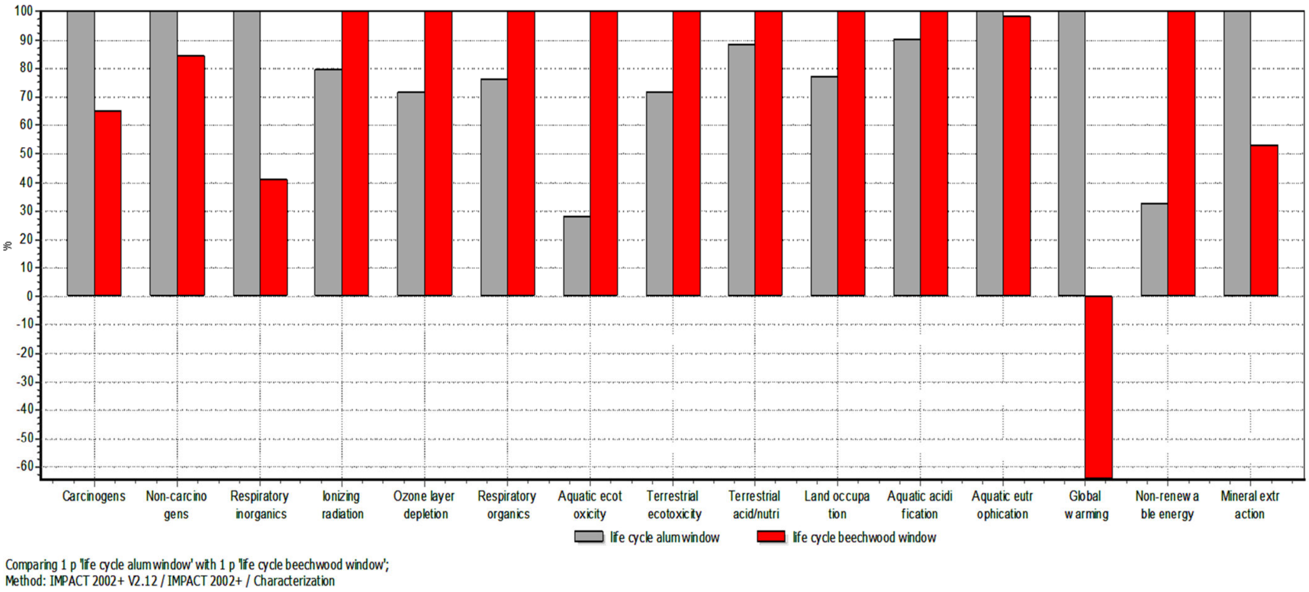

Fig. 12 Characterization factors for aluminum and beech wood windows

Fig. 12 shows a comparison between the impacts of an aluminum window frame and wood window frame. The highest score is scaled to 100% and the lowest is a relative score. In a simple case the difference between all scores is floated percentage from 29%, up to 90% as the allocation factor influences most impacts in the same way, but there is a good effect of wood window on the global warming. In a complex process tree with many allocated processes the result will be different, and it is precisely in these situations where parameterized allocation is extremely powerful.

V. Conclusion

In this study, the differences among the materials that used in window manufacturing are presented to show in clear way, what is the choice in green building design. It's cleared that the wood has a positive impact than the aluminum in case of climate change. Also, removal of, or clarification of the effects of some remaining uncertainties in LCA of wood products will be valuable. The partnership between the forest/forest products sectors and other agencies to develop LCI datasets will greatly support the place of wood in green building design, so the environmental performance through building construction from beech wood window is the best. This study provide a benchmark of environmental performance for forests, mills, and buildings that can be used to evaluate improved performance alternatives in terms of global warming potential, air quality index, water quality index, waste, energy use, and forest structure/health/biodiversity. The results showed that wood products that have been installed and are used in an appropriate way tend to have a favorable environmental profile compared aluminum products.

Acknowledgment

The first author would like to thank Egyptian Ministry of Higher Education (MoHE) for providing him the financial support (PhD scholarship) for this research as well as the Egypt Japan University of Science and Technology (E-JUST) for offering the facility and tools needed to conduct this work. Thanks are also due to my colleague Eng. Ahmed Abdel Monteleb, PhD at E-JUST for his help during the training on SimaPro Software. Thanks are extended also to include people of "PRé Consultants bv" from SimaPro Co. for their support during the ENV605 LCA course at E-JUST.

References

[1] James Salazar, Life cycle assessment case study of North American residential windows, MASTER thesis, the University of British Columbia December 2007.

[2] Recio, J.M.B, Narvaez, R.P., and P. J. Guerrero. 2005. Estimate of energy consumption and CO2 emission associated with the production, use and final disposal of PVC, aluminium, and wooden windows. Department de Projectes d'Engineyeria, Universitat Politecnica de

Catalunya, Environmental Modelling Laboratory Barcelona, Spain. Retrieved on August 23, 2007 from http://www.aboutpvc.org/recursos/12recurso.pdf.

[3] Asif M., A. Davidson, and T. Muneer. "Life cycle of window materials-A comparative assessment." Millennium Fellow School of Engineering, Napier University, Edinburgh http://www. cibse. org/pdfs/Masif. Pdf, 2002.

[4] The World Steel Association, "Life cycle inventory study for steel products", report, 2011.

[5] Mary A. Curran, "Life cycle assessment handbook: a guide for environmentally sustainable products", Wiley, 2012.

[6] Richter K, Kiinniger T, Brunner K. Environmental assessment of window constructions of different frame materials (without glazing) (in German). Empa-SZFF-Forschungsbericht, Schweizerische Zentralstelle fiir Fenster- und Fassadenbau (SZFF), Dietikon, 1996.

[7] Kreissig J, Baitz M, Betz M, Straub W. Ganzheitliche Bilanzierung von Fenstem und Fassaden. Institut for Kunststoffpriifung der Universitat Stuttgart, Stuttgart, 1997.

[8] Werner F., et al, Wooden Building Products in Comparative LCA a Literature Review, Wood and Other Renewable Resource. Int J LCA 12 (7) 47Q-479, 2007.

[9] Jungmeier G. et al, Allocation in LCA of Wood-based Products Experiences of Cost Action E9, Part II. Examples, LCA Case Studies, Int J LCA 7 (6) 369 – 375, 2002.

[10] Elizabeth Minne et al, "Influence of climate on the environmental and economic life cycle assessments of window options in the United States", Buildings, Volume 102, Pages 293–306, 2015.

[11] ISO 14040, "Environmental management - Life cycle assessment - Principles and framework", 1st Edition, 1997.

[12] Alumina Technology Roadmap (minor update), International Aluminium Institute, March 2006. (www.worldaluminium.org/UserFiles/File/AluminaTechnologyRoadmap%20Update%20FINAL%20M y%20 2006.pdf)

[13] Weir, G. and Muneer, T., Energy and Environmental Impact Analysis of Double-Glazed Windows, Energy Convers. Mgmt Vol. 39, No.3/4, pp. 243-256, 1998.

[14] Bjorn Berge, The Ecology of Building Materials, Architectural Press, 2001.

[15] Industrial Technologies Program, "U.S. Energy Requirements for Aluminum Production", Tech. Report, 2007.

[16] Jungmeier G. et al, Allocation in LCA of Wood-based Products Experiences of Cost Action E9, Part I. Methodology, LCA case study, Int J LCA 7 (5) 290 - 294, 2002.

[17] Edwards, D. and Schelling, J., Municipal Waste Life Cycle Assessment Part1, And Aluminium Case Study, Process Safety and Environmental Protection, Aug 1996.

[18] Udo de Haes, H. A., Jolliet, O., Finnveden, G., Hauschild, M., Krewitt, W. & Mueller-Wenk, R. Best available practice regarding impact categories and category indicators in life cycle impact assessment: Part 1. International Journal of Life Cycle Assessment, 4, 66_74, 1999.

[19] The Athena Sustainable Materials Institute Ottawa, ON, Canada and Kutztown PA, USA james.salazar@athenasmi.org. www.athenasmi.org.

[20] Bruce Lippke and President Corri, Wood products life cycle analysis: New research shows the environmental benefits from using wood.

[21] Pennington, D. W., Potting, J., Finnveden, G, Lindeijer, E., Jolliet, 0., Rydberg, T. and G. Rebitzer. Life Cycle Assessment Part 2: Current Impact Assessment Practice. Env. Int. 30(5): 721-739, 2004.

[22] Mark Goedkoop, SimaPro 5, Toutorial the wood example. November 2002.