Sustainable Earth Review

Journal homepage: http://sustainearth.sbu.ac.ir

Direct and indirect carbon footprint assessment in the construction stage of residential buildings

Nava Rashed[a], Mazaher Moeinaddini*[a], Ali Kazemi[b]

[a] Department of Environmental Sciences, Faculty of Natural Resources, University of Tehran, Karaj, Iran
[b] Department of Environmental Science and Engineering, Faculty of Agriculture and Environment, Arak University, Arak, Iran

ABSTRACT

The construction industry, the leading cause of global greenhouse gas emissions, is responsible for at least 37 percent of global emissions. In Iran, greenhouse emissions in the construction sector between 1990 and 2020 have increased from 0.73 to 1.44 tons of carbon dioxide equivalent per person per year. The purpose of the current study is to investigate the direct and indirect carbon footprints for one square meter of the residential building built-area. The system boundary is "gate to gate," and its functional unit is "one square meter of the residential building built-area." Data selection was carried out using the checklist and literature review methods. The carbon footprint assessment was conducted using the IPCC 2013 model and the ReCiPe method. Concrete is the most substantial contributor to carbon footprint among all building materials. The results show that the total, direct, and indirect carbon footprint for one square meter of the residential building built-area is 445, 436, and 9 $kgCO_2e/m^2$, respectively. The building's "excavation, foundation, and framing" phase mainly contribute to the indirect carbon footprint among building construction phases. The carbon footprint for each square meter of the residential building construction is related to different factors, such as total building area, type of buildings, material transportation distance, and type of building materials used.

ARTICLE INFO

Keywords:
Direct carbon footprint
Indirect carbon footprint
Inventory
Life cycle
Residential building

Article history:
Received: 08 Apr 2023
Accepted: 12 Jun 2023

*corresponding author
E-mail address:
moeinaddini@ut.ac.ir
(M. Moeinaddini)

Citation:
Rashed, N. et al., (2023).
Direct and indirect carbon footprint assessment in the construction stage of residential buildings, *Sustainable Earth Review:* 3(4), (23-30).

DOI: 10.48308/ser.2024.235067.1043

1. Introduction

Due to urbanization and population growth, the construction of residential buildings has increased substantially. The construction industry, as the primary contributor to greenhouse gas emissions, is responsible for 37% of global emissions (Programme, 2022; Programme, 2023; Guo et al., 2024). The significant increase in greenhouse gases in the atmosphere has raised the temperature of the earth's surface by 1.1 degrees Celsius compared to the pre-industrial period. In Iran, greenhouse gas emissions from the construction sector have increased from 0.73 to 1.44 tonCO2e/person/year between 1990 and 2020 (Ritchie et al., 2020). The Intergovernmental Panel on Climate Change (IPCC) has recently implemented immediate actions towards global emission mitigation. The actions include settling efficient buildings, switching fuels, substituting building materials, and using renewable energy (Lee et al., 2023). Climate change mitigation strategies have been employed for residential buildings with the objective of the reduction or eradication of carbon emissions (Ezema et al., 2016). The carbon emission process could be calculated based on carbon footprint analysis from the perspective of life cycle analysis and by considering the greenhouse gas emissions, which is done to give more attention to the nature of the carbon emission process and planning on carbon mitigation (Weber and Matthews, 2008). The carbon footprint calculation comprises the products' life cycle analysis, their direct and indirect carbon emissions, and a comparison of the results with other studies on carbon emissions (Huang et al., 2017).

Life cycle assessment (LCA) helps decision-makers in the design process to assess the principal environmental impacts during the comparison between construction systems and building materials substitution (Curran, 2008). According to ISO 14040 and ISO 14044 standards, there are four life cycle phases: goal and scope definition, inventory analysis, Impact assessment, and interpretation (ISO 14044, 2006; Standardization, 2006). Furthermore, the building life cycle comprises four stages: product, construction, use, and end-of-life (Global BRE, 2018). There are three life cycle assessment models for analyzing greenhouse gas emissions. These models are the process-based model, input-output analysis model, and hybrid model. In the present study, due to the more comprehensive system boundary, effortless data collection, and less time and cost consumption, the input-output analysis model is used (Hong et al., 2015). In recent years, many studies have been conducted on carbon footprint assessment, some of which will be reviewed in the following paragraphs. Ayob et al. (2021) calculated the carbon footprint of a hostel building construction in Perlis, Malaysia, in a case study using an Industrialized Building System (IBS) construction method. The system boundary was defined as cradle-to-gate to calculate the carbon footprint of prefabricated sandwich panels manufacturing for machinery operation and their actual site installation process. According to the results, installing prefabricated sandwich panels on their actual site produced a significant carbon footprint due to extensive use of the excavator, especially for the flooring operation with 81.59 tCO_2e and 34%. The building work contributes mainly to the carbon footprint with 159.32 tCO_2e and 63.87%. Preliminary work (35.08 tCO_2e, 14.06%), foundation (34.30 tCO_2e, 13.75%), and earthwork (20.76 tCO_2e, 14.06%) were placed into the following ranks. Among the building materials, the shotcrete mixture used in plastering works significantly contributed to the carbon footprint with 360.04 tCO_2e, 73.11%. Morales-Vera et al. (2021) assessed the life cycle of low-energy mass timber buildings. Features of the mass timber building design could improve the thermal insulation design. The life cycle environmental impact assessment was conducted using the SimaPro 9.0 software, and the thermal performance of buildings was measured using TAS 9.5 software. Mass timber and reinforced concrete buildings' global warming potential were 97.4 and 162.8 kilograms of carbon dioxide equivalent per square meter ($kgCO_2e/m^2$), respectively. By defining the wood materials as the carbon sink, using mass timber products resulted in a 310 $kgCO_2e$/building negative net. The operational emissions from domestic space-conditioning during a 50-year lifespan of mass timber buildings experienced an 83% (288.6 $kgCO_2e/m^2$) reduction compared to conventional reinforced concrete buildings. The results showed that mass timber buildings, compared to those with reinforced concrete structures, had more potential to mitigate the carbon emissions of multi-story buildings in Santiago city. Izaola et al. (2023) studied the whole-life carbon (WLC), embodied carbon (EC) (carbon emissions of building materials), and operational carbon (OC) (carbon emissions of the building's use stage) of the average Spanish residential buildings between the years 1981 and 2010. For this purpose, the average Spanish residential building was identified and modeled based on a real 2013 sample, and its emissions were expressed as scenario 0. Then, five new scenarios were compared to understand variations in the WLC, EC, and OC footprints. As results indicated, the WLC footprint of the average multi-family Spanish apartment with 73.1 m^2 net floor area was reported to be 1944 $kgCO_2e/m^2$ (30.8% EC, 69.2% OC). Based on scenarios 1 to 3, using wood window frames, wooden flooring, and insulating walls with recycled cork reduced the WLC footprint by 26%, 0.8%, and 16.1%, respectively. In scenario 4, calculating all three items together, the WLC footprint was reduced by 36.9%. The maximum mitigation of the WLC footprint was related to scenario 5, with 63.4%. In this study, the footprint of all 18 ReCiPe midpoints and the energy footprint were reduced by an average of 50.4%. Kiehle et al. (2023) calculated Oulu University's carbon footprint using a hybrid model to examine the available methods of carbon footprint calculation in real life, define the limitations of carbon footprint calculation at the organizational level, introduce the best methods of carbon footprint reduction, and achieve carbon neutrality goals in universities. This study mainly focused on indirect and non-energy-related greenhouse gas emissions, such as emissions by commuting, data procurement, and laboratory equipment. In 2019, the sum of Oulu University's emissions inventory was reported as 19072 tCO_2e. These emissions resulted from the district heating of the university campus, restaurant services, business trips, staff and students commuting, and the construction and maintenance of the building.

Based on the results, data availability and the lack of appropriate strategies for data collection are prominent limiting factors. Implementing energy-saving policies and improving procurement policies are favorable actions to mitigate carbon footprints. Owing to urbanization development and the critical role of the construction sector in greenhouse gas emissions and its impacts on global warming, the objective of the current study is to investigate the direct carbon footprint due to energy consumption by excavators and concrete mixer trucks and the indirect carbon footprint due to fuel, electricity, and the building materials manufacturing per 1 m^2 residential building built-area.

2. Material and Methods

2.1. Goal and scope definition

The current study's functional unit (FU) is defined as as 1 m^2 of residential building built-area. According to Fig. 1, stages A1 to A5 should be considered. The system boundary is gate-to-gate, mainly focusing on the construction stage of the residential buildings.

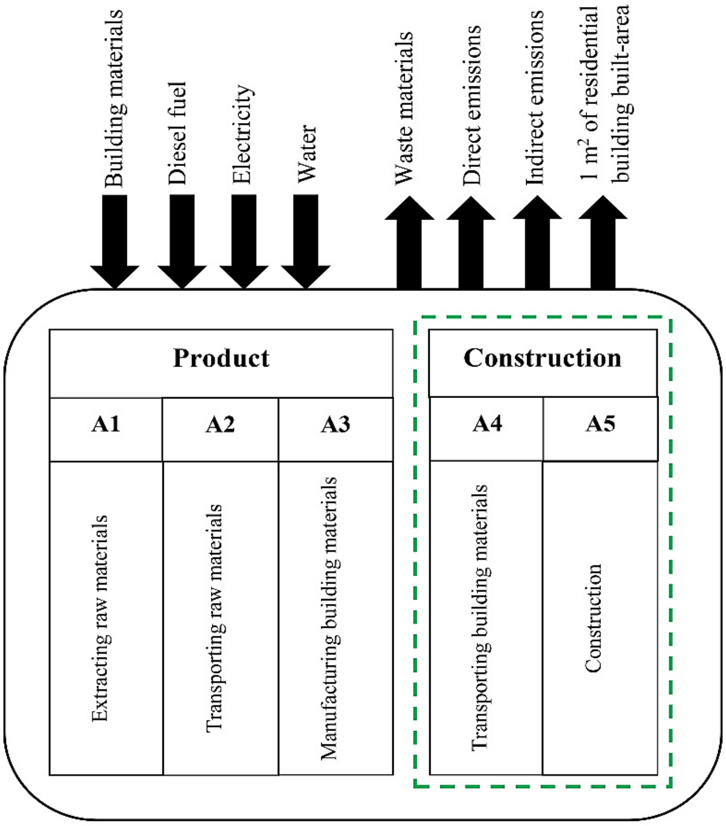

Fig. 1. The boundary of the system under study

2.2. Inventory analysis

Two methods, the questionnaire and literature review, were used to create an inventory for 1 m^2 of residential building built-area in Babolsar city, Mazandaran province. Babolsar has a semi-humid moderate climate with an average annual relative humidity of 80% (Mazandaran Meteorology General Office, 2024). According to the city's climatic condition and the Iran statistical yearbook 2021-2022, 98.7% of construction permits issued for residential buildings in urban areas of Mazandaran belonged to concrete buildings; therefore, buildings with concrete structures were selected to be studied in this paper (Iran Statistical Center, 2023). Firstly, the building materials questionnaires were completed by construction contractors for five concrete buildings in Babolsar. The questionnaires included questions on the buildings' general features (e.g. area and height) and the quantities and types of building materials used. Then, to complement the data on diesel fuel, electricity, and water consumption in the construction stage of residential buildings, several studies on concrete buildings were investigated. Ultimately, the mean quantity of the two methods was calculated. This information was used as input for the SimaPro version 9.2.0.2

software in the input-output (I-O) model. The life cycle inventory has considered the average quantities of building materials, consumed fuel, waste materials, and emissions of each construction phase. Natural resources, e.g., water and energy, e.g., electricity, have also been factored into the inventory. Building materials such as concrete, steel rebar, cement, and fuel are taken into account in the "excavation foundation, and framing" phase. Building materials such as polyvinyl chloride (PVC) and polyethylene pipes are taken into account in the "water and wastewater piping" phase. Building materials such as gypsum plasterboard, ceramic tiles, and double glazing are taken into account in the "finishes" phase (Table 1).

Table 1. Life cycle inventory for 1 m2 of residential building built-area

Construction phases	Inputs		Mean quantities	Sum	Unit/m^2
Excavation, foundation, and framing	Building materials	Concrete	997.03	1366.431	kg
		Cement (excluding cement used in the concrete mixture)	121.26		
		Clay brick	103.90		
		Pumice block	93.62		
		Steel rebar	45.18		
		Expanded polystyrene foam	2.64		
		Diesel fuel	2.81		
	Waste materials			11.323	kg
	Emissions	Carbon dioxide	8.683	8.848	kg
		Carbon monoxide	0.032		
		Methane	0.001		
		Nitrogen oxides	0.108		
		NMVOC	0.017		
		Particulates	0.007		
Water and wastewater piping	Building materials	PVC pipe	0.32	0.413	kg
		HDPE pipe	0.09		
Finishes	Building materials	Ceramic tile	23.29	43.20	kg
		Gypsum plasterboard	8.81		
		Plywood	3.07		
		Double glazing	4.34		
		PVC window frame	1.09		
		Wooden door	2.60		
	Waste materials			1.224	kg
Natural resources	Water			6.29	m^3
Energy	Electricity			4.80	kWh

2.3. Carbon footprint assessment

The inventory's input data were standardized based on the functional unit to make the comparison and generalization of the results possible. Carbon footprint assessment was conducted using the IPCC 2013 model and the ReCiPe method. Moreover, the Ecoinvent 3 and Industry data 2.0 databases were used for the assessment. Both direct and indirect carbon footprints have been reported in kgCO$_2$e in this study. kgCO$_2$e is a statistical scale for evaluating and measuring greenhouse gas emissions based on their global warming potential (GWP). The foremost purpose of using the potential global warming is converting a specific greenhouse gas to a carbon dioxide equivalent, which is a common way of reporting global emissions (Sreedhar et al., 2016).

3. Results and discussion

This study's findings, which aim to assess direct and indirect carbon footprints for each 1 m^2 of residential building built-area, are presented in three subsections.

3.1. Effects of building materials on carbon footprint

In the current study, the results of investigating shares of building materials per 1 m^2 of residential building built-area show that concrete with the maximum mass percentage (71%) is the most significant contributor to each square meter of residential building built-area. Therefore, with 119 kgCO$_2$e/m^2, concrete has the highest contribution to carbon footprint among all building materials. In the Illankoon et al. (2023) study, concrete and aluminum window frames are introduced as building materials with the most significant contribution to carbon footprint. On the other hand, in Chen et al. (2021) study, the most considerable (roughly 60%) contribution to carbon footprint is due to concrete and structural steel, and wood is suggested as the substitution for building materials mentioned before. As suggested by the previously mentioned papers, one of the recommended means to mitigate the carbon footprint of 1 m^2 of residential building built-area is substituting low-carbon building materials with high-carbon ones.

3.2. Effects of building construction features on carbon footprint

The total carbon footprint of the present study is calculated as 445 kgCO$_2$e/m^2, which comprises 436 kgCO$_2$e/m^2 of indirect carbon footprint and 9 kgCO$_2$e/m^2 of direct carbon footprint, respectively. In the Illankoon et al. (2023) study, the carbon footprint for 1 m^2 of buildings with the cradle-to-gate system boundary was reported to be between 193 and 233 kgCO$_2$e. Three one-story residential units in Australia with areas between 200 and 240 m^2 have been examined. Among these three units, the two with wooden structures have contributed less to the carbon footprint than the one with a steel structure. The one with the smaller total area had a lower carbon footprint between two wood buildings. The quantity of building materials in each residential unit is estimated to be lower than that in multi-story office buildings. Suggested carbon footprint mitigation strategies include substituting conventional building materials with those having a lower carbon footprint, using more sustainable raw materials for manufacturing building materials, and transporting locally sourced building materials to reduce the transport distance. In the Chen et al. (2021) study, the carbon footprint per 1 m^2 of floor area for two wood and concrete residential buildings in China with an area of 3524 m^2 has been compared. The system boundary was considered cradle-to-gate, and the carbon footprints of wood and concrete residential buildings were 295.55 and 221.30 kgCO$_2$e, respectively. According to the results of the current and previous studies (Chen et al., 2021; Illankoon et al., 2023), the carbon footprint of each m^2 of residential building built-area relates to the total area of buildings, type of buildings, building materials transport distance, and the kind of building materials consumed. On the other hand, despite the system boundary being the same in previous studies, the carbon footprint/m^2 in previous studies is reported to be lower compared to the present study.

3.3. A Comparison between direct and indirect carbon footprint in each construction phase

The shares of direct and indirect carbon footprints are compared in Table 2. Direct carbon footprint is only 2% of the total carbon footprint, whereas indirect carbon footprint is 98% of it. Due to the considerable share of indirect carbon footprint, its amount and percentage are presented per m^2 of residential building built-area for each one of the construction phases separately. In the “excavation, foundation, and framing” phase, the indirect carbon footprint of building and waste materials is 385.2 kgCO$_2$e/m^2 (86.52%). In the “water and wastewater piping” phase, the indirect carbon footprint of building and waste materials is 1.37 kgCO$_2$e/m^2 (0.31%). The phases mentioned before have the maximum and minimum contribution to indirect carbon footprint, respectively. It is important to note that the indirect carbon footprint of waste materials is neglected in the “water and wastewater piping” phase. The indirect carbon footprint of waste materials in the “finishes” phase is 0.0282 kgCO$_2$e/m^2 (0.0063% share of indirect carbon footprint), which is lower than that of in the “excavation, foundation, framing” phase. the consumed electricity during the construction process of each 1 m^2 of residential buildings is 3.52 kgCO$_2$e/m^2 (0.792% share of indirect carbon footprint).

Table 2. Amount and percentage of the total carbon footprint of 1 m^2 of residential building built-area for each construction phase

Indirect carbon footprint		**kgCO$_2$e/m^2**	**Percentage**
Excavation, foundation, and framing	Building materials	385.08	86.49
	Waste materials	0.1217	0.0274
Water and wastewater piping	Building materials	1.37	0.31
Finishes	Building materials	46.64	10.49
	Waste materials	0.0282	0.0063
Energy	Electricity	3.52	0.792
Total indirect carbon footprint		436	98
Direct carbon footprint		9	2
Total carbon footprint		445	100

The percentage of indirect carbon footprint of 1 m^2 of residential building built-area is shown in Fig. 2 for each construction phase separately. The "excavation, foundation, and framing" phase and The "Water and wastewater piping" phase have the maximum and minimum contribution to indirect carbon footprint, respectively.

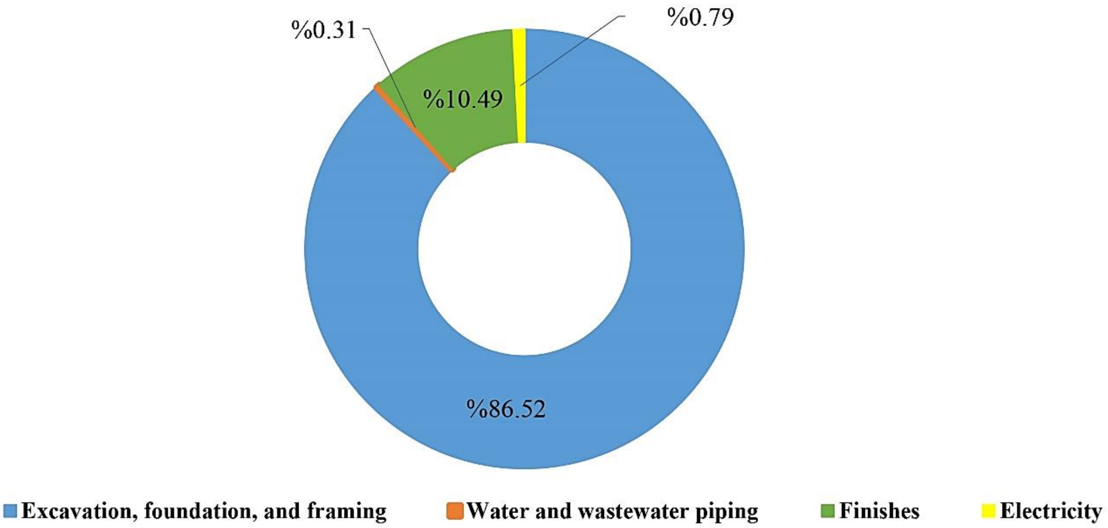

Fig. 2. The percentage of indirect carbon footprint of 1 m^2 of residential building built-area for each construction phase

The percentage of the indirect carbon footprint of all building and waste materials for excavation, foundation, and framing, water and wastewater piping, and finishes phases separately and per FU are compared in Fig. 3 The "excavation, foundation, and framing" phase has the maximum indirect carbon footprint produced by building materials (88.91%) and waste materials (81.19%).

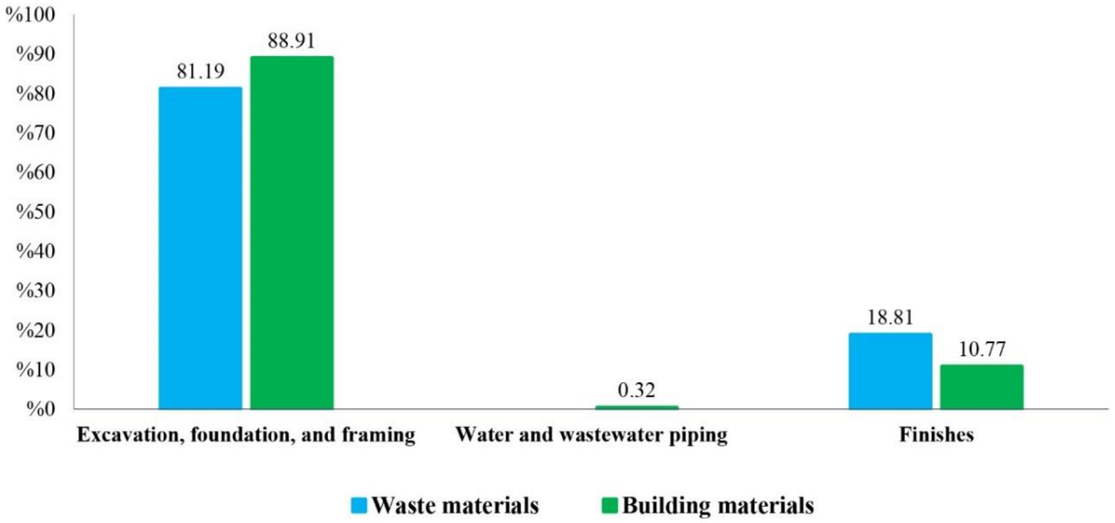

Fig. 3. Comparison of the percentage of indirect carbon footprint of building materials and waste materials for 1 m^2 of residential building built-area for each construction phase

4. Conclusion

The construction sector has the most substantial share in global greenhouse gas emissions, with a 37% share. Iran's greenhouse emissions have increased by 0.71 tonCO2e/person/year between 1990 and 2020. Developing settlements and greenhouse emissions from them could result in climate change impacts and global warming, which makes a better investigation of the construction sector's carbon footprint possible. The current study assessed the direct and indirect carbon footprint per 1 m^2 of residential building built-area. The system boundary under study was defined as gate-to-gate, and the functional unit was suggested to be 1 m^2 of residential building built-area. The data collection methods used were the questionnaires and the literature review. Moreover, the inventory was created using SimaPro 9.2.0.2 software and the input-output model. The carbon assessment method used in the SimaPro software was ReCiPe. The findings were considered in three subsections to assess the carbon footprint. Concrete had the highest mass percentage and the most significant contribution to the indirect carbon footprint among all building materials. Therefore, substituting concrete with building materials with a lower carbon footprint was recommended. According to the current study and the previous studies in China and Australia, factors such as the total area of buildings, building materials' transporting distance, and the types of building materials used are related to the amount of carbon footprint of 1 m^2 of the residential building built-area. These relationships are as follows:

1. Building total area and carbon footprint are correlated positively.
2. Office buildings contribute more to carbon footprint than residential buildings.
3. Building materials transportation distance and carbon footprint are correlated positively.
4. Buildings with concrete or steel structures contribute more to the carbon footprint than wood structures.

Based on the results, the total, indirect, and direct carbon footprints have been calculated to be 445, 436 (98%), and 9 (2%) $kgCO_2e/m^2$ per 1 m^2 of residential building built-area, respectively. In the investigation of the construction phases separately, the "excavation, foundation, and framing" phase has the most significant contribution to indirect carbon footprint with 385.2 $kgCO_2e/m^2$ (86.52%). On the other hand, the "water and wastewater piping" phase has a minor contribution to the indirect carbon footprint with 1.37 $kgCO_2e/m^2$ (0.31%). Plus, the indirect carbon footprint of electricity was 3.52 $kgCO_2e/m^2$ (0.79%). The "excavation, foundation, and framing" phase had the maximum indirect carbon footprint from building materials (88.91%) and waste materials (81.19%) among the phases.

Acknowledgment

This article was not under any financial support.

References

Ayob, A., Razali, N., Hassan, Z., Rahim, M.A. & bin Mohd Zahid, M.Z.A., 2021. Carbon footprint assessment of hostel building construction using the industrialized building system in Pauh Putra, Perlis. *Journal of Physics: Conference Series*.

Chen, C.X., Pierobon, F., Jones, S., Maples, I., Gong, Y. & Ganguly, I., 2021. Comparative life cycle assessment of mass timber and concrete residential buildings: A case study in China. *Sustainability*: 14(1), 144.

Curran, M.A., 2008. Development of life cycle assessment methodology: a focus on co-product allocation.

Ezema, I., Opoko, A. & Oluwatayo, A., 2016. De-carbonizing the Nigerian housing sector: the role of life cycle CO_2 assessment. *International Journal of Applied Environmental Sciences*: 11(1), 325-349.

Global, B., 2018. *BRE Global Methodology for the Environmental Assessment of Buildings Using EN 15978: 2011*.

Guo, C., Zhang, X., Zhao, L., Wu, W., Zhou, H. & Wang, Q., 2024. Building a Life Cycle Carbon Emission Estimation Model Based on an Early Design: 68 Case Studies from China. *Sustainability*: 16(2), 744.

Hong, J., Shen, G.Q., Feng, Y., Lau, W.S.T. & Mao, C., 2015. Greenhouse gas emissions during the construction phase of a building: A case study in China. *Journal of cleaner production*: 103, 249-259.

Huang, W., Li, F., Cui, S.H., Huang, L. & Lin, J.Y., 2017. Carbon footprint and carbon emission reduction of urban buildings: a case in Xiamen City, China. *Procedia Engineering*: 198, 1007-1017.

Illankoon, C., Vithanage, S.C. & Pilanawithana, N.M., 2023. Embodied Carbon in Australian Residential Houses: A Preliminary Study. *Buildings*: 13(10), 2559.

Iran Statistical Center., 2023. Statistical Yearbook of Iran (2021-2022).Tehran: Iran Statistical Center.

ISO, I., 2006. 14040. *Environmental management—life cycle assessment—principles and framework*: 235-248.

Izaola, B., Akizu-Gardoki, O. & Oregi, X., 2023. Setting baselines of the embodied, operational and whole life carbon emissions of the average Spanish residential building. *Sustainable Production and Consumption*: 40, 252-264.

Kiehle, J., Kopsakangas-Savolainen, M., Hilli, M. & Pongracz, E., 2023. Carbon footprint at institutions of higher education: The case of the University of Oulu, *Journal of Environmental Management*: 329, 117056.

Lee, H., Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P., Trisos, C., Romero, J., Aldunce, P. & Barrett, K., 2023. Climate change 2023: synthesis report. Contribution of working groups I, II and III to the sixth assessment report of the intergovernmental panel on climate change.

Mazandaran Meteorology General Office, Babolsar climate. Available from: https://www.mazmet.ir/en/ (accessed 13 March 2024).

Morales-Vera, R., Felmer, G., Salgado, P., Astroza, R., González, I., Tobar, J., Puettmann, M. & Wishnie, M., 2021. A Life Cycle Assessment of Low Energy Residential Multistory Mass Timber Buildings in Central Chile. *Proceedings of the WCTE*.

Programme, U.N.E., 2022. 2022 Global Status Report for Buildings and Construction.

Programme, U.N.E., 2023. *Building Materials and the Climate: Constructing a New Future*.

Ritchie, H., Rosado, P. & Roser, M., 2020. *Emissions by sector: where do greenhouse gases come from?* 'https://ourworldindata.org/emissions-by-sector' [Online Resource]

Sreedhar, S., Jichkar, P. & Biligiri, K.P., 2016. Investigation of carbon footprints of highway construction materials in India. *Transportation Research Procedia*: 17, 291-300.

Standardization, I.O.F., 2006. *Environmental management: life cycle assessment; requirements and guidelines* (Vol. 14044). ISO Geneva, Switzerland.

Weber, C.L. & Matthews, H.S., 2008. Quantifying the global and distributional aspects of American household carbon footprint. *Ecological economics*: 66(2-3), 379-391.