Comparative Analysis of Dynamic and Static Life Cycle Assessment: A Case Study of a Commercial Building

Yahong Dong[1] and Yating Zhao[2]

[1]Associate Professor, Macau University of Science and Technology, Macau, China
[2]PhD Student, Macau University of Science and Technology, Macau, China
Corresponding author's E-mail: yhdong@must.edu.mo

Abstract

Carbon emissions from the building industry has significant impacts to the global warming. In the context of increasingly severe challenges posed by climate change, accurately assessing the carbon emissions throughout the entire life cycle of buildings is crucial. However, most previous studies have employed the traditional static life cycle assessment (LCA) method, neglecting the dynamic changes that buildings undergo during their life cycle. Comparative studies between dynamic and static life cycle assessments of buildings are scarce. The aim of this study is to analyze the differences in LCA results of buildings by incorporating dynamic factors. First, a static LCA model of a commercial building is established in SimaPro. Second, building information modelling (BIM) and building energy modelling program (BEMP) are integrated to generate dynamic inputs for a dynamic life cycle assessment (D-LCA) model. Revit is employed to establish the BIM model, which generates a bill of building materials. The Designer Simulation Toolkit (DeST) is utilized as the BEMP to simulate the operational energy consumption of the studied building, and the results from DeST are subsequently used as data inputs for the dynamic scenarios. The findings indicate that the differences between static and dynamic scenarios can reach up to 66.7%, with optimization of the electricity mix and incorporating global warming influences identified as the primary reasons for this significant discrepancy.

Keywords: dynamic life cycle assessment; comparative analysis; building; static life cycle assessment

1. INTRODUCTION

The rapid development of the building industry has significantly impacted energy consumption and greenhouse gas (GHG) emissions, particularly in China, where extensive construction projects are currently taking place. The carbon emissions from the building sector accounted for approximately 37% of the total global related carbon emissions in 2021, representing a 5% increase from the emission levels in 2020 (GlobalABC, 2022). During the same period, energy consumption in China's building sector constituted 45.5% of the nation's total energy consumption, while carbon emissions from the industry accounted for 50.9% of the country's total emissions (CBEEA, 2022).

Life cycle assessment (LCA) is a systematic evaluation tool used to analyze the environmental impacts of products or services throughout their entire life cycle, providing a scientific basis for decision-making (Kloepffer, 2008). China has begun to require the application of LCA for calculating carbon emissions in building project audits (MHURD, 2021). By scientifically and accurately assessing the carbon emissions of buildings, a foundation can be laid for achieving energy conservation and emission reduction goals (Chastas et al., 2018). In the academic field, LCA methods have also been widely researched and applied in the building industry. For instance, studies have found that traditional buildings exhibit higher carbon emission intensity during the construction phase compared to prefabricated buildings (Qiang et al., 2019). Research on the LCA of different building materials has also garnered attention, with Sudarsan et al. (2022) indicating that using green building materials as a substitute for traditional materials can reduce environmental pollution. However, many existing studies primarily utilize static LCA, failing to account for the effects of temporal changes on energy consumption and carbon emissions, which undermines the credibility of the evaluation results (Anand and Amor, 2017).

Dynamic life cycle assessment (D-LCA) is an emerging method designed to consider the impacts of time-varying factors, which are essential in evaluating the environmental load of buildings. Existing D-LCA research in the building sector can be primarily categorized into two types: one that obtains dynamic energy consumption data during building operation through real-time monitoring (Asdrubali et al., 2019), and the other that predicts future energy consumption through assumptions and modeling (Yeung et al., 2023). Although D-LCA offers significant advantages over static LCA, its application remains limited due to the challenges associated with acquiring dynamic data. This limitation also complicates the comparison of results between D-LCA and static LCA assessments.

This study takes a commercial building in Qingdao, China, as a case example. The building material data were generated using building information modeling (BIM), while operational phase data were generated through Designer Simulation Toolkit (DeST) simulations. A static LCA model was established in SimaPro to assess baseline conditions. Throughout the research process, dynamic factors were collected through literature review and incorporated into the static LCA model as much as possible. Subsequently, the differences between static LCA and D-LCA were compared, addressing the gaps in case studies of D-LCA for buildings and providing a reference for future research.

2. MATERIAL AND METHODS

2.1. Selection of dynamic factors

To ensure a comprehensive analysis of dynamic factors in building LCA, a literature review was conducted using the Web of Science database. The search string used was (“D-LCA” or “dynamic life cycle assessment” or “dynamic LCA” AND “building”). The selection criteria included (i) articles published in English, comprising peer-reviewed papers and conference proceedings; (ii) case studies only, excluding review articles; (iii) exclusion of D-LCA studies focused on single building materials; and (iv) exclusion of articles with low relevance. Ultimately, 29 relevant publications were identified. A review of these 29 articles revealed that the dynamic factors currently considered in research include dynamic consumption, dynamic inventory, dynamic characterization factor, and dynamic weighting factor. Since there are no authoritative and recognized characterization factor in the North China region, and this study focuses solely on the environmental impact category of climate change, the dynamic characterization factor and dynamic weighting factor are not included in this study. Instead, the research primarily examines the influence of dynamic consumption and dynamic inventory on assessment outcomes.

2.2. Description of study case

In this study, the building case is located in Qingdao, China (36° 04′ 01″ N, 120° 22′ 58″ E), which has a temperate monsoon climate characterized by distinct oceanic climate features due to direct modulation from the marine environment. The studied building is a commercial office structure with three underground levels and 22 above-ground levels, covering a total area of 37,774.83 m^2 and constructed with a frame shear wall structure. Construction of the building commenced in 2021 and was completed in 2023, with a designed lifespan of 50 years. The four facades of the building consist of a frame and glass curtain walls, with the average proportion of glass curtain wall accounting for approximately 73% of each facade. The building relies on a central air conditioning system for heating and cooling, while domestic hot water is supplied solely by drinking water dispensers in the pantry. Architectural drawings, design specifications, quantity take-offs, and other relevant support documents were obtained from the project designer to assist with modeling in Revit and DeST-c. The geographical location and photographs of the building under study are presented in Figure 1.

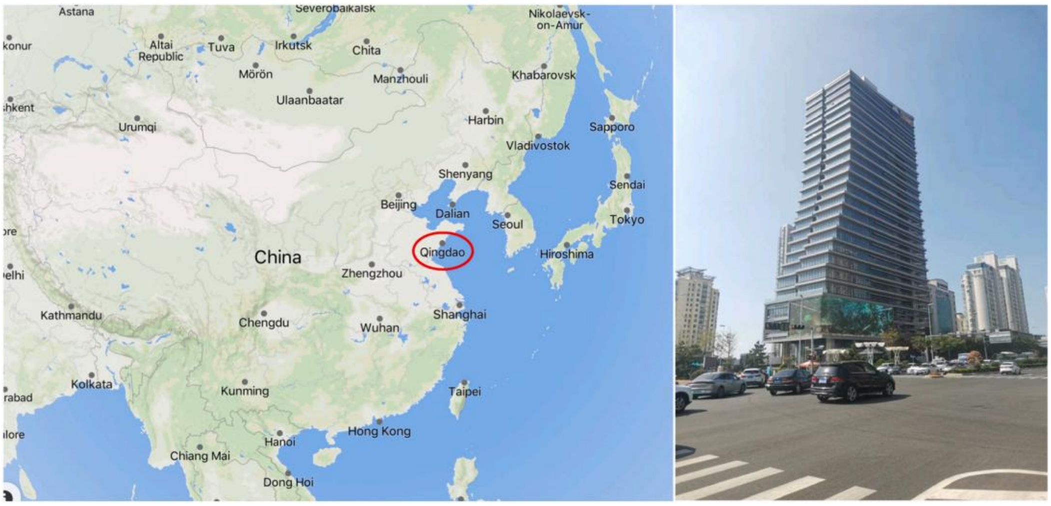

Figure 1. Geographical location and photographs of the studied building (Yang et al., 2024)

2.3. Setups of the baseline scenario (static)

Goal and Scope Definition. The system boundary of this study encompasses the entire life cycle of the building, with the functional unit defined as per square meter of floor area. The primary research objectives are as follows: (i) to verify the data quality of the production phase through BIM and to obtain operational energy consumption data using the DeST model, thereby supporting the assessment of the entire life cycle of the building project; (ii) to consider future changes in energy structure and climate change to predict energy consumption during the operational phase and to establish dynamic scenarios. This involves comparing the differences between static and dynamic scenarios to provide a reference for other LCA studies of commercial buildings.

Inventory analysis. The production phase of building materials was modeled using Revit, incorporating a construction material waste rate of 5.5% (Zhang and Wang, 2017) to verify the quality of the project's quantity take-off data. The difference in concrete consumption compared to the bill of quantities was 6%. After communication with relevant stakeholders, it was confirmed that this difference is within a reasonable range. The list of building material consumption and the corresponding transportation distances are presented in Table 1. It is noteworthy that, due to the inability to obtain actual activity data for the transportation phase, we assumed that the mode of transportation for the building materials is by truck, with transportation distances measured using online mapping software.

Table 1. Building material consumption and the transportation distances

Building material	Amount	Unit	Transport distance	Unit
Concrete	22,025	m^3	14	km
Steel	3,430	t	299	km
Cement mortar	5,299	t	24	km
Bricks	3,823	m^3	587	km
Windows and doors	18,590	m^2	60	km
Pipes	57,533	m	64	km
Insulation materials	291	t	20	km
Wire	150,909	m	440	km
Paint	14	t	569	km
Others	1,348	t	43	km

For the operational phase, the energy consumption of the building is obtained through DeST-c simulation. The water consumption of the building is referenced from the recommended values in the national standard GB/T 55015-2021 "General Code for Energy Efficiency and Renewable Energy Application in Buildings" (MHURD, 2021). For the construction and demolition phases, we refer to the data provided by Zhang and Wang. (2016) and Yang et al. (2018).

Life cycle impact assessment. This study established a static LCA model in SimaPro and conducted the analysis using the ReCiPe midpoint (H) method.

Interpretation. Based on the static LCA, this study considered the impact of temporal factors and established dynamic scenarios. A comparative analysis was conducted between static LCA and D-LCA to clarify energy-saving and carbon-reduction potentials.

2.4. Setups of the dynamic scenario

Dynamic building material consumption refers to the increased consumption resulting from maintenance and replacement (such as doors, windows, glass curtain walls, and pipelines) and considers improved recycling rates and the secondary utilization of construction waste at the end of the building's life cycle. Based on market research, this study assumes that the replacement cycles for doors, windows, glass curtain walls, and pipelines are 25 years, 25 years, and 15 years, respectively, and that the recycling rate for construction waste is improved by 15% compared to the current level.

Building operational energy consumption is the main contributor to building carbon emissions. In this study, the operational energy consumption is simulated using DeST-c, where factors such as outdoor temperature, air conditioning temperature, the thermal conductivity of the glass curtain wall, the energy recovery rate of elevator, and the energy mix structure can cause fluctuations in operational energy consumption. The settings for the aforementioned influencing factors are as follows:

Outdoor temperature. To account for the impacts of global warming, this study utilizes climate data from the BCC-CSM2-MR model under three scenarios: SSP1-1.9, SSP2-4.5, and SSP3-7.0. In the SSP labels, the first number represents the assumed Shared Socioeconomic Pathway, while the second indicates the approximate global effective radiative forcing (ERF) in 2100. Meteorological data for the building lifespan (2024-2073) were downloaded from public databases. Daily temperature data from meteorological stations in Qingdao were exported using ArcGIS, and hourly temperature data were obtained through linear interpolation. These temperature data were then imported into the DeST database for energy consumption simulation.

Air conditioning temperature. Due to the building design parameters set at 24^{o}C for summer and 20 ^{o}C for winter, we established the corresponding temperature gradients for simulation as follows: summer/winter temperatures of 22/22, 23/21, 24/20, 25/19, and 26/18.

Thermal conductivity of the glass curtain wall. The initial thermal conductivity coefficient of the glass curtain wall is set at 1.5. It is assumed that at the end of its service life, it will be replaced with a glass curtain wall that has superior performance. In this regard, we referenced several types of glass with improved thermal performance from the China Glass Industry Information Platform (CGN, 2018), which have thermal conductivity coefficients of 1.4, 1.27, and 1.2, respectively.

Energy recovery rate of elevator. Through interviews, it was determined that the typical lifespan of an elevator is 15 years, with an energy recovery efficiency of approximately 20%. Given that elevators need to be replaced three times throughout their life cycle, it is assumed that the energy recovery efficiency improves by 5% with each replacement, resulting in efficiencies of 25%, 30%, and 35%.

Energy mix structure. The proportions of the energy structure are based on the predicted levels from the “China 2030 Energy and Power Development Planning Study and 2060 Outlook” (GEIDCO, 2021).

The optimal settings for the five aforementioned influencing factors were incorporated into the D-LCA model, and the assessment results were compared with those of the static evaluation. The outdoor temperature was set at a radiative forcing of 4.5, as this value is noted in the "Fourth National Climate Assessment Report" (CMA, 2022) as the most likely scenario for China's future.

3. RESULTS

Table 2 summarizes the D-LCA and static LCA results for the studied building at various stages of its life cycle, while the proportion of dynamic scenarios to static scenarios is presented in Figure 2. It can be observed that, under the dynamic scenario, the total life cycle carbon emissions amount to 3.57E+07 $kgCO_2e$, whereas the total life cycle carbon emissions under the static scenario are 1.07E+08 $kgCO_2e$, indicating the result from the D-LCA is only 33.3% of that from static scenario.

Table 2. D-LCA and static LCA results for the studied building (larger values are shaded)

Stages	Total emission ($kgCO_2e$)		Emission per unit		
	Dynamic	Static	Dynamic	Static	Unit
Building materials	18,500,000	17,100,000	489.7	452.7	$kgCO_2/m^2$
Transportation	328,000	328,000	8.7	8.7	$kgCO_2/m^2$
Construction	7,380,000	13,019,077	19.5	34.4	$kgCO_2/m^2$
Operation	15,558,709	87,300,000	8.2	46.2	$kgCO_2/m^2/yr$
Demolition	576,062	1,170,000	15.2	31	$kgCO_2/m^2$
Whole life cycle	35,700,772	107,198,000	18.9	56.9	$kgCO_2/m^2/yr$

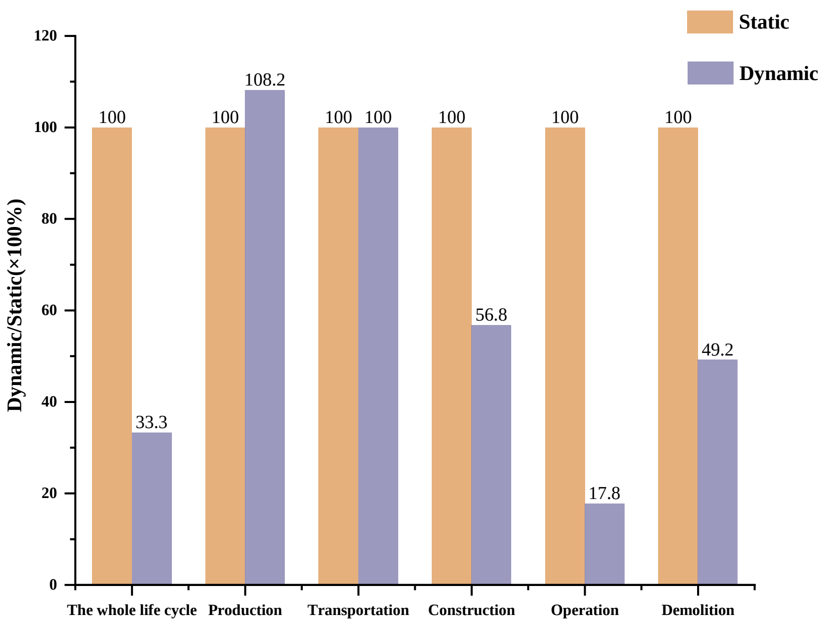

Figure 2. Comparison of D-LCA and static LCA results throughout the life cycle of the studied building (Yang et al., 2024)

The dynamic results for the operational phase account for only 17.8% of the static results, representing a significant difference of 82.2%, which is the primary source of the discrepancy between the two assessment outcomes. This difference arises because the static assessment did not consider changes in the future electricity structure, and the emission factor provided in SimaPro is based on China's electricity emissions from 2015, which is 1.04 $kgCO_2e/kWh$. In contrast, the latest national average carbon emission factor released by the Chinese government is only 0.581 $kgCO_2e/kWh$. Furthermore, over time, the share of non-fossil energy in electricity generation is expected to gradually increase, indicating that future electricity carbon emission factors will be significantly lower than current levels. Additionally, under the SSP2-4.5 scenario, the continuous rise in temperature results in reduced heating demand and increased cooling demand; however, since the energy consumption for heating via air conditioning is greater than that for cooling, the overall energy consumption for air conditioning decreases. For the building materials production phase, the dynamic results are slightly higher than the static results due to the accumulated carbon emissions from the replacement of windows and glass curtain walls in the dynamic scenario.

It is noteworthy that due to the difficulties in obtaining foundational data for building materials production, this study does not consider the emissions reductions resulting from improvements in future building materials production processes. The transportation of building materials typically occurs within a concentrated time period, which is relatively short, and thus was not included in the dynamic analysis. For the construction phase, the carbon emissions under the dynamic scenario account for 56.8% of those in the static scenario, a difference attributed to the varying electricity emission factors used. In the demolition phase of the dynamic scenario, carbon emissions represent 49.2% of those in the static scenario, which is due to the increased recycling rates of key building materials such as concrete, steel, glass, and bricks.

The significant differences between static LCA and D-LCA have been also reported by other studies. It is found that the differences between dynamic and static assessment results are case-specific and are influenced by a combination of factors, including selected dynamic variables, building types, assessment periods, and geographical locations (Su et al., 2022). For example, Su et al. (2021) considered seven dynamic factors—household size, usage behavior, replacement and improvement of components, waste treatment, energy mix, weighting factors, and characterization factors—in their D-LCA study of residential buildings in Nanjing, China. They found that the differences between dynamic and static results under different scenarios ranged from -34.88% to +6.27%. Therefore, it has become a consensus that D-LCA can yield more accurate results and provide a more reasonable basis for decision-making (Lueddeckens et al., 2020).

4. CONCLUSIONS

This study conducted a case study of a commercial building in Qingdao, China to compare the differences from dynamic and static LCA models. A digital model of the building was created using Revit to obtain the bill of quantities and ensure data quality. Based on this, a static LCA model was developed in SimaPro. Considering the impacts of dynamic factors such as outdoor temperature, air conditioning temperature, thermal conductivity of the glass curtain wall, energy recovery rates of elevator systems, and energy mix structure, a time-based dynamic energy consumption simulation was conducted using DeST-c, providing a dynamic input inventory for the operational phase of the building and resulting in dynamic assessment outcomes.

This study found that the building's life cycle carbon emissions under the dynamic scenario are only 33.3% of those under the static scenario. This significant reduction is primarily due to the transformation of the energy structure throughout the future years, which lowers the carbon emission factor for electricity, greatly reducing carbon emissions during the operational phase. Additionally, the rise in outdoor temperatures leads to a decrease in heating energy consumption that exceeds the increase in cooling energy consumption, further reducing carbon emissions during operation. Furthermore, if users choose air conditioning temperatures with a smaller temperature difference from the room temperature, energy consumption can be further minimized. Therefore, to reasonably and accurately assess carbon emissions related to buildings, future research and application of D-LCA should be further emphasized and strengthened.

5. ACKNOWLEDGMENTS

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