Life Cycle Carbon Footprint Assessments, Case Study of Malaysian Housing Sector

Syed Shujaa Safdar GARDEZI^{1*}, Nasir SHAFIQ², Ishtiaq HASSAN³, M. Usman ARSHID⁴

^{1,3}*Department of Civil Engineering, Capital University of Science & Technology (CUST), Islamabad Expressway, Kahuta Road, Zone-V 44000 Islamabad, Pakistan*

²*Department of Civil and Environmental Engineering, Universiti Teknologi PETRONAS, 32610 Seri Iskandar, Perak Darul Ridzuan, Malaysia*

⁴*Department of Civil Engineering, University of Engineering and Technology, Taxila, Pakistan*

Abstract – The ever-increasing concentration of Carbon footprint into the environment has drastically changed the climatic conditions. Among many anthropogenic activities, the housing sector remains one of the major contributors. However, a complete assessment of these environmental impacts throughout the life cycle still remains an area of concern. Most of the study does not assess the impacts by each phase of lifecycle. The current work presents a complete approach for carbon footprint assessment including planning, construction, operational, maintenance and dismantling & dispose-off phase. Life Cycle Assessment (LCA) with boundary limitations of ‘cradle to grave’ was adopted. Thirteen housing units were selected as case study. These included detached, semi-detached and terraced types of construction. Selected units were developed in a virtual environment using Building Information Modeling (BIM). The study observed the average contribution range from 1.48 tons-CO₂/yr to 2.85 tons-CO₂/yr. On individual basis, the execution phase dominated the five phases with almost 43 %. The operational phase shared 39 % followed by maintenance (15 %), dismantling & dispose-off (1.8 %) and planning at the last (1.5 %). The categorization of environmental impact into embodied and operational carbon footprint observed the embodied part in dominance. A strong positive relationship between the area of housing units and resulting carbon impact was also observed. The work presents one of few environmental studies for a tropical housing sector assessing complete life cycle. The study provides a vital guideline to the designers for ensuring a sustainable environment by assessing and opting less carbon intensive options at early stage of planning and design.

Keywords – Building Information Modelling; CO₂; embodied carbon; Life Cycle Assessment; operational carbon

1. INTRODUCTION

The increasing concentration of Carbon dioxide (CO₂) in particular, due to anthropogenic activities has seriously transformed the global climate system as compared to pre-industrial times [1]. An yearly addition of almost 30 billion tons of CO₂ into atmosphere is expected to cause a rise in the sea level by 10–20 cm during the 20th century with a 30 % increase in global CO₂ emissions and a temperature rise by 0.3 to 0.68 °C [2]–[4]. The construction sector remains a basic pillar for many economies. Despite its vital role, it is not considered an environmentally friendly industry. Significant energy consumption and corresponding

* Corresponding author.

E-mail address: dr.shujaasafdar@cust.edu.pk

Greenhouse Gas (GHG) emissions by this sector has been reported [5], [6]. Besides utilization of 60 % raw materials extracted from the Earth, it causes 50 % of all atmospheric CO₂, during raw materials transformation [7]. Presently, various largest sources of carbon footprint at global level relate to this sector [8]. In US, it remained the third largest contributor in carbon footprint sharing 38 % [9] and 39 % [10]. For EU-15, it consumes 46 % of the total energy usage and generates 46 % of CO₂ with 40 % of all man-made waste [11], [12]. Ireland observed 11.7 % (13.81 Mt CO₂eq) [13], [14]. For Spain, Germany, and France, it represented 40 %, 23 % and 22 % share of construction in their overall carbon emission respectively [15]. In industrialized countries, a consumption of 40 % of primary energy use and 36 % of energy related CO₂ has been recorded [16], [17]. For China it accounts 25 % of its national carbon emissions [18]. For Korea, the construction materials contribute 14.1 % in an overall share 34 % in industrial sector [12]. Similarly, Singaporean construction emitted 16 % in overall emissions and ranked 3rd largest source [10], [19].

Based upon the consumption of more than 40 % of global energy and generating 30 % greenhouse gas emissions globally, buildings are considered a major player in environmental degradation [20]. 30–40 % of energy utilization along with 33 % of global GHGs and almost 20 % of the fuel for global material production industry had been attributed to building sector [21]–[24]. According to Nematchoua and Reiter [25], 40% of total energy usage along with 24 % of CO₂ emissions comes from buildings worldwide as result of energy usage. In Australia, buildings (residential and non-residential) use almost 7.6 % of overall primary energy and approximately result 6.0 % of total GHG (equivalent) emissions in Australia [26]. Rosello-Batle et al. [15] reported 30 % greenhouse gas CO₂ emissions in Spain. About 29 % of total secondary energy use with nearly 27 % of total GHG emissions has been reported for Canada [27], [28]. The Turkish residential sector consumes 32 % of its total energy [20]. 32.6 % of final energy consumption has been reported for Iranian building sector [29].

The construction sector is striving hard for sustainable solutions. Life Cycle Assessment (LCA) has been implemented as, both, methodology and research scope in numerous studies with various models for the fields of energy, environment, social politics, and economy [30]. Its application in the building has observed multidimensional utilization as management tool [9], [31]–[34], evaluation system [35], method/methodology [36], [37] and approach for environmental impacts [16]. However, a generic policy development for building environment assessment has been seriously challenged by varying characteristics including location, size and construction material etc. [38]. Most of previous LCA studies can be limited on the basis of different variables involved. Based upon the experience of ‘usage’ phase for Mexican housing, Arvizu-Pina, et al. [39] also stressed on whole life cycle approach in sustainability concerns at strategic level. Similarly, Nasab, et al. [40] has also recommended to include other phases of life cycle including operations, maintenance, and demolition to achieve a complete life cycle assessment. So, a comprehensive approach based on whole life cycle still remains the fundamental to set the criteria and exploit the opportunities of achieving the required goal of sustainability [41]. With 40 % expected increase in population of 2005 and 60 % urbanization by 2030 [42], a massive global construction activity would be required. Although various environmental assessment (BEA) concepts have developed, but practically, the present approaches limit to generic environmental performance evaluations of building rather than actual carbon footprints. The current lack of systematic auditing and benchmarking the lifecycle carbon emissions encourage to explore further for sustainable endeavours [43].

2. METHODOLOGY

The main source of primary data was acquired through preliminary survey of the relevant construction organization working in housing sector. The secondary data acquired from construction firms included drawings, specifications, bill of quantities along with published literature on GHG emissions relevant to construction sector.

2.1. Selection of Case studies and Virtual Modelling

Housing units were selected as case studies adopting a specific criterion governed by following conditions to exclude insignificant differences in carbon footprint contributions. After fulfilling, thirteen (13) housing units, Table 1, were selected.

1. The area between two different units in same category should not be less than 100 sft;
2. The difference of one size, either length or width, between two options in same category should not be less than 5 ft;
3. Units shall be limited to single and double story type of housing;
4. The units existing in actual or planned construction in conventional Malaysian housing sector to be considered only.

TABLE 1. DETAILS OF SELECTED CASE STUDIES

Model ID	Area	Story	Type	Model ID	Area	Story	Type
H – 01	1625.00	Single	Semi-detached	H – 08	2625.00	Single	Semi-Detached
H – 02	2925.00	Single	Detached	H – 09	3870.83	Double	Terraced
H – 03	2800.00	Single	Detached	H – 10	3414.90	Double	Terraced
H – 04	4401.36	Double	Terraced	H – 11	2965.50	Double	Terraced
H – 05	3941.68	Double	Semi-Detached	H – 12	3672.01	Double	Terraced
H – 06	3026.66	Double	Terraced	H – 13	3893.75	Double	Terraced
H – 07	4000.00	Single	Detached				

Building Information modelling (BIM) process developed case studies in virtual environment. According to National Building Information Modelling Standards (NBIMS), BIM is ‘the digital representation of physical and functional characteristics of a facility’ [44]. The quantification of carbon footprint sources was achieved by 3D virtual prototyping whereas regression tools helped in empirical modelling. In current work, 3D parametric models up to LOD-300 (construction drawings) were developed.

2.2. Life Cycle Assessment (LCA)

According to International Organization for Standardization (ISO), Life cycle assessment (LCA) is defined as ‘a technique to assess the environmental performance of a product, process or activity from cradle to grave, i.e. extraction to its final disposal’ [45]. Life cycle assessment (LCA) was divided into five phases; planning & design (P&D), construction, operation, maintenance and end-of-life (EOL). Critical literature review and the consultation of industry experts guided to highlight the sources of CO₂ emissions. The total carbon footprint for the housing project is the summation of contributions from these phases, mathematically by Eq. (1).

$$\sum \text{CO}_2 (\text{LCA}) = \sum \text{CO}_2 (\text{P\&D}) + \sum \text{CO}_2 (\text{exe}) + \sum \text{CO}_2 (\text{oper}) + \sum \text{CO}_2 (\text{maint}) + \sum \text{CO}_2 (\text{d\&d}) \quad (1)$$

At the moment, no clear standard guidelines were available to quantify the CO₂ emissions generated from P&D. A questionnaire was developed to achieve the sources which were

categorized into three main heads; travel to office facility, accessories utilized for works and operation of office facility. The cumulative sum of each identified factor provided with the contribution of total carbon footprint for this phase.

For construction phase, the quantities of materials were extracted from virtual models. The quantities of major materials from virtual BIM models, the bill of quantities (B.O.Qs) and the original estimates were cross checked using Triangulation method. The carbon footprint potential was assessed using the Inventory of Carbon and Energy (ICE) [46] and Guidelines to Department for Environment, Food & Rural Affairs (DEFRA) [47]. The embodied carbon for each of material was calculated by multiplying the weights with respective carbon emission factors. For transportation, a carrier vehicle with a standard load carrying capacity (6 tons), normally used in Malaysia, was considered with a radial distance of 50 km for the material availability [48].

The electricity is one of major source of energy to run day to day operations throughout the design life. The provision of equipment was based on the design features of facilities according to the income level and house hold report by department of statistics [49]. The daily time of operation followed the guidelines and recommendation of Tenaga Nasional Berhad, Malaysia. The operational carbon footprint was calculated utilizing carbon emission factors; based on electricity generation mix reported in Malaysian energy statics handbook 2014 [50], and International energy Agency (IEA) statistics report 'CO₂ emissions from fuel combustion – edition 2015 [51]’.

A service life with an interval of 10 years each for a range of 50 to 100 years, was considered for maintenance phase. The replacement cycles were calculated based on the design life with the respective service life, Table 2. The total recurrent carbon footprint was achieved from manufacturing and transportation to the construction facility for replacement.

TABLE 2. SERVICE LIFE AND REPLACEMENT DETAILS DURING DESIGN PHASE

Description of Material	Service Life	Source
Ceramic Tiles	30	[52]
False Ceiling	10	[53]
Paint	10	
Plaster	30	
PVC Door Panels	10	
Wood	25	
Mild Steel	40	[52]
Roof Tiles	25	[54]

The involvements of mechanical equipment in dismantling and dispose-off operations contributed in this last phase, EOL. However, the quantum of such emissions relied on the type of equipment, duration of its operation, type of fuel and distance for disposal, a recycling unit for some of materials or waste pit. The dismantling operation was based on standard equipment locally available in construction market. Diesel operated Excavator/Loader (M318) and Dump truck (6 tons load carrying capacity) have been considered with a fuel consumption rate of 3.5–5.0 gallons/hr and 6 km/litre respectively. The data pertinent to the duration for dismantling operation projects was based upon the feedback from the construction industry experts and professional organizations involved in such operations for housing stocks. Table 3 summarizes the carbon footprint assessment models for each of the phase.

TABLE 3. CARBON FOOTPRINT ASSESSMENT MODELS ADOPTED FOR CALCULATION OF CO₂ EMISSIONS FROM EACH PHASE

Phase	Carbon Footprint Assessment Model	Explanations
Planning and Design Phase	$\sum_{i=0}^n CO_{2(P\&D)} = \sum CO_{2(manower)} + \sum CO_{2(eqpts)} + \sum CO_{2(facility)}$ $\sum CO_{2(manower)} = d_{(avg)} \cdot F_{(lit)} \cdot E_{(f)}$ $\sum CO_{2(eqpts)} = N \cdot E_{(kWh)} \cdot E_{(e)}$ $\sum CO_{2(facility)} = N \cdot E_{(kWh)} \cdot E_{(e)}$	n = No. of housing units, $d_{(avg)}$ = Average distance travelled from office to home, $F_{(lit)}$ = Fuel consumption for distance travelled, $E_{(f)}$ = Emission factor / unit fuel consumed, N = No. of equipment in operation, $E_{(kWh)}$ = Energy consumption in kWh per unit of equipment in operation, $E_{(e)}$ = Emission factor / unit electricity consumed.
Construction Phase	$\sum_{i=0}^n CO_{2(cxc)} = \sum CO_{2(materials)} + \sum CO_{2(transport)}$ $\sum CO_{2(materials)} = Qty \cdot E_{(f)}$ $\sum CO_{2(transport)} = N_{(trips)} \cdot d_{(avg)} \cdot F_{(lit)}$	$d_{(avg)}$ = Average distance travelled for trip, $F_{(lit)}$ = Fuel consumption for distance travelled, $E_{(f)}$ = Emission factor / unit fuel consumed, $N_{(trips)}$ = No. of trips, Qty = Quantity of respective materials.
Operational Phase	$\sum_{i=0}^n CO_{2(oper)} = L_{des} \{ N_{eqpt} \cdot Pwr \cdot OP_{hrs} \cdot NO_{days} \cdot E_{(f)} \}$	L_{des} = Design life, N_{eqpt} = No. of Equipment, Pwr = Power rating, OP_{hrs} = Operating hours, NO_{days} = No. of operating days, $E_{(f)}$ = Emission factor / unit fuel consumed.
Maintenance Phase	$\sum_{i=0}^n CO_{2(maint.)} = \sum CO_{2(materials)} + \sum CO_{2(transport)}$ $\sum CO_{2(materials)} = \frac{L_{des}}{L_{ser}} \cdot Qty \cdot E_{(f)}$ $\sum CO_{2(transport)} = N_{(rep)} \cdot N_{(trips)} \cdot d_{(avg)} \cdot F_{(lit)} \cdot E_{(f)}$	N = frequency of replacements, L_{des} = Design life of facility, L_{ser} = Service life of materials, $d_{(avg)}$ = Average distance travelled for trip, $F_{(lit)}$ = Fuel consumption for distance travelled, $E_{(f)}$ = Emission factor / unit fuel consumed, $N_{(trips)}$ = Number of trips, Qty = Quantity of respective materials, $N_{(rep)}$ = Number of replacements = L_{des} / L_{ser} .
Dismantling and Dispose-off Phase	$\sum_{i=0}^n CO_{2(d\&d)} = \sum CO_{2(dism)} + \sum CO_{2(dispose-off)}$ $\sum CO_{2(dism)} = N_{(days)} \cdot Hrs_{(opr)} \cdot F_{(lit)} \cdot E_{(f)}$ $\sum CO_{2(dispose-off)} = N_{(trips)} \cdot d_{(avg)} \cdot F_{(lit)} \cdot E_{(f)}$	$N_{(days)}$ = Number of days of operation, $Hrs_{(opr)}$ = Number of average operating hours in a day, $E_{(f)}$ = Emission factor / unit fuel consumed, $N_{(trips)}$ = Number of trips, $d_{(avg)}$ = Average distance travelled for disposal trip, $F_{(lit)}$ = Fuel consumption for distance travelled.

3. RESULTS AND DISCUSSIONS

The life cycle was divided into five sections according to the different phases opted. For P&D phase, a summary comprising contribution of housing units was formulated in accordance with the main heads through questionnaire. Usually, this phase varies up to six months. The reliability test was performed and found consistent with value of 0.86, higher than 0.70. The total contribution from P&D phase remained from 2200 to 3600 kg-CO₂ with standard deviation of 16.5 % and variation of 63 % in the carbon footprint. The intensity of refrigerator and AC was also observed to dominate all the sources involved. Fig. 1 details the contribution relevant to type of housing units based upon respective contributions. The results show that the contribution of traveling ranged 450 to 1000 kg-CO₂, office operation 1500 to 2400 kg-CO₂ and equipment 215 to 390 kg-CO₂. On average, the three heads shared 67 %, 23 % and 10 % contributions respectively. Comparison observed the operation of the office facility as the top main head followed by travel to office facility and accessories.

Fig. 1. Head wise contribution of carbon footprint during the P&D phase.

The total contribution from construction phase ranged from 50 tons-CO₂ to 103 tons-CO₂. The bricks, concrete, steel rebar and mild steel were top four contributors which, on average, contributed almost 85 % of the overall emissions. A variation 24 tons-CO₂ was observed in case of bricks, 22 tons-CO₂ for concrete, 11.40 tons-CO₂ for steel and 11.60 tons-CO₂ for mild steel. The materials contribution trend behaved almost uniformly, Fig. 2. However, the terraced housing units resulted in 88 tons-CO₂, 24 % higher than detached and 32 % than that of semi-detached type.

Fig. 2. Category wise percentage share of material in total CO₂.

For the current study, the service life varied from 50–100 years, with an interval of 10 years, opted in compliance with previous studies on the environmental impact for housing facilities. The contribution range has been elaborated in Fig. 3.

Fig. 3. Operational carbon footprint (kg-CO₂), 50–100 years of service life.

The operational carbon impact was further categorized into six major activities, Table 4. The refrigeration and air conditioning were the top two categories of energy utilization with an average share of more than 75 % in each of the case. On average, the terraced type generated less amount of carbon footprint as compared to the semi-detached and detached. The attribute of income level of residents was a vital factor. According to house hold statistics survey 2014, the distribution of housing sector is based upon the income levels. The terraced type units accommodate the low-income level whereas the other two types target the middle- and upper-income levels respectively. As per survey, 44 % of the residents of middle- and higher-income category utilized the air conditioning facility. The statistics observed the upper level, top 20 %, on average spends almost 15 % of house-hold income on electricity, gas and air conditioning utilities. Similarly, the middle level, also known as middle 40 %, spends 9.50 % for these facilities. However, the bottom 40 % or low-income level spends only 3 % to 5 % of their household income on such facilitation.

TABLE 4. OPERATIONAL CARBON FOOTPRINT STATISTICS

Description	Avg. contribution, %			Standard Deviation		
	Terraced	Semi-detached	Detached	Terraced	Semi-detached	Detached
Air Conditioning/Fan	11.26	33.41	37.91	0.63	0.85	3.86
Cleaning	10.63	6.81	7.55	0.17	2.07	0.45
Cooking	4.09	2.76	2.90	0.07	0.55	0.17
Lighting	5.59	3.05	3.05	0.76	1.73	0.32
Refrigeration	64.26	50.38	45.63	1.04	3.86	2.74
Entertainment	4.17	3.59	2.96	0.07	0.79	0.18

For maintenance phase, roof tiles (23 %) were the top contributing material followed by plaster (22 %), ceramic tiles (21.50 %), false ceiling (16.50 %) and paint (10 %), with individual contribution more than 10 %. The share of PVC door panels and wood remained almost 2 % or less, Table 5.

TABLE 5. INDIVIDUAL CONTRIBUTION TREND FOR RECURRENT CARBON FOOTPRINT

Description of Material	Percentage Contribution for service life opted					
	50	60	70	80	90	100
Ceramic Tiles	21.71	17.33	24.20	21.21	21.21	23.99
False Ceiling	18.42	18.29	15.49	15.77	15.77	15.33
Mild Steel	5.57	4.46	3.33	2.90	2.90	4.28
Paint	11.40	11.32	9.57	9.76	9.76	9.48
Plaster	21.92	17.38	24.53	21.40	21.40	24.29
PVC Doors Panels	1.99	1.98	1.68	1.71	1.71	1.66
Roof Tiles	18.01	27.69	20.10	25.82	25.82	19.88
Wood	0.98	1.53	1.10	1.43	1.43	1.09

For each of life span adopted, the top four materials contributed more than 80 %. However, the average contribution depicted a mix trend. The variation in service life of different materials was the main reason of such mix trend. The terraced housing units contributed the most as compared to the semi-detached and detached one, Fig. 4.

Fig. 4. Category wise recurrent CO₂ contribution, 50–100 years span

The 1st span of 10 years (50 to 60) observed 26 % increase, 2nd span (60 to 70 yrs.) 41 %, 3rd span (70 to 80 yrs.) 15 %, 4th span (80 to 90 yrs.) 7 % and the last span (90 to 100 yrs.) observed an increase of 24 %. The quantity of materials was the main source of these high contributions. The terraced housing comprised of double story height, the semi-detached both single and double story whereas the detached limit to single story height only. The height parameter directly contributed in higher carbon footprint. Transport activity also observed similar trend for contributions. The total carbon footprint from EOL remained 2.3 tons-CO₂ to 3.85 tons-CO₂ with 64 % variation. The dismantling dominated the contributions over the dispose-off operation, Fig. 5.

Fig. 5. Total carbon footprint from D & D.

On average, the dismantling operation shared 66 % of the contributions and varied over a range of 60 % to 71 %. In case of dismantling activity, detached housing observed lowest contributor with an average of 1.8 tons. This emission was 15 % lower than semi-detached and 38 % less than terraced type.

The activity wise analysis observed that dismantling of the terraced units resulted almost 20 % and 38 % more carbon than the other types of construction respectively. Similarly, in case of disposal, semi-detached and detached housing units resulted in a 21 % and 18 % lesser content of emissions than that of terraced ones. With lesser average quantity of materials, semi-detached units were the lowest in resulting CO₂ content from the dispose-off activity. The ease of access for equipment operation was one factor affecting the carbon level with direct impact on movement, operational time and fuel consumption. On overall basis, the terraced housing units dominated this phase followed by the semi-detached and detached type construction. These contributions were higher by 20 % and 30 % as compared to semi-detached and detached housing units respectively. After detailing the life cycle inventory (LCI), the total carbon footprint for the housing project was the summation of contributions, Eq. (1). Based upon the average contribution for each of the phase, the following phase wise range were observed.

2.20 tons-CO ₂	<	Planning & Design (P&D)	>	3.60 tons-CO ₂
50.0 tons-CO ₂	<	Execution /Construction	>	103.0 tons-CO ₂
35.0 tons-CO ₂	<	Operation/ Usage	>	122.0 tons-CO ₂
10.0 tons-CO ₂	<	Maintenance	>	58.0 tons-CO ₂
2.3 tons-CO ₂	<	Dismantling & Dispose-off	>	3.90 tons-CO ₂

The environmental impact resulted in a standard deviation of 12 %, 11 %, 11 %, 10.5 %, 10 % and 10 % respectively. The average percentage share of each phase for each case study, Fig. 6.

Fig. 6. Phase wise percentage contribution trend on individual basis.

The construction and operational phase remained the top two contributors with more than 80 % share. On average, the construction phase dominated (42.7 %) followed by operational phase (39 %), maintenance (15 %), EOL (1.8 %) and P&D (1.5 %). However, the category wise assessment on the basis of type of construction does not follow the average trend. For life scenario 50, 60 and 70 years, the construction phase dominated the life cycle. However, beyond 70 years, the operational phase appeared to be dominant. Both phases achieved a transitional point by intersecting almost at 80 years. The maintenance phase observed a gradual increase whereas a constant uniform trend has been achieved for the P&D and EOL phases, Fig. 7.

Fig.7. Phase wise variations in average contribution trend.

The category wise carbon footprint contributions throughout the phases of life cycle highlighted certain variations from the overall trend. Interestingly, the construction and operational phases depict a noticeable variation with respect to time, Fig. 8. The construction phase dominated the whole life cycle in case of terraced type housing with a possible point of intersection with the operational phase just after the 100 years. However, in case of semi-detached and detached housings, the point of intersection was achieved after 60 years.

In other words, after this point, the operational phase contribution remained dominant among all phases. A fairly consistent pattern for P&D and EOL was observed. As far maintenance was concerned, the trend remained the similar but observed gradual increase in carbon footprint. One of the important factors observed was that even as the area varied by 170 % (1625 sft to 4400 sft), the total carbon footprint, on average, varied by 50 % for 50 years of time span.

Fig. 8. Variation in contribution trend of each phase w. r. time.

4. CONCLUSIONS

The current work assessed the carbon footprint throughout the life cycle for housing sector. Life cycle assessment (LCA) was adopted with boundary limitations of cradle to grave. Five

phases were adopted; planning & design (P&D), construction, operation, maintenance and end-of-life (EOL). The selected units were developed in a virtual environment using building information modelling (BIM). The case studies included detached, semi-detached and terraced type housing units. The following has been concluded:

- The average contribution range remained from 148 tons-CO₂ to 284 ton-CO₂ for the design life of 100 years;
- The execution phase contributed the most in almost all the cases with a share of 42.70 % followed by the operation phase with an average contribution of 39 %, the maintenance phase (15 %), planning & design phase (1.8 %) and dismantling and dispose-off (1.60 %) remained at the bottom of list;
- As the design life varied with an interval of almost 20 % to 10 % (50 to 60 to 70 to 80 to 90 to 100yrs.), the corresponding carbon footprint increased by 8.46 %, 9.88 %, 7.08 %, 5.77 % and 7.96 % for each to the respective time interval.

The overall change for 50-year-time interval worked out nearly 50 %. The duration of operational phase in whole project life cycle was more than 95 %, however, its emission contribution remained almost 10 % less than embodied category. A significant positive relationship between the dependent (carbon foot print) and independent variable (area) was observed. The physical design features were important factor in variance of environmental effects.

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