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Article

Evaluation of the Environmental Performance of Residential Building Envelope Components

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Received: 12 November 2019; Accepted: 6 December 2019; Published: 31 December 2019

Abstract: The role of buildings in the context of addressing the consequences of climate change and the energy deficit is becoming increasingly important due to their share in the overall amount of green house gas (GHG) emissions and rapidly growing domestic energy consumption worldwide. Adherence to a sustainability agenda requires ever-increasing attention to all stages of a building's life, as such approach allows for the consideration of environmental impacts of a building, from design, through construction stages, until the final phase of a building's life—demolition. A life cycle assessment (LCA) is one of the most recognized and adopted models for the evaluation of the environmental performance of materials and processes. This paper aims to perform an LCA of four different types of residential buildings in Nur-Sultan, Kazakhstan. The assessment primarily considered embodied energy and GHG emissions as key assessment indicators. Findings suggest that the operational stage contributed to more than half of the GHG emissions in all the cases. The results of the study indicate that there is a dependence between the comfort levels and the impact of the buildings on the environment. The higher the comfort levels, the higher the impacts in terms of the CO_2 equivalent. This conclusion is most likely to be related to the fact that the higher the comfort level, the higher the environmental cost of the materials. A similar correlation can be observed in the case of comparing building comfort levels and life-cycle impacts per user. There are fewer occupants per square meter as the comfort level increases. Furthermore, the obtained results suggest potential ways of reducing the overall environmental impact of the building envelope components.

Keywords: life cycle assessment; building envelope; environmental impact; embodied energy; greenhouse gas emissions

1. Introduction

The consumption of energy and various products has been dramatically increasing at both national and global scales over the last several decades [1–3]. Steadily increasing consumption levels, along with human activities, are causing significant negative impacts on the environment in terms of resource depletion, air contamination, and solid waste-related pollution. The construction industry and buildings, in general, are becoming one of the most significant contributors to environmental pressures. For instance, it was reported that in 2016, buildings around the world were responsible for 125 EJ, which is about 30% of the overall energy consumption [1]. Moreover, processes related to the extraction of resources, manufacturing and transporting construction materials, are also energy-hungry. For example, manufacturing construction materials such as steel and cement has been reported to account for 26 EJ, which equals 6% of global energy consumption [1]. Similarly, the construction industry and the building sector are also responsible for a considerable share of green house gas (GHG) emissions globally. While the building sector is responsible for almost 28% of the global energy-related CO_2 emissions, the construction of buildings claims another 11% of the total CO_2 emissions [1]. With the continuously growing global population and the increasing demand for housing and infrastructure, it is anticipated that energy consumption will also consistently grow. A retrospective outlook of the period between 2010 and 2017 supports such predictions, as the total energy consumption was reported to grow by more than 5% which is equal to 6 EJ [2].

The alarming rate of increase in terms of energy and resource consumption, as well as the associated environmental degradation, has made environmental agencies, commercial entities, and governments concerned. The status quo is no longer satisfactory and requires urgent actions from all parties to ensure a sustainable and safe future [4]. These entities need to seek and develop more sustainable solutions. This is particularly true in the case of construction industry due to the impact of the above-mentioned rates. In order to address such impacts, understand their full scale, and see opportunities where positive changes can be made, it is imperative to learn how to estimate the overall impact of buildings over their life-cycle.

In contrast to other industries, it is more challenging to evaluate the building sector and suggest long-term sustainability solutions [5]. Such difficulty is partially associated with the complexity and differences of buildings. For example, buildings differ depending on their location (region), used construction standards and norms, varying customer requirements and preferences, etc. [3]. In this context, it is a challenging task to make a precise environmental impact assessment of the entire building stock. Though energy and water use data are extensively available, for example, in the operational stage, there are still a lack of quantitative data on the pre-construction (extraction, manufacturing, and transportation) and post-construction (demolishment and disposal) stages [3].

Life Cycle Assessment (LCA)

Despite the complexity of building a life-time impact evaluation, a life cycle assessment (LCA) is a technique that can perform the above-mentioned task. An LCA is a tool with a comprehensive methodology that can assess the environmental impact of a whole building from cradle to grave. The life cycle of buildings span the processes of material resources extraction, manufacturing and transporting construction products and components, construction and operation stages, and it ends with the demolition and disposal of construction waste. Among others, an LCA assesses the overall environmental impact as a result of waste generation and GHG emissions, including CO_2 emissions, throughout all stages of a building life [6–10].

The main components of an LCA are: (1) the definition of goal and scope, with functional unit and system boundaries; (2) a life cycle inventory where necessary data are collected; (3) an impact assessment where the significance of the potential environmental impacts from the LCA's results is evaluated; (4) an interpretation phase where main findings are evaluated, and; (5) conclusions and recommendations. Despite the relative ease of use of the LCA approach, there is criticism related to several impediment factors such as the complexity of some of the assessment components, the necessity for large amounts of data and information, and subjective and/or inaccurate results [11]. Another challenge with the application of an LCA is associated with the relatively high costs of respective software licenses and the accessibility of the tools in general. One of the possible ways to tackle this barrier is to use simplified excel-based solutions. For example, the Energy Saving through promotion of Life Cycle analysis in Building (ENSLIC Building) Project developed an LCA tool for the European building context called the ENSLIC Basic Energy and Climate Tool, which is perceived as a simplified version of other types of LCA tools, has relatively comprehensive guidelines to follow (nine steps), and consists of a number of excel sheets [12,13]. This study narrowed its scope by focusing on the major ones for existing buildings.

As a part of continuous efforts to introduce sustainability principles and measures into the residential sector of Kazakhstan, this study aimed at assessing the life cycle impact of one the most energy and resources consuming components of buildings. Though a life-cycle assessment requires evaluating all stages of a building's life, this study limited its scope by focusing on the major ones for existing buildings. In terms of the significance of stages from a building's life cycle perspective, energy use in regions with cold temperature in operational stage can reach 80%–90%, which is the main merit or simplification, whereas the manufacturing of construction materials and on-site construction and demolition account for 10%–20% and 1%, respectively [6–10]. Hence, for simplification purpose, as well as due to limited amounts of data on the construction materials and the methods of existing building stocks, it was thought to be reasonable to focus on the operational and embodied energy of the buildings [14,15].

2. Methodology

The methodology adopted in this study aimed to assist in assessing the life-cycle performance of typical residential buildings in Nur-Sultan, Kazakhstan, a category that constitutes the majority of buildings in Kazakhstan. Addressing this type of building allowed for the replication of the results in order to achieve a wider-scale assessment of buildings. The study chose one case study building per 4 major residential building types (BTs). These four categories, namely (1) economy, (2) comfort, (3) business, and (4) premium were identified in a previous study of the authors [16].

Among all the parts of a multistory building envelope, the most impactful ones are external walls because they have direct exposure to ambient temperatures with the most extensive interfaces. An assessment of the impacts of external walls is specifically essential in the context of Kazakhstan's extremely harsh climatic conditions, with temperatures ranging from −40 to +35 degrees Celsius. The extended length of cold weather with a district heating period of nearly 8 months starting in October and lasting till May, along with the fact that the significant part of the exiting building stocks are multistory apartment blocks, justified the choice of external walls as it is the building envelope component that is responsible for the central portion of energy loss and material use [15,17,18]. This decision can be supported by findings of the life-cycle energy use assessment studies conducted in regions with cold temperatures, studies which suggested that increasing the insulation of external walls and roofs, for example, can lead to significant savings ranging from 10% to 30% depending on climatic conditions. Since the area of the external walls is significantly larger than the area of roofs in typical multistory buildings, it has been suggested to use the external walls, among other elements, for life-cycle assessments [10].

This study required the completion of nine steps, as shown in Figure 1. The first stage started with defining the aims of the study to quantify the environmental performance with crucial parameters, which were CO_2 emissions in our case. This parameter itself is a reasonable means of assessing the climate impact as well as the embodied energy. The assessment was performed for four building types with 50-years life cycle in Nur-Sultan, Kazakhstan. The second stage required the identification of the assessment tool. The reason behind the choice of this particular tool was explained in the previous section. The third stage required the choosing a building reference time (50 years, in this case) as well as setting the system boundaries, which were limited to the embodied energy (materials manufacturing and transportation) and operational stage. The operational stage is concerned with energy use but does not consider household electricity use. The fourth stage required explaining the scenarios of the building life-cycle. In this case, it was assumed that buildings experienced no renovations and no change in the usage mode throughout their life-cycle.

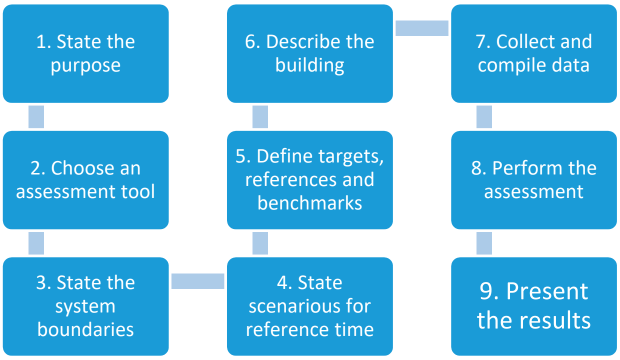

Figure 1. Life-cycle assessment methodology [11].

They have been operated in a usual way without unusual user-behavior. The study did not consider the end-life of the buildings since this stage was not considered in this assessment. The fifth stage required defining the values that were anticipated in the analysis. For example, the maximum energy use was anticipated to be 55 kWh/m^2/year, and CO_2 was anticipated to be least 10 kg CO_2-equivalents/m^2/year. The remaining stages are explained in the Results section.

3. Results

3.1. Description of the Case Examples of the Studied Building Types

The first building type was the economy class (Figure 2). Construction started in 2015 and was completed in 2017. The building consists of 11 floors with apartments (three-to-four apartments per unit) and a ground floor with various amenities such as shops, cafes, and other commercial facilities. The indoor temperature in winter was anticipated to be a minimum of 20 degrees Celsius. The primary building materials of the external wall are concrete, clay bricks, and insulation (mineral wool).

Figure 2. Economy class building.

The second building type was the comfort class (Figure 3). Construction started in 2013 and was completed in 2016. The building consists of 14 floors and a ground floor with a parking area. Floors two-to-fourteen are apartments with six-to-eight flats per unit. The first floor accommodates shops, cafes, children centers, and other commercial facilities. The indoor temperature in winter was anticipated to be 20 degrees Celsius. The primary building materials of the external wall are monolithic reinforced concrete with autoclaved aerated concrete and clay bricks, as well as insulation (mineral wool). The façade is covered with granite tiles.

The third building type was the business class (Figure 4). Construction started in 2010 and was completed in 2016. The building consists of 13 floors, with floors two-to-thirteen being apartments with 12 flats per unit. The first floor consists of kinder gardens, shops, cafes, gym, and other commercial places. The indoor temperature in winter was anticipated to be 22 degrees Celsius. The primary building materials of the external wall are reinforced concrete, clay brick, insulation (mineral wool), and a facade tiled with gypsum tiles.

Figure 3. Comfort class building.

Figure 4. Business class building.

The fourth building type was the premium class (Figure 5). Construction started in 2008 and was completed in 2010. There are 13 floors and a ground floor with a parking area. Floors two-to-thirteen are apartments with three-to-five flats per unit. The first floor mainly consists of shops, cafes, restaurants and other commercial amenities. The indoor temperature in winter was anticipated to be 22 degrees Celsius. The primary building materials of the external wall are monolithic, reinforced concrete with aerated concrete blocks, foamed polystyrene, and granite.

Figure 5. Premium class building.

3.2. *On the Data Collected*

The data required for the LCA analysis, among others, included district heating energy use, which includes hot water heating energy use (district); data on buildings' materials used in the building envelopes, data on the number of years of maintenance; and data on the amount of used water. The needed data also included the types of transportation used and the distance to the construction site. The data were collected from the residents of four case study buildings and were input into the ENSLIC Basic Energy and Climate Tool for analysis. The district heating period was selected to be eight months in accordance with general heating season in Nur-Sultan city. The study also made several estimations regarding the case study buildings. For instance, it was found that the number of occupants per apartment depended on building class. On average, economy and comfort class buildings tend to have four persons per apartment, whereas business and premium class buildings tend to have three and two persons per apartment, respectively. This tendency, in part, can be explained by the fact that the former two classes of buildings are more affordable for middle-class income families. Such families tend to have a higher number of people per family.

In contrast, the last two class buildings tend to be populated by smaller families or used only for business purposes. The material use values in kg were computed based on the dimensions of the building envelope components. (Table 1)

Table 1. Key parameters and estimations.

Building Class	Floor Area (m^2)	Number of Users (Person)	Materials Used (kg)
Premium	90	2	Concrete: 30,997 Aerated concrete: 12,153 Mineral wool: 6 Foamed polyester: 267 Steel: 1097 Glass: 375 Granite tiles: 5545
Business	55	3	Concrete: 18,304 Clay brick: 8475 Mineral wool: 96 Steel: 693 Glass: 125 Gypsum: 1953
Comfort	64	4	Concrete: 21,977 Clay brick: 20,391 Mineral wool: 86 Steel: 796 Glass:190 Granite tiles: 3267
Economy	75	4	Concrete: 21,551 Clay brick: 27,414 Mineral wool: 106 Steel: 903 Glass: 250 Gypsum: 6375

3.3. *On the Model Results and Calculations*

The amounts of energy and construction materials were calculated per unit (apartments of different sizes) due to the fact that all selected case study buildings are of different sizes. Choosing one apartment from each case study building and assuming different materials used for building envelopes and different rates of heating and hot water-related energy, the study allowed for comparisons of the differences in terms of life-cycle impact per units, such as square meter and user (Table 2). More detailed calculations are presented in Table 3.

Table 2. Calculated values of CO_2 equivalents.

Building Class	Total Heat Use (MJ)	Impact Total (kg CO_2 Equivalent)	Impact Relative (per m^2)	Impact Relative (per User)
Premium	273,658	1,189,829	13,220	594,915
Business	209,388	657,107	11,947	219,086
Comfort	167,040	625,523	9777	156,431
Economy	200,822	737,237	9829	184,309

Table 3. Life cycle assessment of building envelope components.

Premium Class

	Type	Amount MJ	Life time years	Potential Impact	Unit
OPERATING ENERGY	District heating - Nur-Sultan	273 658		615 730	kg eqv CO2
			Sum	615 730	kg eqv CO2
	Granite tiles	12 421	50	41 362	kg eqv CO2
BUILDING MATERIALS	Glass	625	50	1 012	kg eqv CO2
	Steel	1 229	50	1 130	kg eqv CO2
	Polyeten	278	50	158	kg eqv CO2
	Mineral wool	6	50	10	kg eqv CO2
	Aerated concerete	13 733	50	274 660	kg eqv CO2
	Concrete, reinforced	33 787	50	255 767	kg eqv CO2
			Sum	574 099	kg eqv CO2
		Both Energy & Materials		**1 189 829**	kg eqv CO2

Business class

	Type	Amount MJ	Life time years	Potential Impact	Unit
OPERATING ENERGY	District heating - Nur-Sultan	209 398		473 239	kg eqv CO2
			Sum	473 239	kg eqv CO2
	Gypsum	4 375	50	14 568	kg eqv CO2
BUILDING MATERIALS	Glass	208	50	343	kg eqv CO2
	Steel	776	50	713	kg eqv CO2
	Mineral wool	100	50	168	kg eqv CO2
	Clay brick	9 577	50	17 047	kg eqv CO2
	Concrete, reinforced	19 951	50	151 029	kg eqv CO2
			Sum	183 868	kg eqv CO2
		Both Energy & Materials		**657 107**	kg eqv CO2

Comfort class

	Type	Amount MJ	Life time years	Potential Impact	Unit
OPERATING ENERGY	District heating - Nur-Sultan	167 040		377 510	kg eqv CO2
			Sum	377 510	kg eqv CO2
	Granite tiles	7 318	50	24 368	kg eqv CO2
BUILDING MATERIALS	Glass	317	50	523	kg eqv CO2
	Steel	892	50	820	kg eqv CO2
	Mineral wool	89	50	149	kg eqv CO2
	Clay brick	23 042	50	41 014	kg eqv CO2
	Concrete, reinforced	23 955	50	181 339	kg eqv CO2
			Sum	248 213	kg eqv CO2
		Both Energy & Materials		**625 723**	kg eqv CO2

Economy class

	Type	Amount MJ	Life time years	Potential Impact	Unit
OPERATING ENERGY	District heating - Nur-Sultan	200 822		453 857	kg eqv CO2
			Sum	453 857	kg eqv CO2
	Gypsum	14 598	50	48 611	kg eqv CO2
BUILDING MATERIALS	Glass	417	50	688	kg eqv CO2
	Steel	1 011	50	930	kg eqv CO2
	Mineral wool	110	50	185	kg eqv CO2
	Clay brick	30 978	50	55 140	kg eqv CO2
	Concrete, reinforced	23 491	50	177 826	kg eqv CO2
			Sum	283 380	kg eqv CO2
		Both Energy & Materials		**737 237**	kg eqv CO2

4. Discussion and Conclusions

Figures 6 and 7 present the data on total heat use and impact (kg CO_2 equivalent) concerning building comfort level, respectively. The total energy utilization in the selected building types (Table 2) indicates that all the selected buildings are "A+ class" energy class buildings with less than 25 kWh/m^2 energy consumption per year [18]. According to Figure 8, it can be observed that there was a strong correlation between comfort level and environmental impact. Specifically, the higher the comfort levels, the higher the impacts in terms of CO_2 equivalent. This was most likely related to the fact that the higher the comfort level, the higher the environmental cost of the materials. There are also fewer occupants per square meter as the comfort level increases. Comfort and economy class buildings presented the same levels of impact per m^2. This can be explained by the similar types of construction materials used in the respective building envelopes. A positive correlation could be observed when comparing building comfort levels and life-cycle impacts per user. According to Figure 9, the higher the comfort level (fewer occupants), the higher the overall impact. While the trend seemed to stabilize across the economy, comfort, and business classes (which were found to have approximately four, four, and three occupants, respectively), it seemed to change dramatically in premium class buildings, which were found to have only two occupants.

In conclusion, it can be stated that this study identified several correlations between building comfort levels and life-cycle impacts, both in terms of square meter and per user (occupant). However, some limitations should also be considered while interpreting the results. For example, demolition and waste disposal stages were omitted despite their impact (1%–2%). Further research should also consider all other components of the buildings, such as roofs and floors. A comparison between the materials used and other overall impacts should be considered.

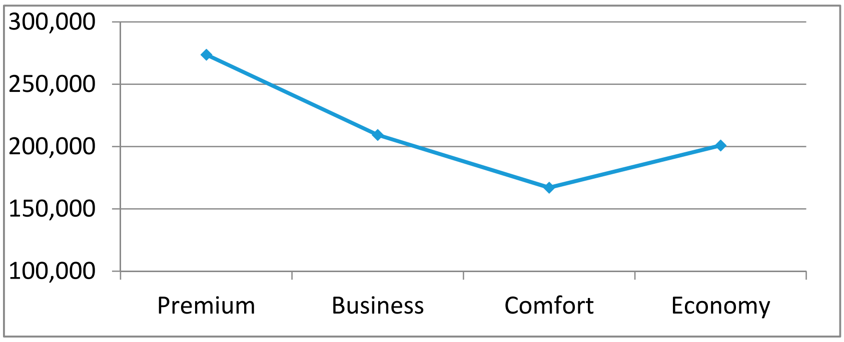

Figure 6. Total heat use (MJ) vs. building comfort level.

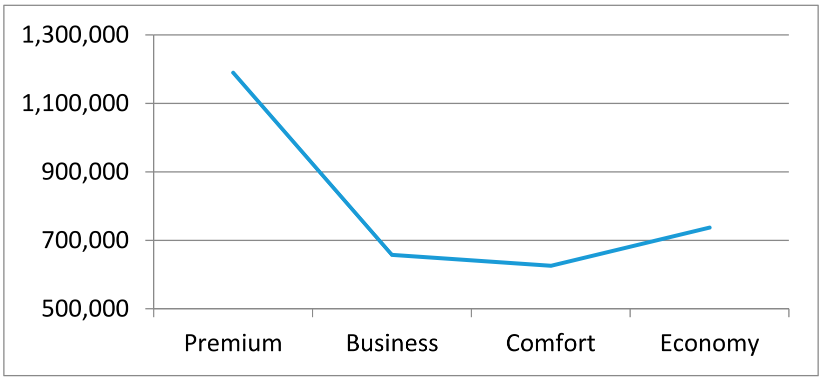

Figure 7. Impact total (kg CO_2 equivalent) vs. building comfort level.

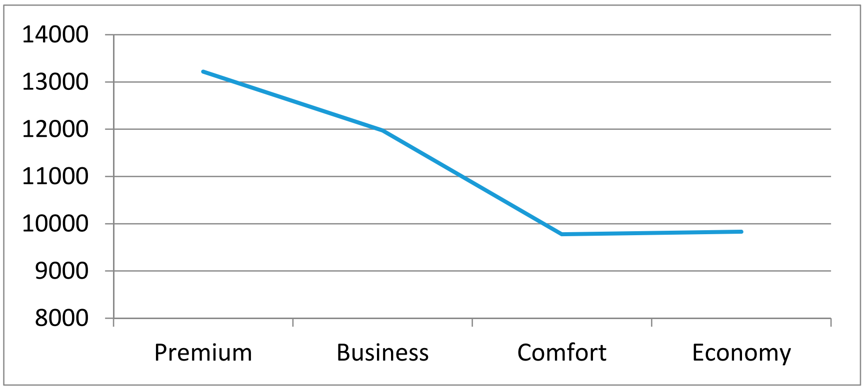

Figure 8. Impact relative (per m^2) vs. building comfort level.

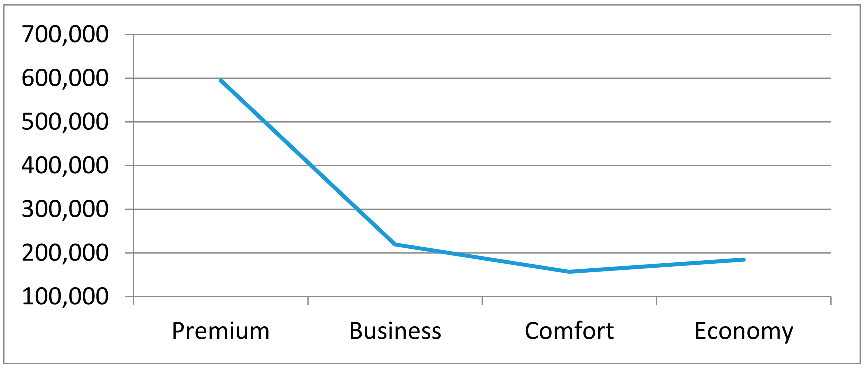

Figure 9. Impact relative (per user) vs. building comfort level.

Author Contributions: Conceptualization and funding acquisition, J.R.K.; Data curation, F.N.; Writing—original draft, S.T. and F.N.; Writing—review & editing, F.K. All authors have read and approved the final manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Nazarbayev University Research Fund under Grant #SOE2017003. The authors are grateful for this source of support. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the Nazarbayev University.

Acknowledgments: The authors gratefully acknowledge the ENSLIC Basic Energy and Climate Tool for LCA modeling used in this publication. We also thank the anonymous reviewers for their careful reading of our manuscript and their insightful comments and suggestions.

Conflicts of Interest: The authors declare no conflict of interest.

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