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The Application of Life Cycle Assessment to a Building: A Systematic Literature Review

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***Abstract*—The increased population and rapid urbanisation are the major contributors to Greenhouse Gas (GHG) emission which has drastic impact on environment. Several studies are conducted on Life Cycle Assessment (LCA) approach which has been applied on different areas of building from its material production stage to end of life stage. This review assembles and encapsulates recent endowments associated with environmental impact evaluation using the LCA methodology. The study classifies the recent contributions in this sector into six different streams, such as (i) different types of residential buildings, (ii) building rehabilitation work, (iii) recycled building materials, (iv) building materials, (v) building elements, (vi) Construction and Demolition Waste (CDW). The review shows that many research have conducted based on lifecycle assessment using variegated methods particularly process LCA, input-output LCA and hybrid LCA on different stages of a building. Various impact categories were considered in each paper to determine the intensity of environmental impact. The success of LCA approach lies on data availability and framework modelling.**

***Index Terms*— GHG emission, Lifecycle Assessment (LCA), Environmental impact, Sustainable construction, Embodied carbon, Low carbon building.**

I. INTRODUCTION

The construction industry with a reinvigorating development has harmful impact on environment. The studies conducted by U.K. Green Building Council stated that the construction sector alone uses about 400 million tons of resources out of which many are harmful to the environment. Excessive utilization of materials causes depletion of natural resources, thus creates adverse impact on environment. It has been said that the construction industry give rise to natural resource depletion by 40 – 60% and GHG emission by 40 – 50% [1,2]. At this context the sustainable development is an important terminology which the people are conscious about. Sustainability should be ensured in each phase of a building construction to its end of life stage to attain eco friendly buildings such as green building. Lifecycle assessment (LCA) is a world widely accepted sustainability analysis tool. The Figure.1 shows the diagrammatic representation of LCA of a building. LCA implies an authentic analysis of any product lifecycle in terms of sustainability. Every phase of a product lifecycle that means from material procurement from the environment through the manufacturing of product, use phase up to end of life phase could make impact on the environment in many ways. Thus by the application of LCA, we can evaluate the environmental impacts of any product or service from the very first phase to the very last phase or

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from cradle to grave. LCA is a methodology used in environmentally- conscious manufacturing (ECM) to evaluate the environmental burden formed during product life cycle with an intention of employing an effectual improvement programmes. LCA comprises four stages. The first phase, goal and scope definition, defines the aim, objectives, assumptions etc. At this phase the system boundary and the functional unit are being defined well. In inventory analysis, within the defined functional unit the input and output of the particular product system are identified. During the lifecycle of the product system the inventory flow for a specific process, raw materials flow, energy input and output, various emission occurred etc are analysed. It also constitutes the data collection, validation and quality assurance. The third phase called impact assessment determines the aggregate results to evaluate the environmental load through impact category selection, classification and normalisation process. The lifecycle interpretation phase summarizes the results and compare the alternatives thus recommends the most environmentally viable solution.

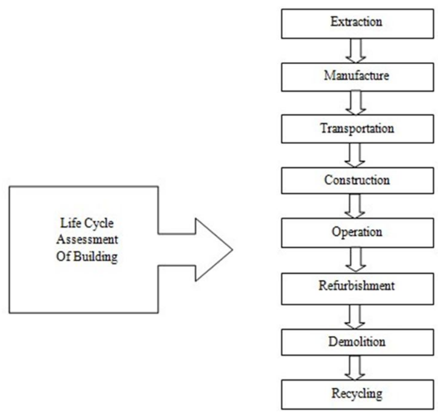

Figure 1. Diagrammatic representation of LCA of a building

II. LIFECYCLE ASSESSMENT OF A BUILDING

This section deals with the six different streams such as (i) different residential buildings, (ii) building materials and recycled aggregate products, (iii) building rehabilitation work, where LCA is applied.

A. LCA of Different Residential Buildings

[3] The total energy consumed by the building is 42,887.93 tce out of which it emits about 146,053.09 t CO_2 during its useful life span. Further reduction in Life Cycle Energy (LCE) can be achieved through reuse and recycling of building materials at the end phase of the building [3]. [4] The total emission for case-1 building was about 59.3 to 62.6 ktCO_2e and for case-2 was 43.6 to 46.2 ktCO_2e. It has been observed that the hybrid methods widen the system boundary mainly in production and construction stages. In case of parametric uncertainty, stochastic simulation was dependable than deterministic point of view. The coefficient of variation for Input-Output (IO) methods has shown higher difference and imprecision than other methods. Considering the scenario uncertainty, four types of heating systems were scrutinized which revealed that process based and hybrid methods has similar results whereas IO process exhibited less sensitivity. It is said that solid IO method may produce inaccuracy and apprehension in the outcome of life cycle emission assessment. Otherwise one can use IO method as which may perform compatible with hybrid methods or which could augment system boundary of process based method [4]. [5] The results obtained from process analysis were, (i) the building material manufacturing and chemical reaction together shown higher carbon dioxide emission, which is 83.06 percent of total carbon emission, (ii) Reinforced concrete structures exhibited more carbon dioxide emission than steel frame structures, (iii) Construction materials has greater impact on total embodied carbon emission of buildings. The outcome of IO analysis was (i) residential buildings emitted higher amount of embodied carbon compared to non residential buildings (ii) unveiled more impact of about 13 percent in the total embodied carbon. The embodied carbon emission result obtained from process-based method was 1421.70 Mt and that of IO model was 1599.6216 Mt [5]. [6] The results revealed that for case-1, the increased volume of wood intensified the environmental impact factors. The most sensitivity criterion for case-1 was stratospheric ozone depletion and the least one was global warming potential. In case-2, the most sensitivity criterion was eutrophication and the least one was stratospheric ozone depletion. [7] In cluster-1 it is stated that the key parameters that intensifies the

environmental load was project area, structural landscape work, transportation and location. For cluster-2, the building typology and urban structure were the backbone parameters. Three middle income group sample projects are considered, (i) sample-1 has total area of 45,812 m^2, (ii) sample-2 has total area of 67,597 m^2, (iii) sample-3 has total area of 35,518 m^2. The results uncovered that the average carbon emission of three neighbourhood scale projects was 409.2 $kgCO_2$-eq/m^2. The average percentage of emission derived from buildings, landscape structure and transportation infrastructure are 66.6%, 9.1% and 24.3% respectively, where the chief contributor on carbon emission was transportation infrastructure. [8] In this study the emission factors were evaluated by applying a top down approach whereas the activity intensities are calculated using bottom up approach. The paper concluded that the total carbon footprint (CF) estimated for CU was about 95,418 metric tons CO_2-e. The carbon emission for Scope-1, 2 and 3 were 18,041, 38,718, and 38,659 metric tons CO_2-e respectively. In [9] it was observed that the solvent based method (17.0 kg CO_2eq) was accountable for prime impact in Global Warming category while the Ion-exchange resins produces impact on Ozone layer depletion category. From the results it is recognized that there were no significant difference in results and the ranking amidst the cleaning methods were similar. [10] Noticed that the wind and earthquake lateral loads had striking impact on EGHGE of structural systems of tall building by about 22%. [11] The study reported that smaller sizes of home-stays and simplicity of amenities used, reduced GHG emission of home-stays compared to other types of tourist homes. The GHG emission per guest night was higher. The substantial donor of carbon footprint was electricity consumption. Another facility which generates negative impact on environment was swimming pool and air conditioning units. The summary on the LCA of different residential buildings is shown in the Table I.

B. LCA of Building Materials and Recycled Aggregates Products

[12] The implementation of midpoint analysis on the three scenarios and the PC-based concrete blocks shown that the latter has greater environmental impact for the categories such as climate change biogenic and non-biogenic, resource depletion minerals, ecotoxicity freshwater, land use, eutrophication freshwater, acidification, human toxicity cancer and non-cancer effect whereas former shown greater impact on ionising radiation, particulate matter, ozone depletion, resource depletion water, eutrophication marine and terrestrial, and photochemical ozone formation [12]. [13] Including mechanical property, recycled gypsum from plasterboard waste revealed a better environmental performance. The study showed that the application of recycled gypsum products will reduce the CO_2 emission by about 60% in 2050. The effect of using light weight materials in building construction in terms of carbon emission investigated impact assessment and found that the building material manufacturing process produces about 98.9 % indirect emission [14]. Regarding recyclability, biodegradability, and renewability Natural Fibre Reinforced Composites (NFC) they have best environmental performance [15]. The natural fibre reinforced polymer composites represents similar mechanical strength to that of glass fibre reinforced polymer composites, only if the volume of natural fibre are higher than glass fibre. Natural fibres are now used as a substitute for synthetic fibre. LCA approaches are applicable only when the relevant data are available for all the life cycle stages considered. The significant increase in GWP value in plant fibre blocks usage was due to usage of Nitrogen, Phosphorous, Potassium (NPK) fertilizers on crop which can be controlled by applying other alternatives. The comparative study on plant fibre blocks and other commonly used building materials showed that the former reduces ozone depletion by about 60% [16]. Ornamental Stone Processing Waste (OSPW) has less impact when compared to limestone filler, sand, and stone dust on the other side the imposition of artificial mode of drying intensifies the environmental impact [17]. Rotary dryer was found to have lower incorporated impact significantly on GWP basis. It has revealed that OSPW transportation distance is directly proportional to impact indicator (GWP). It was observed that replacement of lime with OSPW up to 100% implicated about 22% to 32% reduction in the impact indicator, also replacement of cement with OSPW for conventional concrete had a reduction of 20%. In case of High Strength Concrete (HSC) the 100% replacement of sand by OSPW made a 7% reduction and for self compacting concrete (SCC), replacement of cement by OSPW made 25% reduction on impact indicators. For Concrete Masonry Blocks (CMB) and Concrete Paving Blocks (CPB) on replacement of cement by OSPW, a decrease in impact indicators was observed by 13% and 36% respectively. The impact intensity analysis shown that OSPW and heat-treated waste (HTOSPW) cannot be used as substitute for materials that demand high performance of mechanical strength [17]. [18] In circular economy point of view Natural Aggregate (NA) substituted by Recycled Concrete Aggregates (RCA) can reduce the environmental impact of concrete block manufacturing. [19] The results obtained on application of LCA on concrete structure showed that choosing Recycled Aggregate Concrete (RAC) strategies elevated the impact indicators at the material stage but disclosed a curtailment effect at transportation and disposal stage. On the application of Design for Deconstruction (DfD) reuse strategy, GWP

TABLE I. SUMMARY ON LCA OF DIFFERENT RESIDENTIAL BUILDINGS

Study	Objective	Functional Unit	System Boundary	Assessment Tool/Methodology	Main Result
[3]	To calculate the embodied emission (EE) of a green research building in China	-	Cradle-to-grave	Hybrid Analysis method/ SimaPro	The installation rooftop solar photovoltaic system reduces operational energy and use of energy efficient building materials and reduced wastage of materials bounds the EE throughout the usage of building
[4]	To compare and assess uncertainty of the life cycle emission of two residential buildings in China	The whole building	Cradle-to-grave	DQI-based stochastic simulation	In view of model uncertainty, all the four methods unveiled similar results with the exception of slight increase in emission on the implementation of lognormal distribution
[5]	To analyse the embodied carbon emission of building sectors in China	-	Cradle-to-grave	Process-based method/ statistical method/ IO analysis	Demolition and rehabilitation of building can reduce the carbon emission considerably
[6]	LCA on sensitivity study of hybrid timber building on the basis of variation in type and amount of materials	1m^2 of floor area	Cradle-to-grave	Athena IE4B/ TRACI 2.1	Athena (IE4B) could be used as a tool to get expeditious environmental analysis for engineers and architects in case of new construction, rehabilitation and maintenance works
[7]	LCA on embodied carbon assessment of three neighbourhood scale residential building projects in Ankara	1m^2 of floor area	Cradle-to-gate	CML 2001	It is unavoidable to lay a significant importance in large scale built environment
[8]	To assess the carbon emission of Clemson University (CU) campus in South Carolina	-	GHG emission sources and buildings on or related to CU's main campus, with the inclusion of the Madren Conference Center and CU Wastewater Treatment Plant	Consumption-based hybrid LCA (HLCA)/ EIO-LCA	The CF is more for GHG emission generated from electricity that is about 41% of total emission
[9]	LCA approach for the case of cleaning works in historical buildings	Cleaning of 1m^2 of a plain vertical surface affected by a normal black crust	Cradle-to-grave	CML-IA baseline/IMPACT 2002+/IPCC GWP 100a/ TRACI 2.1	LCA approach is applicable for maintenance works with superior credentials on cleaning
[10]	To study the influence of lateral load, facade load and imposed load on EGHGE of structural systems for tall buildings	-	Production stage and construction stage	ETABS software/ Path exchange (PXC) method	Developed and illustrated three new functional units (kgCO_2-e/m^2)/kPa, (kgCO_2-e/m^2)/(kN/m),(kgCO_2-e/m^2)/(10 MNm)
[11]	Carbon footprint assessment on home-stays in Thailand	-	Inputs and outputs during operational stage	LCEA method/Surveys/Interviews	Necessary to pay attention on selecting amenities for the home-stay considering its environmental performance

increased at demolition stage but the impact was less at material and disposal stage. It was found that conventional demolition gobbles diesel while deconstruction process gobbles electricity. In case of conventional construction the GWP value obtained from both methods were similar, however conventional LCA was found to be more significant for the reusable components. The [19] has selected RAC and DfD as representative examples for recycling and reuse strategies. But application of both the strategies at a time has no remarkable effect but it increases the overall benefits. Also it was notable that total replacement of a reusable structure by RAC has 15% reduction in GWP and 13.3% reduction in ADP. [20] The total GWP_{100} estimated from the manufacturing of normal concrete blocks was 5.53% more compared to Recycled Concrete Aggregates (RCA) blocks, similarly 19.21% - 65.14% reduction was observed in the other four impact categories due to use of RCA blocks. The environmental load impact produced by cement was found as 87.7% of total GWP_{100}. Comparably manufacturing concrete blocks from RAC has 56% more GHG emission than blocks manufactured from NA. The summary on the LCA of building materials and recycled aggregate products is shown in the Table II.

C. LCA of Rehabilitation Works in a Building

[21] For a building renovation alternative analysis it can be seen that for each step of analysis the exogenous impact parameters has shown an incremental nature. The results monitored the heating replacement as the most predominant parameter for life cycle environmental impact (LCEI) and life cycle cost analysis (LCC). Another factor highlighted in the study was, since building refurbishment has greater influence on climate change, the only life-cycle assessment (LCA) indicator examined was global warming potential (GWP), otherwise GWP will go on proportionate to pollution. [22] The architects converted the old mill building into a five storey residential building with total 12 apartments. It can be seen that GWP has greater influence during the operational stage by 56%. Due to usage of steel greater influence was seen in the impact category of photochemical ozone creation potential (PCOP) by 26%. The contribution of abiotic depletion potential of elements (ADP-E) during product stage was 90%. In total 1900 kg CO_2^{-}equiv/m^2 energy produced by the reconstruction of the building. The impact categories, GWP, POCP, ADP-FF and PENRT were mostly influenced by reinforcing steel which is used for floor and ceiling. [23] Aimed at the impact analysis of different building floor systems for use in building floor rehabilitation using LCA. In case of Primary Non Renewable Energy Consumption (PE-NRe), timber enacted as the inferior floor solution. The carbon emissions due to window retrofitting with a case study of a multi apartment school building in Johor, Malaysia, four types of windows, (i) general window glass, (ii) single glazing, (iii) double glazing and (iv) triple glazing were evaluated [24]. All the four Life-Cycle Thinking (LCT) categories were assessed and compared for both before and after renovation process. The results of noise assessment was triple glazing windows (6.34 L_{Aeq} dB(A)) has the higher noise reduction capacity and the double glazing windows (3.7 L_{Aeq} dB(A)) has acquired the second position. The CO_2 emission value obtained for preference window, single glazing, double glass, and triple glazing, were 3.39E+04 $KgCO_2$eq, 3.58E+04 $KgCO_2$eq, 3.68E+04 $KgCO_2$eq, and 5.10E+04 $KgCO_2$eq, respectively. Both double glazing and triple glazing windows are desirable for the school building, although double glazing windows exhibits lower CO_2 emission value during its life span. The analysis of LCC shown that cost of triple glazing windows are more compared to other two alternatives, but the total LCC value is higher for double glazing. Through social life cycle assessment it was clear that double glazing has better social performance than others [24]. [25] Considering the low cost and least values of all the environmental impact categories except the PE-Re category, timber floors are more eco-friendly. Composite sandwich panel made of glass-FRP skins and polyurethane (PUR) foam core were found to be the worst floor solution compared other four floor solutions. [26] The assessment of environmental performance of the office building shown that since the operational demand of the building stock in renewable energy (RE) scenario was less compared to BAU scenario, therefore potential impact of office building in Business as usual (BAU) scenario was found to be eminent than the former scenario. Out of the four aforementioned conditions in the study refurbished building with roof top PV installed on site (Rb PV) has economical potential impact except that of ionizing and abiotic depletion of resources categories. [27] The LCA analysis of the retrofit improvement measures showed that the product/material manufacturing phase has the greater environmental impact compared to other phases. In comparison with heating, ventilation and air-conditioning (HVAC) and window replacement the foundation wall insulation made greater embodied energy impact in terms of SP and GWP. HVAC replacement revealed the most significant contribution towards all the environmental impact categories [27]. The summary on the LCA of rehabilitation work in a building is shown in the Table III.

II. FUTURE STUDY

There are many uncertainties occurred among these papers it should be given crucial weightage by considering the relations between metrics and sensitivity for implementing improvement tactics for emission reductions. The LCA framework developed in each study can be used in future studies by introducing additional hierarchy to it. In case of hybrid approaches its other forms should be evaluated in future studies which is not yet investigated.

TABLE II. SUMMARY ON LCA OF BUILDING MATERIALS *AND* RECYCLED AGGREGATES PRODUCTS

Study	Objective	Functional Unit	System Boundary	Assessment Tool/Methodology	Main Result
[12]	LCA was applied on the production of carbonated construction blocks	1 m^2 of compared materials	Production of carbonated blocks	Characterisation models - problem-oriented/Midpoint/Damage-oriented or endpoint/International Reference Life Cycle Data System (ILCD) v.1.09 framework	Carbonated blocks manufactured from SSS has lower impact on all categories compared to PC-based concrete blocks
[13]	Environmental assessment of production of natural and recycled gypsum in Spain	1 ton of gypsum	Cradle-to-gate	Simapro 8.5	The recycled gypsum has lowest environmental impact at endpoint analysis. Recycled gypsum from gypsum powder waste has better environmental performance
[14]	Environmental impact of construction materials	-	Cradle to gate	SimaPro 8.4	Use of AAC masonry over fire clay bricks made significant reduction on environmental impact categories. Fly ash displayed an optimal role over the GGBS mix in terms of structural and environmental aspects. Emission from fire clay bricks are more compared to AAC masonry
[15]	LCA on the natural fibre reinforced composite materials	-	Cradle-to-Grave	Two models were meshed, the plastic comparator (PC) and EIO-LCA (EIO)	NFC has less raw material costs, lightweight property and best environmental performance
[16]	LCA on plant fibre blocks used in building construction material	-	Product manufacturing stage, construction process, use, replacement and operational energy use	Ecometro tool	PFB has better sustainability
[17]	LCA of OSPW used in building materials	Volume of equivalent material to obtain 1 MPa of compressive strength	Cradle-to-gate	SimaPro 8.4	Partial cement replacement by OSPW can show off smaller reduction in impact indicator. It is not even visible in case of high strength mortars and concretes
[18]	LCA approach on use of recycled concrete aggregates from precast block for the production of new building blocks	$1m^3$ of concrete blocks	Cradle-to-gate	SimaPro 9.0	RCA on concrete blocks has no significant effect on any of the impact categories. Addition of RCA on concrete blocks reduced its compressive strength, hardened density and the durability
[19]	LCA, of concrete structure at Shangai, China with reuse and recycling strategies	Concrete structure with certain structural form and mechanical properties	For natural materials-cradle-to-grave For recycled materials-cradle-to-cradle	LCI results multiplied by characterization factors	DfD has about 1.8-2.8 times reduction impact indicators compared to that of RAC
[20]	LCA of recycled concrete aggregate block building at Nanjing Tech University in China	$1m^3$ concrete mixture	Cradle-to-gate	Microsoft Excel	Cement generates higher GHG emission. Replacement of NA concrete blocks by RAC blocks could minimise the environmental burden

TABLE III. SUMMARY ON LCA OF REHABILITATION WORKS IN A BUILDING

Study	Objective	Functional Unit	System Boundary	Assessment Tool/Methodology	Main Result
[21]	To pick out a robust building renovation alternatives in terms of environmental and economic performance	-	-	Monte Carlo Simulation (MCS)	Uncertainty throughout the life cycle of the building could be minimized by applying a risk index through uncertainty quantification
[22]	To assess environmental impact due to reconstruction of a old mill in Humenne	-	Cradle-to-gate with options	eToolLCD	A reconstruction of an object is recommended as the better option other than entire new construction by considering all geotechnical factors, technical, social, economical and market feasibility studies of the object.
[23]	Impact analysis of different building floor systems for use in building floor rehabilitation	1m^2 of floor area	Cradle-to-gate	SimaPro software	Timber portrayed best behaviour in most of the impact categories except PE-NRe and GFRP systems is the worst floor system
[24]	To assess the carbon emissions due to window retrofitting of a multi apartment school building in Johor, Malaysia	120cm x 120cm piece of product	Cradle to grave	SimaPro software	The best alternative outcome of multi-criteria decision making factor was double glazing windows and the second position was given to single glazing
[25]	To investigate the environmental and economic impacts of five floor retrofitting solutions	1 m^2 of floor area	Cradle-to-gate	SimaPro software	Timber floors are best floor solution whereas GFRP sandwich panles are the worst floor option
[26]	LCA on rehabilitation of an existing office building in New Zealand	1m^2 floor area for 30 years of service life	Cradle to grave	CML impact assessment	All nRb. Rb BCP, Rb PV buildings produces about 30-50% embodied impacts and 99% ozone depletion category.
[27]	A study to decrease the operational energy consumption of single family residential building through retrofitting measurements	Embodied primary energy and environmental impacts associated with improvement options	Embodied primary energy and environmental impacts associated with cradle to grave system	Process based LCA model/ SimaPro 8.1/ Athena Impact Estimator for Buildings 5.2	To reduce the energy consumption rate all through the effective life cycle of buildings the policy makers should take necessary effort to consider the embodied emission

Expert interviews and field survey are essential part of carbon emission evaluation. Combining environmental analysis and cost assessment has greater advantages in sustainable, eco-friendly, economic designing of a building.

III. CONCLUSIONS

The calculated carbon emission and impact categories can be used by the practitioners, designers and technology developers at the designing stage of building and the end of evaluation phase. The review on LCA in different fields related to a building put forward valuable enlightenment for a reader. The study states that during the lifecycle of a building from the raw material extraction to its material recycling phase, the manufacturing and operational phases are the main contributors of carbon emission. Moreover the recycling and reuse of materials could reduce the environmental emission rate to a great extent. Throughout all the papers one of the main uncertainty was due to the unavailability of data and the limitation of parameter setting in scenario analysis. Incorporating decision making strategies and design optimization with LCA could make more effective assessment on environmental impacts. Assimilating lifecycle cost analysis (LCCA) to LCA would make a better choice of selecting the correct alternatives. In total LCA provides the basis for get down to consequences of pollution and depletion of natural resources. The advantage of LCA is ecolabelling, since in environmental standpoint it helps to enterprise product and process improvement.

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