UDC 699.86:504.06:658.567
IRSTI 67.09.37
RESEARCH ARTICLE

LIFE CYCLE OF ENERGY-EFFICIENT FACADE SYSTEMS: ECONOMIC-ENVIRONMENTAL ASSESSMENT BASED ON SECONDARY DATA AND LCA METHODS

A.K. Malakhanov[1], M.R. Bakiev[2], G.O. Karshyga[3], M.A. Kambarov[1], B.O. Nukhayeva[4*], D.O. Bazarbayev[4*], A.K. Slyambayeva[5]

[1]M. Auezov South Kazakhstan Research University, Shymkent, Kazakhstan
[2]Tashkent Institute of Irrigation and Agricultural Mechanization Engineers, Tashkent, Uzbekistan
[3]Korkyt Ata Kyzylorda State University, Kyzylorda, Kazakhstan
[4]L. N. Gumilev Eurasian National University, Astana, Kazakhstan
[5]International Educational Corporation, Almaty, Kazakhstan

Abstract. *This article presents a methodology for the comprehensive assessment of facade systems that combines LCA and LCC approaches and is adapted to the climatic and economic conditions of Kazakhstan. A MATLAB-based software implementation automates calculations based on ISO and EN standards, integrating life cycle matrix models with discounted cash flows and Monte Carlo simulation to account for uncertainties. The effectiveness of the methodology is demonstrated using a sample case: a comparison of four types of facades (SFTC, a ventilated facade with ceramic granite, PIR/PUR sandwich panels, and a facade with integrated photovoltaic modules) over a 50-year period. The input data for this example were taken from publicly available secondary sources and are not tied to a specific project. Therefore, the resulting values illustrate the structure of the model's input data and the order of magnitude, but do not constitute a project-specific assessment. Even from this example, it is clear that the difference in life-cycle costs between the systems is significantly smaller than the difference in capital costs. The rate of growth in energy tariffs and the discount rate have the strongest influence on the LCC variance, while the price of materials has a weaker influence. After filling in the input matrices with data from a specific project, the methodology can be used to compare different options for building envelopes in various climatic regions of Kazakhstan.*

Keywords: *Life Cycle Assessment (LCA); Life Cycle Cost (LCC) analysis; energy-efficient facade systems; carbon footprint; embodied energy; mathematical modeling in MATLAB; Monte Carlo method.*

***Corresponding author**
Daniyar Bazarbayev, e-mail: daniyar.bazarbayev.86@mail.ru
Bakhytnur Nukhayeva, e-mail: bakhytnurnukhayeva@gmail.com

https://doi.org/10.51488/1680-080X/2026.3-17

ӘОЖ 699.86:504.06:658.567
ҒТАМР 67.09.37
ҒЫЛЫМИ МАҚАЛА

ЭНЕРГОЭФФЕКТИВТІ ҚАСБЕТ ЖҮЙЕЛЕРІНІҢ ӨМІРЛІК ЦИКЛІ: ҚАЙТАЛАМА ДЕРЕКТЕР МЕН LCA ӘДІСТЕМЕЛЕРІ НЕГІЗІНДЕ ЭКОНОМИКАЛЫҚ-ЭКОЛОГИЯЛЫҚ БАҒАЛАУ

А.К. Малаханов[1], М.Р. Бакиев[2], Ғ.О. Қаршыға[3], М.А. Камбаров[1], Б.О. Нухаева[4*], Д.О. Базарбаев[4*], А.К. Слямбаева[5]

[1]М. Әуезов атындағы Оңтүстік Қазақстан зерттеу университеті, Шымкент қ., Қазақстан
[2]Ташкент ирригация және ауыл шаруашылығын механизациялау инженерлері институты, Ташкент қ., Өзбекстан
[3]Қорқыт Ата атындағы Қызылорда университеті, Қызылорда, Қазақстан
[4]Л. Н. Гумилев атындағы Еуразиялық ұлттық университет, Астана, Қазақстан
[5]Халықаралық білім беру корпорациясы, Алматы, Қазақстан

Аңдатпа. *Мақалада LCA және LCC тәсілдерін біріктіретін және Қазақстанның климаттық және экономикалық жағдайларына бейімделген қасбеттік жүйелерді кешенді бағалау әдістемесі ұсынылған. MATLAB ортасында бағдарламалық қамтамасыздандыру ISO және EN стандарттарына негізделген есептеулерді автоматтандырады, өмірлік циклдің матрицалық модельдерін дисконталған ақша ағындарымен және белгісіздіктерді есепке алу үшін Монте-Карло модельдеуімен біріктіреді. Әдістеменің өнімділігі демонстрациялық мысалда көрсетілген: 50 жылдық көкжиекте қасбеттердің төрт түрін (SFTK, фарфордан жасалған желдеткіш қасбет, PIR/PUR сэндвич панельдері және біріктірілген фотоэлектрлік модульдері бар қасбет) салыстыру. Мысал үшін бастапқы деректер ашық қайталама көздерден алынған және белгілі бір объектіге байланбаған. Сондықтан алынған мәндер модельдің Шығыс құрылымын және шамалардың ретін көрсетеді, бірақ жобалық бағалау емес. Қазірдің өзінде бұл мысалда жүйелер арасындағы өмірлік цикл құнының айырмашылығы күрделі шығындар айырмашылығынан айтарлықтай аз екенін көруге болады. LCC таралуына энергия тарифтерінің өсу қарқыны мен дисконттау мөлшерлемесі қатты әсер етеді, материалдардың бағасы әлсіз әсер етеді. Кіріс матрицаларын нақты жоба деректерімен толтырғаннан кейін әдістемені Қазақстанның әртүрлі климаттық аймақтарындағы қоршау конструкцияларын вариантты салыстыру үшін пайдалануға болады.*

Түйін сөздер: *өмірлік цикл бағалау (LCA); өмірлік цикл шығындарын талдау (LCC); энергия үнемдейтін фасад жүйелері; көміртегі ізі; ендірілген энергия; MATLAB-та математикалық модельдеу; Монте-Карло әдісі.*

***Автор-корреспондент**
Данияр Базарбаев, e-mail: daniyar.bazarbayev.86@mail.ru
Бахытнур Нухаева, e-mail: bakhytnurnukhayeva@gmail.com

https://doi.org/10.51488/1680-080X/2026.3-17

УДК 699.86:504.06:658.567
МРНТИ 67.09.37
НАУЧНАЯ СТАТЬЯ

ЖИЗНЕННЫЙ ЦИКЛ ЭНЕРГОЭФФЕКТИВНЫХ ФАСАДНЫХ СИСТЕМ: ЭКОНОМИКО-ЭКОЛОГИЧЕСКАЯ ОЦЕНКА НА ОСНОВЕ ВТОРИЧНЫХ ДАННЫХ И МЕТОДИК LCA

А.К. Малаханов[1], М.Р. Бакиев[2], Г.О. Каршыга[3], М.А. Камбаров[1], Б.О. Нухаева[4*], Д.О. Базарбаев[4*], А.К. Слямбаева[5]

[1]Южно-Казахстанский исследовательский университет имени М. Ауэзова, г. Шымкент, Казахстан
[2]Ташкентский институт инженеров ирригации и механизации сельского хозяйства, Ташкент, Узбекистан
[3]Кызылординский университет имени Коркыт Ата, Кызылорда, Казахстан
[4]Евразийский национальный университет имени Л. Н. Гумилева, Астана, Казахстан
[5]Международная образовательная корпорация, Алматы, Республика

Аннотация. *В статье представлена методика комплексной оценки фасадных систем, объединяющая подходы LCA и LCC и адаптированная к климатическим и экономическим условиям Казахстана. Программная реализация в среде MATLAB автоматизирует расчеты на основе стандартов ISO и EN, интегрируя матричные модели жизненного цикла с дисконтированными денежными потоками и моделированием Монте-Карло для учета неопределенностей. Работоспособность методики показана на демонстрационном примере: сравнении четырёх типов фасадов (СФТК, вентилируемый фасад с керамогранитом, сэндвич-панели PIR/PUR и фасад с интегрированными фотоэлектрическими модулями) на горизонте 50 лет. Исходные данные для примера взяты из открытых вторичных источников и не привязаны к конкретному объекту. Поэтому полученные значения показывают структуру выходных данных модели и порядок величин, но не являются проектной оценкой. Уже на этом примере видно, что разница в стоимости жизненного цикла между системами значительно меньше, чем разница в капитальных затратах. Сильнее всего на разброс LCC влияют темп роста энерготарифов и ставка дисконтирования, цена материалов влияет слабее. После заполнения входных матриц данными конкретного проекта методику можно использовать для вариантного сравнения ограждающих конструкций в разных климатических районах Казахстана.*

Ключевые слова: *оценка жизненного цикла (LCA); анализ совокупной стоимости владения (LCC); энергоэффективные фасадные системы; углеродный след; эмбедированная энергия; математическое моделирование в MATLAB; метод Монте-Карло.*

***Автор-корреспондент**
Данияр Базарбаев, e-mail: daniyar.bazarbayev.86@mail.ru
Бахытнур Нухаева, e-mail: bakhytnurnukhayeva@gmail.com

https://doi.org/10.51488/1680-080X/2026.3-17

1 INTRODUCTION

In the context of the ratification of international climate agreements and the consistent implementation of ESG (Environmental, Social, Governance) principles in the construction sector of the Republic of Kazakhstan, the tightening of regulatory requirements for building energy efficiency highlights the need to rethink approaches to the design of building envelopes. Given that facade systems can account for up to 40-60% of a building's heat loss, their role in achieving the required energy efficiency class ratings becomes critical [1]. Rising energy costs and tight operating budgets are forcing designers and investors to rethink their approaches to decision-making. Rather than focusing on short-term metrics, there is now a need for strategic planning that takes into account the long-term consequences of the decisions made. Recent studies show that the operational phase of a building's life cycle, which previously accounted for the largest share of energy consumption, is gradually losing its dominant role. The role of "hidden" (embedded) costs and environmental impacts associated with the production, transportation, and subsequent disposal of materials is growing [2; 3].

Despite the existing regulatory requirements [4], when selecting facade solutions in Russia, the primary focus is still on initial costs and the thermal resistance coefficient [5]. However, this approach fails to account for how the facade system will affect the building's operating costs and environmental performance over the next 30-50 years. As a result, errors arise in estimating the total cost of ownership and the carbon footprint of the building. Studies show that there are currently no standardized methodologies that allow for an accurate comparison of different facade systems, taking into account Kazakhstan's climatic conditions, as well as regional rates and logistical considerations [6; 7]. The lack of clear and reproducible calculation tools adapted to local conditions reduces the accuracy of comparative assessments and complicates the implementation of economic principles in construction practice.

This study aims to develop a methodology for the comparative economic and environmental assessment of facade systems based on the LCA (Life Cycle Assessment) and LCC (Life Cycle Costing) approaches. As part of this work, data on materials and energy consumption were systematized, life cycle boundaries were adapted to the climatic conditions of Kazakhstan's regions, and a computational core was created in MATLAB to automate multi-variant scenarios. A sensitivity analysis of key parameters was conducted, and practical recommendations were prepared for design and construction organizations.

A sensitivity analysis of key parameters was conducted, and the methodology's operation is illustrated using a demonstration example. This article is methodological in nature. Its subject is the evaluation procedure itself: the composition of the input data, the calculated relationships, the system boundaries, and the method for accounting for uncertainty. The numerical example in Section 5 is based on data from secondary sources. It is intended to show what results the model produces and how to interpret them.

The scientific novelty of this work lies in the integration of matrix-based LCA calculations and discounted cash flows into a single software environment, taking into account regional climatic (GSOP, temperature gradients, heating season duration) and economic (tariff trends, inflation expectations) parameters

In recent years, life cycle assessment (LCA) and life cycle cost (LCC) analysis methods have been increasingly applied in the design of building envelopes. According to research findings, there has been a gradual shift in the focus of specialists' work from exclusively operational energy consumption to a comprehensive consideration of embedded costs and environmental impacts [8]. This shift is due to the fact that modern buildings are becoming more energy-efficient, and the share of operating costs is gradually decreasing. At the same time, requirements for reducing the carbon footprint in the construction industry are becoming stricter. In studies [9; 10]. It is noted that without taking all stages of the life cycle into account, the selection of facade solutions remains incomplete and, in the long term-over 30 to 50 years-may prove to be economically inefficient.

https://doi.org/10.51488/1680-080X/2026.3-17

The methodological framework for LCA/LCC of building structures is based on the ISO 14040/14044, EN 15978, and ISO 15686-5 standards. Although approaches to LCA and LCC are gradually being standardized, their practical application is still limited by the quality of the input data. The main sources of information remain Environmental Product Declarations (EPDs), industry databases (Ecoinvent, ICE, and OpenLCA), and regulatory reference guides. Results may vary due to inconsistencies in input parameters. System boundaries, data allocation methods, approaches to accounting for material recycling, and regional logistics conditions differ. In some cases, discrepancies in the analysis of similar design solutions reach 20-35% [11; 12].

To reduce such errors, data from several independent sources are typically compared, confidence intervals are used, and the sensitivity of key parameters is analyzed. This makes the calculations more reliable even in cases where field tests are not available during the design phase [13; 14].

The adaptation of LCA and LCC methods to the climatic and economic conditions of Central Asia remains understudied. Most existing models were developed for Europe, North America, or East Asia, where the climate, duration of the heating season, and tariff structures differ from those in Kazakhstan. Studies show that ignoring regional climatic parameters, such as the average annual temperature and wind loads, can lead to errors in the assessment of environmental and economic indicators ranging from 15% to 25% [15; 16].

Kazakhstan has a sufficient amount of open data that can be used to create localized calculation models. Data from Comstat RK, regulatory documents from the State Agency for Standardization and Metrology of the Republic of Kazakhstan, as well as open EPDs (Environmental Product Declarations)-manufacturers' catalogs-can be used for this purpose. This makes it possible to perform calculations without conducting costly laboratory tests.

Advances in computational tools have significantly expanded the capabilities for analyzing facade systems. Today, research increasingly combines LCA and LCC methods with optimization algorithms and probabilistic modeling. Using MATLAB makes it possible to automate the processing of large data sets, apply Monte Carlo methods to assess uncertainties, and build multi-criteria models-for example, to find solutions with minimal CO_2 emissions within a given budget [17; 18]. Compared to conventional tabular calculations, these approaches make the results more reproducible, allow for a clear illustration of the trade-off between environmental and economic indicators, and enable the model to be adapted in response to changes in tariffs or regulatory requirements.

However, there are still not enough off-the-shelf solutions specifically tailored to Kazakhstan's climatic conditions. This is particularly true for models that combine LCA calculations, discounted cash flow analysis, and parametric optimization within a single software environment.

An analysis of the research indicates an interest in developing reproducible and climate-adapted methods for evaluating facade systems. The main challenges today stem from the fragmented nature of regional data, the lack of standardized approaches to integrating LCA and LCC into design practice, and insufficient attention to uncertainty analysis.

2 MATERIALS AND METHODS

The overall sequence of the materials and methods applied in this study, from initial data collection to multi-objective optimization, is shown in Fig. 1. It includes the preparation of input data, parallel calculation of environmental (LCA) and economic (LCC) indicators, adaptation of the model to the climatic conditions of Kazakhstan, uncertainty and sensitivity analysis using the Monte Carlo method, and multi-objective optimization with the construction of a Pareto front.

https://doi.org/10.51488/1680-080X/2026.3-17

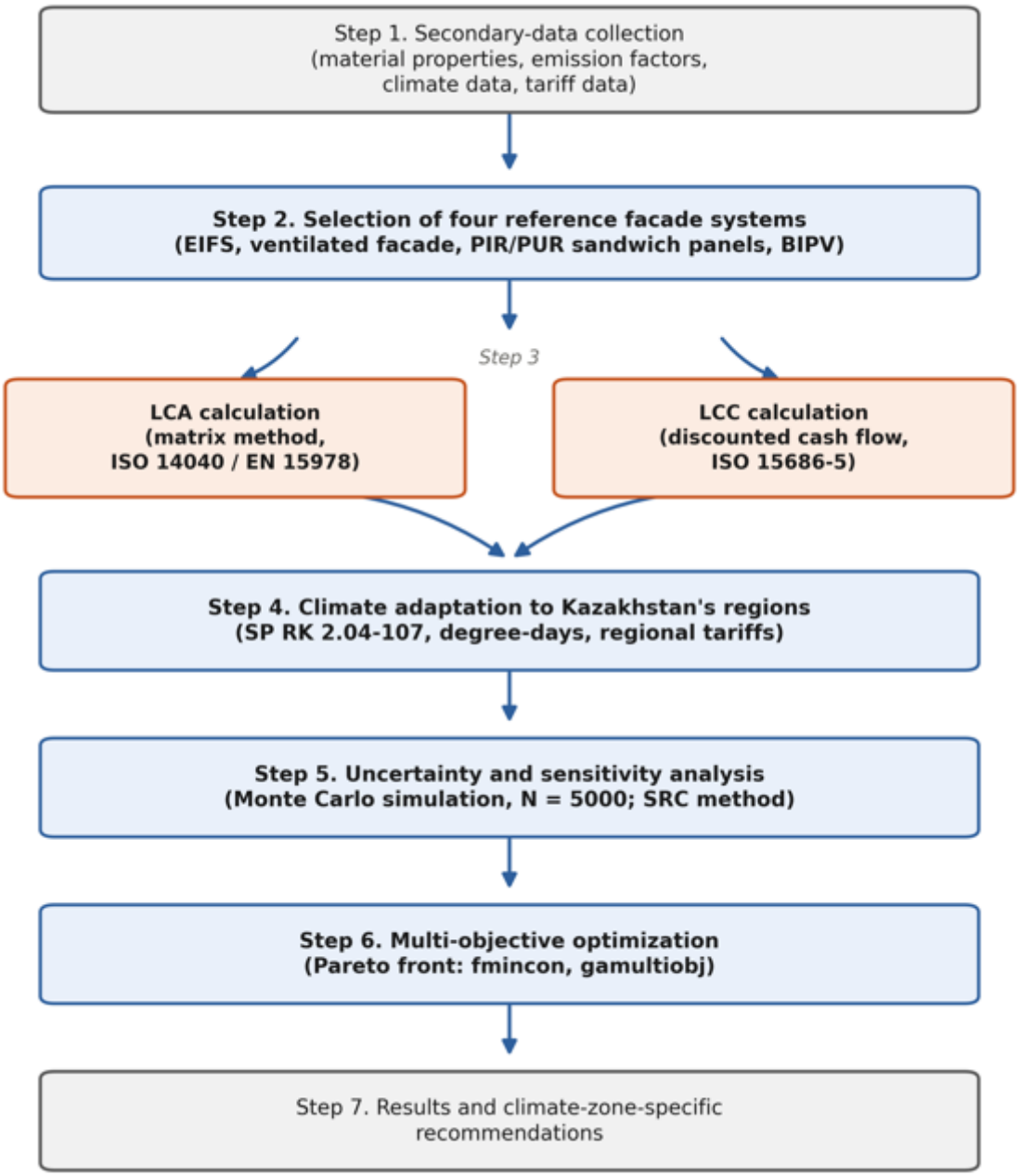


Figure 1 – Sequence of research materials and methods

2.1 Regulatory and Methodological Framework

The research methodology is based on three international standards that complement one another. ISO 14040 standards [19] set forth the general principles for conducting a life cycle assessment: from setting objectives and defining the system boundaries to analyzing impacts and interpreting the results. Standard EN 15978 [20] adapts these approaches for the construction industry and introduces a modular framework for assessing the life cycle of buildings and building envelopes. ISO 15686-5 [21] sets forth the rules for analyzing total cost of ownership, including the calculation of discounted costs for operation, maintenance, replacement of components, and disposal.

Using these standards within a unified system makes it possible to compare results with international best practices, take ESG reporting requirements into account, and subsequently integrate the model into digital design tools [22; 23].

https://doi.org/10.51488/1680-080X/2026.3-17

2.2 System Boundaries and Life Cycle Stages

The functional unit of analysis is 1 m² of the opaque portion of an exterior wall, which, over a 50-year period, provides a reduced thermal resistance of R_0 = 3.8 m²·°C/W under the climatic conditions of Astana. The indoor air temperature is assumed to be +20 °C, indoor humidity conditions are normal, and the building is a multi-story residential structure. All systems are compared under identical conditions: the same R_0, the same design life (50 years), and the same climate.

The study employs a "cradle-to-grave" approach, which covers the entire life cycle of the facade system-from the production of materials to their disposal.

The production phase (A1-A3) includes the extraction of raw materials, their transportation to manufacturing facilities, and the production of facade elements and components. The logistics and installation phase (A4-A5) covers the delivery of materials to the construction site, loading and unloading operations, the installation of structures, and the adjustment of assemblies.

The operational phase (B1-B7) is considered over a 50-year period, which corresponds to the standard service life of capital buildings in Kazakhstan and international life-cycle assessment practices. The calculation includes energy costs for heating and cooling, maintenance, repairs, and partial replacement of facade elements.

The final phase (C1-C4) involves the dismantling of structures, the sorting of waste, and its transport for recycling or disposal. Additionally, Phase D is taken into account, which examines the potential environmental benefits of material reuse, recycling, and energy recovery.

A photovoltaic facade not only encloses the building but also generates electricity; therefore, its boundaries are defined separately. The same rules apply to both the environmental and economic assessments.

The electricity generated is divided into two parts. The portion consumed by the building itself reduces operational energy consumption according to EN 15978. Therefore, in Module B6 for BIPV, it is subtracted taking into account the emission factor of Kazakhstan's power grid, and in the LCC analysis, it reduces electricity purchase costs. The portion fed into the grid lies outside the system's boundaries. It is accounted for in Module D and reported separately; in the LCC analysis, it generates revenue only in the "green" scenario, where a feed-in tariff applies. In the base scenario, this revenue is assumed to be zero. The embodied indicators for BIPV (the sum of A1–C4, excluding power generation) are compared with the other systems on a level playing field.

2.3 Secondary Data Sources

The study's data set was compiled from verified and publicly available sources, which can be broadly divided into three groups.

The first group includes environmental indicators. The embodied carbon and energy factors for the production stage (A1-A3) of typical materials (expanded polystyrene, rock wool, porcelain stoneware, steel, aluminum, and mortars) were taken from the ICE Database v3. For materials from specific manufacturers (sandwich panels, rock wool), priority was given to the data in the Environmental Product Declaration (EPD) when one was available. Ecoinvent v3.9 was used for processes not included in ICE: truck and rail freight transport (A4), waste incineration and landfilling (C3–C4), and the production of photovoltaic modules. Datasets for the RoW region were used. If multiple sources were available for a material, their variation was taken into account in the demonstration calculation: this variation defines the lower and upper limits of the ranges in Table 1. The values adopted for each system are shown in Table 1 (Section 5.1).

The second group relates to economic parameters. It includes data on the cost of materials, capital expenditures, and expenses for maintenance, repairs, and disposal. The information was gathered from publicly available price lists, statistical data from the National Statistics Bureau of the Republic of Kazakhstan, rates charged by heat and electricity suppliers, and regulatory documents governing building operations.

https://doi.org/10.51488/1680-080X/2026.3-17

All cost figures are given in 2025 prices, excluding VAT. Capital costs per 1 m² of facade include materials and installation. These figures were derived as a range based on the price lists of 3-5 suppliers and contractors for each system. The costs of repairing and replacing components were calculated using the same unit prices, taking into account the replacement scenario (Table 3). For heat and electricity rates, the approved rates of Astana's energy supply organizations for 2026 were used.

The third group includes climate data. Calculations of operational energy consumption were performed based on degree-days of the heating season (DDHS) in accordance with the requirements of SP RK 2.04-107 [SP RK 2.04-107-2022 Thermal Protection of Buildings]. The modeling took into account the average outdoor air temperature, the duration of the heating season, air permeability, and humidity characteristics for the northern, central, and southern climatic zones of Kazakhstan [24].

The calculation module allows you to specify these parameters for any construction site. The sample calculation in Section 5 is based on a single site, Astana, which represents the northern and central parts of the country.

Sensitivity analysis and Monte Carlo probabilistic modeling were used to assess the impact of uncertainties. The calculations varied key parameters: the discount rate, the rate of increase in energy tariffs, the actual service life of thermal insulation and cladding, and the proportion of materials sent for recycling. This approach allows us not only to obtain a single final value, but also to assess the range of possible outcomes and identify the parameters that most strongly influence the final LCA and LCC indicators.

The use of probabilistic modeling makes conclusions more robust and allows for assessments to be made without costly field tests, which is particularly important in the early stages of design [25; 26].

Mathematical modeling and implementation in Matlab

2.4 Architecture of the Computational Model

To ensure that the calculations are reproducible, flexible, and easy to expand upon, a software architecture consisting of four interconnected modules was developed in MATLAB (Fig. 2).

The first module is responsible for the environmental assessment (LCA module). It calculates material and energy flows and determines environmental impacts based on standard emission factors.

The second module is designed for economic analysis (LCC module). It calculates capital and operating costs on a discounted basis and also takes into account the costs of maintenance, replacement of facade components, and their subsequent disposal.

The third module adapts the calculations to the climatic conditions of Kazakhstan. The model takes into account the average annual temperature, temperature fluctuations, and humidity conditions in accordance with the requirements of SP RK 2.04-107, which allows for a more accurate assessment of operational energy consumption.

The fourth module performs optimization calculations. To find the most balanced solutions, the "fmincon" and "gamultiobj" algorithms are used, which allow for finding a compromise between the environmental and economic performance of facade systems.

This modular structure is in line with current recommendations for integrating LCA/LCC methodologies into computer-aided design environments and allows for the flexible replacement of individual components when regulatory frameworks or data sources are updated [27; 28].

2.5 Key Algorithms of the Computation Core

The LCA core is based on a matrix calculation of embedded environmental indicators. It is used to determine the total carbon footprint of a design, as well as the amount of embodied energy associated with the production, transportation, operation, and disposal of materials. The calculation is performed using the following formula:

$$EC = \Sigma(Q_i \times F_i \times K_i) \quad (1)$$

https://doi.org/10.51488/1680-080X/2026.3-17

where:

-Q_i - the mass or volume of the i-th material in the facade system (kg or m^3);

- F_i - specific emission factor from the database (kg CO_2-eq/kg or MJ/kg);

- K_i - regional adjustment factor. It applies only to materials produced in Kazakhstan and accounts for the difference between Kazakhstan's energy balance and that of the region for which the original dataset was compiled:

$$K_i = 1 + s_i \cdot (EF_{KZ} / EF_{ref} - 1), \quad (2)$$

where s_i is the share of emissions from electricity consumption in the A1–A3 indicator for the material (based on the dataset structure); EFKZ and EFref are the emission factors for the Kazakhstan power grid and the dataset region, respectively, in kg CO_2-eq/kWh. For imported materials for which the dataset or EPD corresponds to the country of origin, $K_i = 1$. Transportation is not included in this factor and is accounted for separately as stage A4.

The matrix-based implementation in MATLAB ensures high performance in multivariate analysis. This approach (Fig. 2) allows for the rapid recalculation of metrics when the list of materials changes or when coefficients in the database are updated, which is important for scenario modeling [29; 30].

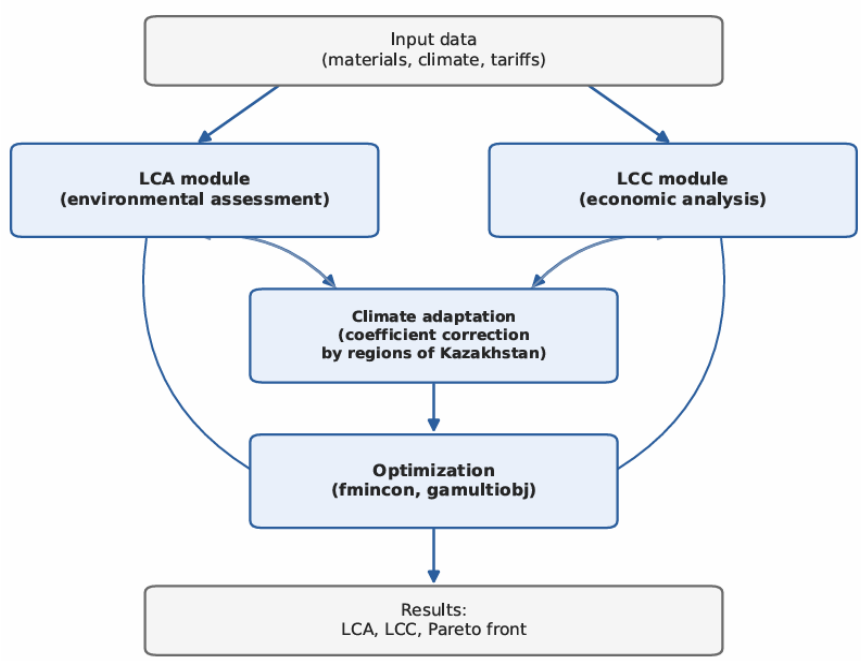


Figure 2 – Architecture of the computational model [Authors' material]

The LCC core of the model is responsible for calculating the total cost of ownership, taking into account the discounting of cash flows. The calculation accounts for all costs incurred throughout the life cycle of the facade system: initial investment, operating expenses, maintenance, repairs, replacement of components, and subsequent disposal. The total cost is determined as the sum of all discounted costs over the estimated service life:

$$LCC = \Sigma(C_t / (1+r)^t) + \Delta E_{cost} \quad (3)$$

where:

- C_t - costs in year t (capital, operating, maintenance, and disposal costs);

- r - discount rate (set within the range of 3–7% in accordance with World Bank recommendations for sustainable construction projects);

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- ΔE_{cost} - Cumulative energy savings resulting from improved thermal insulation of the facade.

A sample LCC calculation using equation (3) for the four facade systems under comparison (SFTC/EIFS, ventilated facade, PIR/PUR sandwich panels, and BIPV facade), broken down by cost category, is shown in Fig. 3.

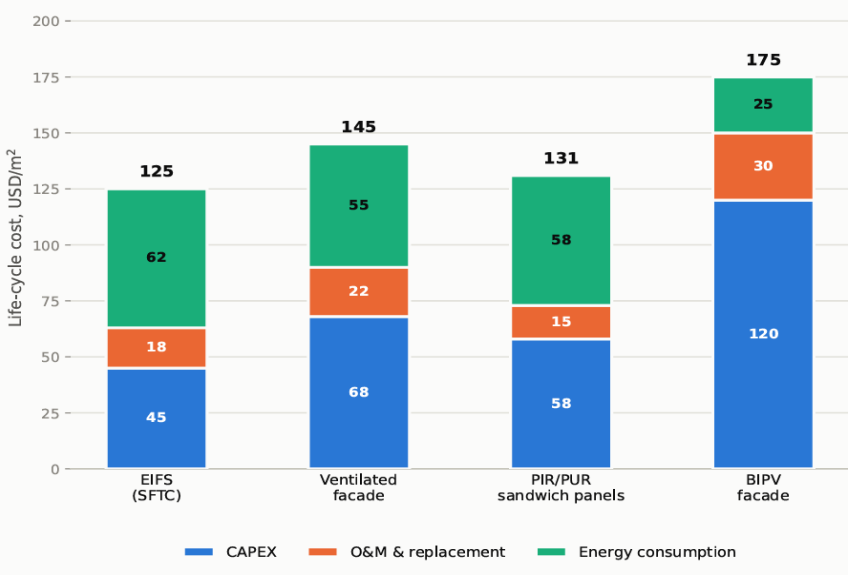


Figure 3 – Life-cycle cost (LCC) structure by facade system (illustrative calculation) [Authors' material]

Inflation in rates and fluctuations in material costs are accounted for through parameterized scenarios, which enhances the model's adaptability to macroeconomic changes [31; 18].

To provide a more accurate estimate of operational energy consumption, the model takes into account the region's climatic characteristics. The adjustment is based on degree-days of the heating period (DH), which reflect the duration and intensity of the heating season, as well as the normalized thermal resistance (R0) of the building envelope. This approach allows the calculations to be adapted to various climatic conditions and provides a more realistic estimate of the energy costs for heating the building:

$$Q_{heat} = 24 \times HDD \times A / R_0\, 10^{-3},\ kWh \qquad (4)$$

where:

- A - the area of the building envelope;
- HDD - the duration of the heating season in days.

In MATLAB, this relationship is implemented as a function that takes climatic parameters for regions of Kazakhstan as input and returns an adjusted value of Qheat for the subsequent calculation of ΔEcost.

Uncertainty Analysis: The Monte Carlo Method. To assess how changes in the initial parameters affect the LCA and LCC results, the study uses Monte Carlo probabilistic modeling. This approach allows for the uncertainties in the input data and provides not a single fixed value, but a range of possible calculation results. Several key parameters are varied during the calculations.

If only the bounds are known, a uniform distribution is used. If both the bounds and the most probable value are known, a triangular distribution is used. The normal and beta distributions are used when there is reason to believe that values near the center are more probable than extreme values.

The discount rate is adopted without taking inflation into account, as recommended by ISO 15686-5 when calculating in constant prices. The normal distribution N(5%; 1.5%) is chosen so that

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95% of the values lie within the range of 2.1-7.9%. This covers the 3–7% range for sustainable construction projects.

The growth in energy tariffs is modeled using a triangular distribution with a minimum of 5%, a mode of 8%, and a maximum of 12% per year in nominal terms. These limits correspond to the actual changes in heating and electricity rates in Kazakhstan for 2016-2026, according to data from the National Bureau of Statistics. The real rate of increase ranges from -0.9 to 5.7% per year, with the most likely value being 1.9%. The service life of the thermal insulation is specified as a uniform distribution within ±20% of the calculated value from Table 3. There are no failure rate statistics for insulation in facade systems under Kazakhstani conditions; therefore, all values within the interval are assumed to be equally probable. The ±20% range corresponds to the range of correction factors from 0.8 to 1.2 in the factorial method specified in ISO 15686-1. This method takes into account the quality of the material, installation, operating conditions, and maintenance.

The material recycling rate is described by a beta distribution Be (2; 5). It is restricted to the interval [0; 1], just like the recycling rate itself, and is skewed toward lower values: the mean is 0.29, the median is 0.26, and 90% of the values fall within the interval 0.06-0.58. The distribution applies only to non-metallic materials (insulation, porcelain stoneware, glass, mortars). For steel and aluminum, the recycling rate is assumed to be constant and equal to (0.85-0.95): scrap metal is already being collected and recycled.

Capital expenditures are assigned a uniform distribution within the range derived from the price lists of suppliers and contractors (Table 3). Based on this data, it is impossible to determine which price within the range occurs more frequently; therefore, all values are assumed to be equally likely. All parameters are considered independent of one another. Distributions are specified using the `makedist` functions from the Statistics and Machine Learning Toolbox, and samples are generated using the `random` function. The simulation results are shown in Fig. 4.

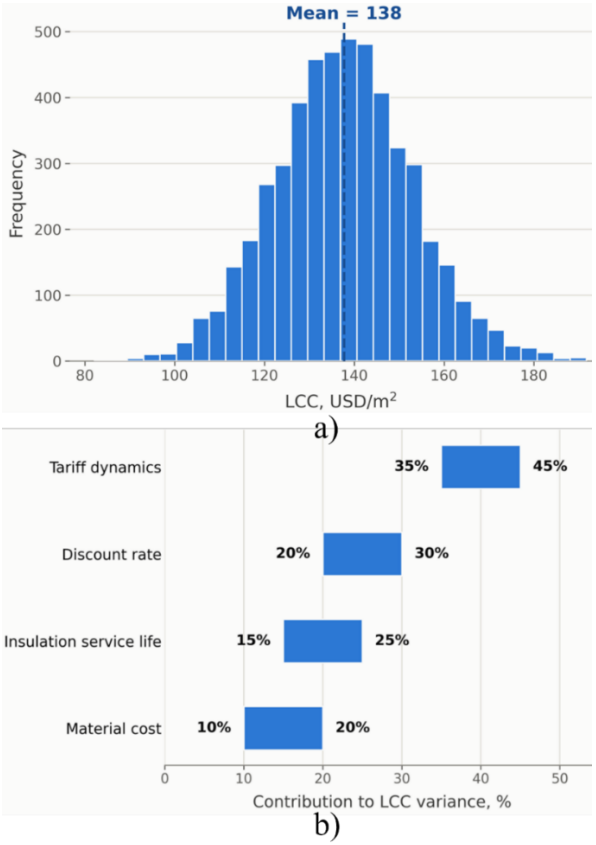


Figure 4 – LCC distribution from Monte Carlo simulation and the contribution of factors to its variance a) Monte Carlo LCC distribution (N = 5000) b) Sensitivity: factor contribution to LCC variance [Authors' material]

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For each facade system, N = 5,000 iterations were performed. The sufficiency of this number was verified by checking for stabilization of the estimates: after N = 2,000, the mean value of LCC and its 95th percentile changed by no more than 0.5% with each additional iteration. To ensure reproducibility, the random number generator is initialized with a fixed value (rng(2026)). The same sample of input parameters is used for all systems; therefore, differences between systems are not due to random variation in the samples.

To determine the sensitivity analysis, the contribution of individual parameters to the LCC variance was estimated using the same Monte Carlo sample via the standardized regression coefficients (SRC) method.

2.6 Visualization and Interpretation of Results

To clearly illustrate the relationship between environmental and economic indicators, the study uses several types of visualizations.

Scatter plots illustrate the relationship between «carbon footprint » and «total cost of ownership» and color coding helps compare results across different climate zones in Kazakhstan.

To find the most balanced solutions, “Pareto fronts” are constructed using the «gamultiobj» function. These help identify scenarios in which improving one metric is impossible without worsening another. This aids in selecting the optimal design or technology. In addition, “scenario heat maps” are used to show how changes in key parameters, energy rates, the service life of materials, and the recycling rate affect the final calculation results (Fig. 5).

An example of a trade-off visualization:

The distribution of data points shows that the values of economic and environmental indicators vary significantly depending on the selected parameters of the facade system and its operating conditions. At the same time, no clear correlation can be observed between life-cycle cost and carbon footprint, which highlights the need to strike a balance between the economic and environmental performance of solutions.

The diagram identifies the areas with the most favorable options, where a relatively low carbon footprint is combined with moderate LCC values. The visualization helps compare the distribution of the calculated scenarios across different climate zones in Kazakhstan.

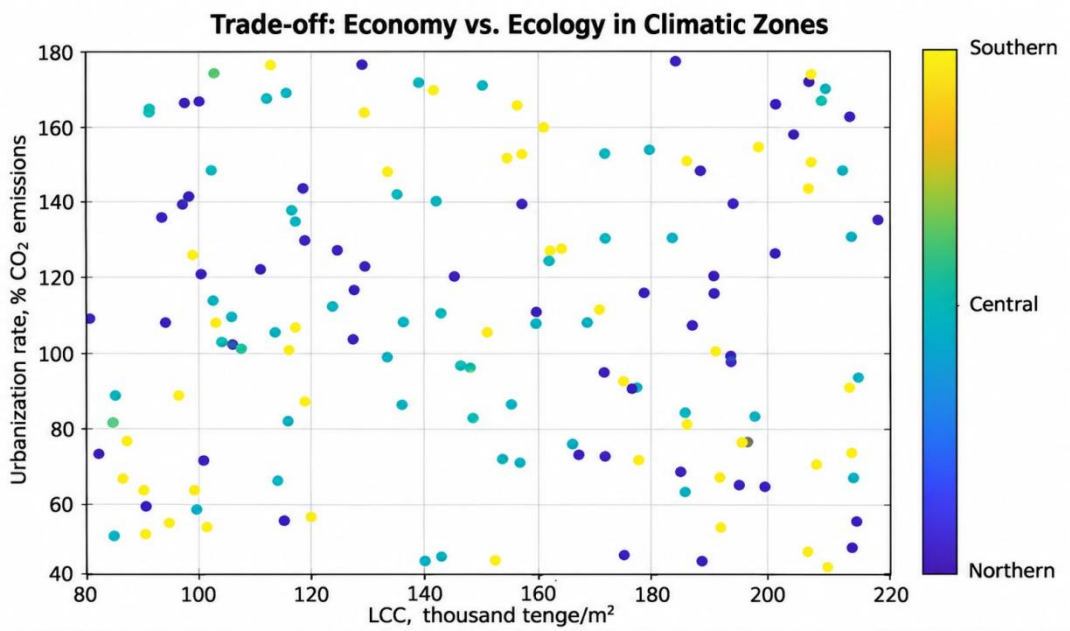


Figure 5 – Relationship between carbon footprint and life-cycle cost by climate zone [Authors’ material]

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Such visualization tools are in line with current practices for presenting the results of multi-criteria analysis in the field of construction science and contribute to more informed design decisions [32; 33].

2.7 Ensuring Reproducibility

To ensure that the results could be reproduced and independently verified, the structure of the model and the source data were organized as transparently as possible. The approach used is consistent with the principles of open science and current requirements for transparency in computational research in the field of sustainable construction [34].

All ".m" files are organized by functional modules and include detailed comments and built-in documentation in MATLAB Help format. Input data, including material matrices, coefficients, and climatic parameters, are stored in CSV format with sources and units of measurement specified.

The script titles explicitly specify the version of MATLAB used (R2022b and later), as well as the required toolboxes: the «Statistics and Machine Learning Toolbox, » the «Optimization Toolbox, »and the «Global Optimization Toolbox. » Additionally, the «run_validation.m» script has been implemented, which automatically verifies the correctness of the input data and the operation of the computational procedures.

3 RESULTS AND DISCUSSION

3.1 Valuation Objects and Initial Assumptions

The model's operation is illustrated by a demonstration calculation for four typical facade systems widely used in construction practice in the Republic of Kazakhstan:

1. SFTC/EIFS (exterior insulation and finish system with a thin plaster layer) based on PSB-S-25F expanded polystyrene;

2. A ventilated facade clad with porcelain stoneware and featuring a layer of rock wool insulation with a density of 90-110 kg/m³;

3. Sandwich panels with a polyisocyanurate (PIR) or polyurethane foam (PUR) core and metal cladding;

4. A facade with integrated photovoltaic cells (BIPV) based on a ventilated substructure with combined insulation.

All systems are normalized to an equivalent thermal resistance of R0 = 3.8 m²·°C/W, which complies with the regulatory requirements of SP RK 2.04-2017 for the northern climate zone of Kazakhstan. The design analysis horizon is set at 50 years, with a discount rate of 5% (base case).

All quantitative results in Sections 4.2-4.5 were obtained from a demonstration calculation. The initial values (specific emission factors, material prices, tariffs, service lives) are specified as ranges based on the open sources listed in Section 3.3. They show the form in which the results are obtained and what differences between systems can be expected. For such a calculation, the input matrices must be filled with information on specific materials and suppliers, current rates, and climatic parameters of the construction site. This separation of the methodology and its numerical illustration is standard practice in computational studies on construction topics [32; 35].

The key initial parameters for the demonstration calculation are listed in Table 1.

Table 1 – Key Parameters of the Illustrative Calculation (per 1 m² of facade, 50 years)

Parameter	SFTC/EIFS	Ventilated facade	PIR/PUR sandwich panels	BIPV facade
Composition (from the outside in)	3 mm decorative plaster; 5 mm reinforced base layer; PSB-S-25F	10 mm porcelain stoneware; 40-60 mm gap; wind barrier membrane;	0.5 mm steel sheet; 100 mm PIR; 0.5 mm steel sheet; fasteners	Glass-glass PV modules covering [30] % of the area, porcelain granite on

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	150 mm; adhesive layer	150 mm rock wool; aluminum subsystem		the remainder; 150 mm rock wool; subsystem
Mass of primary materials, kg/m²	PSB 2.3-3.8; mortar ≈13; mesh 0.16; anchors 0.15	rock wool 13.5–16.5; ceramic granite ≈23; aluminum 2.0–2.5; anchors ≈0.5	PIR ≈4.0; steel ≈8.0; fasteners ≈0.3	[by model]
F_i (A1–A3), kg CO_2-eq/kg, source	PSB 3.29 (ICE); solutions 0.22-0.30 (ICE, EPD)	rock wool 1.28 (ICE, EPD); porcelain stoneware 0.78 (ICE); aluminum 9.2–13.0 (ICE)	PIR 3.5–4.3 (EPD, ICE); coated steel ≈2.8 (ICE)	PV module: 90–140 kg CO_2-eq/m² (Ecoinvent 3.9); other aspects are the same as for a ventilated facade
Service life and replacement intervals over 50 years	System: 30 years → 1 complete replacement; topcoat: 15–20 years → 2 refinishes	50 years or older; no substitutes	Panels: ≥ 50 years; joint sealants: 12–15 years → 3 replacements	PV modules: 25–30 years → 1 replacement; inverter: 12–15 years → 3 replacements
End of the life cycle (C3–C4)	PSB – incineration; solutions – landfill	aluminum – recycling (Stage D); other – testing ground	Steel – recycling (D); PIR – incineration or landfill	Glass and aluminum—recycling (D); other items—landfill
Capital expenditures, in thousands of tenge per square meter	80–120	180–260	130–190	350–550
Routine maintenance, % of annual capital expenditures	1,0–1,5	0,3–0,5	0,5–1,0	1,0–1,5

The following parameters are common to all systems:

- Transportation (A4) - Locally produced materials (PSB, mortar, rock wool) are delivered by truck over distances of 300-800 km. Imported materials (keramogranite, sandwich panels, aluminum profiles, PV modules) are transported by rail over a distance of 1,500–3,500 km, then by truck for 100 km. Specific emissions: ≈0.10 kg CO_2-eq/(t·km) for a 16–32-metric-ton truck and ≈0.03 kg CO_2-eq/(t·km) for rail transport (Ecoinvent 3.9, RoW);
- installation losses (A5) - 5% for piece goods and bulk materials, 2% for factory-finished panels;
- service life spans are assigned based on manufacturers' data and the BBSR handbook "Service Life Spans of Building Components for Life Cycle Assessments According to BNB," taking ISO 15686 into account. The number of replacements is determined by the integer part of the ratio of 50 years to the service life of the component;
- operational energy is calculated using formula (3) with R_0 = 3.8 m²·°C/W and the annual degree-day value (at t_(in) = 20 °C) for Astana = 6,042 °C·day. The tariff for thermal energy is 3,728.72 tenge/Gcal (excluding VAT), and for electricity, 28.12 tenge/kW·h;
- waste disposal- 637 tenge per person. The discount rate, tariff growth rates, and prices are provided in Section 4.2 and Table 4.

3.2 Environmental Indicators

The embedded impacts were calculated using the ReCiPe 2016 methodology (midpoint level), based on factors from the Ecoinvent v 3.9 databases and publicly available EPDs from manufacturers. The results are presented in Table 2.

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Table 2 – Environmental performance metrics for facade systems per 1 m² (illustrative calculation)

Indicator	SFTC/EIFS	Ventilated facade (mineral wool)	PIR/PUR Sandwich Panels	BIPV facade
Carbon footprint, kg CO_2-eq	45–65	55–80	35–55	70–110*
Embodied energy, MJ/m²	600–900	800–1200	500–800	1100–1800*
Recycling potential, %	15–25	40–60	20–35	30–50**
Water footprint, l-eq/m²	80–150	120–200	60–110	150–250
Thermal uniformity coefficient r	0,85–0,90	0,70-0,80	0,85-0,90	0,70-0,80

Notes: * The higher figures are due to the energy intensity of photovoltaic module production;
** The recycling potential for BIPV takes into account the possibility of recycling glass and aluminum frames, but not semiconductor cells.

In the demonstration calculation, the lowest embodied values were observed for sandwich panels with a PIR/PUR core. This is due to their high thermal efficiency despite their relatively small thickness, as well as the relatively low energy intensity of the manufacturing processes for polymer cores [36]. The highest proportion of recyclable materials was found in the ventilated facade with rock wool, which is consistent with data from international studies confirming the advantages of mineral wool insulation materials in the context of circular economy principles [37].

The operation of BIPV systems is characterized by significant initial environmental costs, which are subsequently offset by the generation of clean energy during operation. However, in a "cradle-to-grave" life-cycle analysis that does not apply the electricity substitution method, the calculated carbon footprint of these systems remains the highest. Accounting for the substitution effect would require expanding the system boundaries, which is beyond the scope of this study and is consistent with the methodological limitations outlined in [38].

3.3 Economic Indicators

The total cost of ownership (LCC) was calculated taking into account capital costs, maintenance expenses, component replacement costs (for components with a service life of less than 50 years), and energy consumption. The values for the baseline scenario are shown in Table 3. Capital costs for the systems vary by a factor of 2 to 3, while the total LCC is much lower: for solutions that are inexpensive to install, costs for repairs and component replacements accumulate over 50 years.

Table 3 – Economic indicators for facade systems per 1 m² over 50 years, baseline scenario (illustrative calculation)

Facade Systems	Costs	Conclusions
SFTC/EIFS	low capital costs (80,000–120,000 tenge per square meter), but higher costs for repairing the plaster layer (replacement of the decorative finish every 15–20 years)	Total LCC over 50 years: 210,000–290,000 tenge/m²
Ventilated facade	High initial investment (180,000–260,000 tenge per square meter), but minimal operating costs thanks to the durability of porcelain stoneware and the stability of mineral wool insulation	Total LCC: 240,000–320,000 tenge/m².
PIR/PUR Sandwich Panels	Moderate capital costs (130,000–190,000 tenge/m²), but potential expenses for replacing seals and repairing joints increase the operating costs	Total LCC: 220,000–300,000 tenge/m².

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BIPV facade	maximum capital costs (350–550 thousand tenge per square meter), partially offset by energy savings.	Total LCC: 280,000–380,000 tenge/m². The payback period for additional investments is 18–32 years, depending on tariff trends and the site's solar radiation characteristics.

The net present value (NPV) for BIPV systems becomes positive only when "green" tariffs or subsidies are applied, as shown by the scenario analyses in Section 5.4. This is consistent with international studies that note the high sensitivity of BIPV's economic efficiency to regulatory and tariff factors [39].

3.4 Scenario Modeling and Sensitivity Analysis

To assess the extent to which the results of the demonstration calculation depend on external conditions, the calculation was repeated for three scenarios (Table 4).

Table 4 – Types and conditions of scenarios

Script	Indicators
Basic	Inflation in material costs is 6% per year, energy prices are rising by 8% per year, and the discount rate is 5%.
Stress Test	A 20% increase in material costs relative to the baseline, a 15% annual increase in utility rates, and a 20% reduction in the service life of thermal insulation.
"Green"	Subsidies for energy-efficient materials (−15% of capital costs), a "green" feed-in tariff for power generation (for BIPV), and consideration of disposal costs using a recycling factor

In the sample calculation, the factors were distributed according to their contribution to the LCC variance as follows:

- energy price trends – 35-45%;
- discount rate - 20-30%;
- service life of the thermal insulation layer – 15-25%;
- cost of initial materials – 10-20%.

The illustrative example shows that, when making long-term investment decisions, it is more important to ensure the durability and energy efficiency of building envelopes than to minimize initial costs [40]. The authors of review articles [41; 14] and [42] reach the same conclusion.

3.5 Preliminary recommendations for selecting facade systems for the climatic regions of Kazakhstan

Based on the results of the demonstration calculations, preliminary recommendations have been formulated for selecting façade systems for various climatic regions of the Republic of Kazakhstan (Table 5).

Table 5 – Preliminary recommendations for selecting facade systems

District (base)	Key climatic factors	Preliminary preferred solutions	Basis	What to verify through calculations
Northern and central (Astana, Petropavlovsk, Karaganda)	large heat supply areas, a long heating season, low winter temperatures	Ventilated facades with mineral wool insulation; PIR sandwich panels for frame buildings. SFTCs are acceptable	Sample calculation (Sections 5.2–5.4)	The feasibility of R_0 being higher than the standard value; the sensitivity of LCC to the service life of the SFTC finishing layer

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		when used with reinforced plaster mixes and taking into account more frequent repairs in the LCC		
Southern (Shymkent, Turkestan)	lower GSOP values, significant summer overheating, high solar radiation	SFTK with reflective finishes; ventilated facades, in which an air gap reduces summer heat gain; BIPV, provided there is regulatory support	qualitative assessment	cooling costs (formula (3) does not account for them); BIPV power generation calculated using formula (3a) for the PVGIS data for the southern location
Western (Atyrau, Aktau)	strong winds, high humidity, and salt spray in the coastal zone	Ventilated facades with a subsystem made of corrosion-resistant aluminum or stainless steel; sandwich panels with factory-sealed joints	qualitative assessment	costs of corrosion protection and reduced service life of fasteners in LCC

These recommendations are of a methodological nature and require further refinement when applied to specific sites, taking into account local microclimatic conditions, the availability of materials, and logistical constraints.

4 CONCLUSIONS

The main results of this work are the methodology and the computational kernel. The numerical values in paragraphs 2-3 were obtained using a demonstration example and are provided to illustrate the capabilities of the methodology.

1. A methodology for the comprehensive assessment of facade systems has been developed and implemented in MATLAB, combining the principles of life cycle assessment (LCA) in accordance with ISO 14040/14044 and EN 15978 with the calculation of life cycle cost (LCC) per ISO 15686-5. The scientific significance of the model lies in the adaptation of the calculation algorithms to the climatic parameters and macroeconomic indicators of the Republic of Kazakhstan, which allows for the consideration of tariff trends and inflation expectations when assessing the long-term effectiveness of design solutions.

2. A sample calculation for four facade systems with the same thermal resistance (R_0 = 3.8 $m^2 \cdot °C/W$) shows that the model clearly distinguishes the systems based on their environmental profile. In this example, the smallest carbon footprint is achieved by PIR/PUR sandwich panels (35–55 kg CO_2-eq/m^2), while ventilated facades have the greatest potential for secondary use, as reflected in the D module, due to their metal subsystem. BIPV facades have high primary energy intensity, and the final assessment of these systems largely depends on whether electricity generation is included within the system boundaries.

3. A 50-year LCC calculation in the same example shows why it is risky to select a facade based solely on initial costs. The capital costs of the SFTC (80,000-120,000 tenge/m^2) are 2-2.5 times lower than those of a ventilated facade, but by the end of the calculation period, the difference in LCC narrows to 10-15% due to periodic restoration of the plaster layer. The payback period for BIPV in this example was 18-32 years and depends primarily on electricity rates and government support measures.

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4. A sensitivity analysis based on a sample example shows that the rate of increase in energy prices (35-45%) and the discount rate (20-30%) contribute most to the variance in LCC, while the cost of materials accounts for 10–20%. If this ratio is confirmed by calculations for actual projects, greater attention should be paid during the design phase to operating costs and the durability of structures than to the initial price.

5. Based on the results of the illustrative calculations, preliminary recommendations have been formulated for selecting facade systems for the climatic regions of Kazakhstan. These should be refined through calculations based on the climatic data of the specific construction site:

- in northern regions, it is advisable to use systems with maximum thermal resistance and durability (ventilated facades and PIR panels);
- in southern regions, it is justified to use solutions that combine thermal insulation with light-reflective properties or passive cooling;
- for western and eastern regions, the critical factors are the corrosion resistance of the substructures and the airtightness of the joints.

6. The developed calculation algorithm is characterized by modularity and data transparency, which ensures its potential for further development. A promising area of focus is the integration of the model with BIM design tools to automate variant analysis, as well as the expansion of local databases based on Environmental Product Declarations (EPDs) from manufacturers of construction materials in Kazakhstan.

REFERENCES

1. **Maussymbek, Sh.T., Tulbayeva, L.M., Kaliev**, **A.K.** (2022). Analysis of the Energy Efficiency of Designed Buildings. Vestnik KazGASA. No. 2(84), pp. 363–372. https://doi.org/10.51488/1680-080X/2022.2-40
2. **Lo, Y-L., Wu, Y-T., Fu, C-L., Yu**, **Y-Ch.** (2020). Wind Load Reduction Effects on Interior Spaces of Buildings via Exterior Porous Facades. Building and Environment, Volume 183, , 107148, ISSN 0360-1323. https://doi.org/10.1016/j.buildenv.2020.107148
3. **Barbhuiya, S., Das, B.Bh.** (2023). Life Cycle Assessment of Construction Materials: Methodologies, Applications, and Future Directions for Sustainable Decision-Making. Case Studies in Construction Materials, Volume 19, , e02326, ISSN 2214-5095. https://doi.org/10.1016/j.cscm.2023.e02326
4. SP RK 2.04-107-2022 Thermal Protection of Buildings, MSN RK 2.04-02-2004 Thermal Protection of Buildings
5. **Selyaev, V.P. , Nurlybaev, R.E. ,Kiselev, N.N. , Liyaskin, O.V. , Sangulova, I.B. (**2019) Optimization of the Filler Composition in Vacuum Insulation Panels Based on Konasil-200 [Optimizacia sostava napolnitelya vakumnyh izolyacionnyh panelei na osnove konasil-200]. KazGASA Bulletin, No. 2, , pp. 169–174. URL:https://vestnik.kazgasa.kz/frontend/web/uploads/archive/doc/1608188198_IYi48v.pdf
6. **Apostolopoulos, V., Mamounakis, I., Seitaridis, A., Tagkoulis, N., Kourkoumpas, D-S., Iliadis, P., Angelakoglou, K., Nikolopoulos**, **N.** An integrated life cycle assessment and life cycle costing approach toward sustainable building renovation via a dynamic online tool. Applied Energy, Volume 334, 2023, 120710, ISSN 0306-2619. https://doi.org/10.1016/j.apenergy.2023.120710
7. **Khan, S.N., Joarder, Md.A., Razin**, **S.** (2026). Climate-Responsive Form and Facade Design for Educational Spaces to Achieve Net-Zero Energy Buildings in Dhaka. https://doi.org/10.1007/978-3-032-14019-7_16
8. **Francesco, P., Wolf, C.D., & Moncaster, A.** (2018). Embodied Carbon in Buildings: Measurement, Management, and Mitigation. https://doi.org/10.1007/978-3-319-72796-7
9. **Zhang, Y., Lu, Y., Huang, Z., Chen, D., Cheng, B., Wang, D., & Lu, C**. (2025). Insight from

https://doi.org/10.51488/1680-080X/2026.3-17

Review Articles of Life Cycle Assessment for Buildings. Applied Sciences, 15(14), 7751. https://doi.org/10.3390/app15147751

10. **Vidhyalakshmi, Ch., Jolanta**, **D. (**2022) A Review of the Environmental Impact of Buildings with an Emphasis on Performance Assessment Tools and Their Incorporation of LCA, Advances in Civil Engineering, 9947920, 22 pages, https://doi.org/10.1155/2022/9947920
11. **Guilherme, G., João, C., & Vieira, D. & Bravo, A.** (2023). BIM and LCA integration methodologies: A critical analysis and proposed guidelines. Journal of Building Engineering. 73. 106780. https://doi.org/10.1016/j.jobe.2023.106780
12. **Soudian, S., Berardi**, **U. (**2022) Experimental performance evaluation of a climate-responsive ventilated building façade, Journal of Building Engineering, Volume 61, , 105233, ISSN 2352-7102. https://doi.org/10.1016/j.jobe.2022.105233
13. **Yıldız, B.N., Arslan, H., & Yılmaz, E.** (2020). Life Cycle Assessment of Building Materials: Literature Review.
14. **Lu, K., Deng, X., Jiang, X., Cheng, B., & Tam, V. W. Y**. (2023). A review on life cycle cost analysis of buildings based on building information modeling. Journal of Civil Engineering and Management, 29(3), 268–288. https://doi.org/10.3846/jcem.2023.18473
15. **Jorge, S-P., Beatriz, R-S, Jesús, B.-R., & Gabarrell, X.** (2018). "Integrated life cycle assessment and thermodynamic simulation of a public building's envelope renovation: Conventional vs. Passivhaus proposal," Applied Energy, Elsevier, vol. 212(C), pages 1510-1521. https://doi.org/10.1016/j.apenergy.2017.12.101
16. **Dormohamadi, M., Rahimnia, R. & Bunster, V**. (2024).Life cycle assessment and life cycle cost analysis of different walling materials with an environmental approach (comparison between earth-based vs. conventional construction techniques in Iran). Int J Life Cycle Assess 29, 355–379. https://doi.org/10.1007/s11367-023-02259-6
17. **Kayaçetin, N. C., & Tanyer, A. M**. (2018). Embodied Carbon in Buildings: Measurement, Management, and Mitigation. https://www.springer.com/gp/book/9783319727950#aboutAuthors
18. **Shan, R., & Junghans, L.** (2023). Multi-Objective Optimization for High-Performance Building Facade Design: A Systematic Literature Review. Sustainability, 15(21), 15596. https://doi.org/10.3390/su152115596
19. ST RK ISO 14040-2010 Environmental Management. Life Cycle Assessment. Principles and Framework (ISO 14040:2006 "Environmental Management. Life Cycle Assessment. Principles and Framework," IDT and ISO 14044 [GOST R ISO 14044-2021 Environmental Management. Life Cycle Assessment. Requirements and Guidelines
20. EN 15978:2026 Environmental Sustainability of Construction Works. Assessment of the Environmental Performance of Buildings. Requirements and Guidelines
21. ISO 15686-5:2017(E) Buildings and constructed assets. Service life planning. Part 5: Life-cycle costing
22. **Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, Fr., Vieira, M., Zijp, M., Hollander, A., Zelm, R.** (2017). ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int J Life Cycle Assess 22, 138–147. https://doi.org/10.1007/s11367-016-1246-y
23. **Martin N. Nwodo, Chimay J. Anumba**. (2019). A review of life cycle assessment of buildings using a systematic approach, Building and Environment, Volume 162, 106290, ISSN 0360-1323. https://doi.org/10.1016/j.buildenv.2019.106290
24. **Taubaldieva, A.S., Tilepbergen, A**. (2019). Modeling of Energy-Efficient Envelope Structures for Monolithic Buildings [Modelirovanie enorgoeffectivnyh ograjdaiushh construkcii monolotnyh zdanii]. Bulletin of KazGASA. No. 1. pp. 170–175. https://vestnik.kazgasa.kz/frontend/web/uploads/archive/doc/1608188056_Fd6PuL.pdf (In Russ.)

https://doi.org/10.51488/1680-080X/2026.3-17

25. **Albanese, P. M., Baglivo, C., & Congedo, P. M**. (2026). Integrating LCA with BIM-Based Technologies in the Building Construction Context: A Review. Buildings, 16(1), 168. https://doi.org/10.3390/buildings16010168
26. **McNeil-Ayuk, N., Jrade, A**. (2024). A Building Information Modeling-Life Cycle Cost Analysis Integrated Model to Enhance Decisions Related to the Selection of Construction Methods at the Conceptual Design Stage of Buildings. Open Journal of Civil Engineering, 14, 277-304. https://doi.org/10.4236/ojce.2024.143015
27. **Pomponi, F., De Wolf, C., Moncaster, A.** (2018), Embodied Carbon in Buildings. Published by Springer International Publishing, ISBNs 978-3-319-72796-7. 512 pages. https://doi.org/10.1007/978-3-319-72796-7
28. **Islam, H., Jollands, M., & Setunge, S.** (2015). Life cycle assessment and life cycle cost implication of residential buildings—A review. Renewable and Sustainable Energy Reviews, Elsevier, vol. 42(C), pages 129-140. https://doi.org/10.1016/j.rser.2014.10.006
29. **Bolognesi, C., Bassorizzi, D., Balin, S., Manfredi, V**. (2025). An Overview on LCA Integration in BIM: Tools, Applications, and Future Trends. Digital, 5(3), 31. https://doi.org/10.3390/digital5030031
30. **Abd Rashid, A.F., & Yusoff, S.** (2015). A review of life cycle assessment method for building industry. Renewable and Sustainable Energy Reviews, Elsevier, vol. 45(C), pages 244-248. https://doi.org/10.1016/j.rser.2015.01.043
31. **Mahlan, S., Francis, A., Thumuganti, V., Thomas, A., Sadick, A.-M., Tokede**, **O.** (2024) An integrated life cycle assessment and energy simulation framework for residential building walling systems, Building and Environment, Volume 257, 111542, ISSN 0360-1323. https://doi.org/10.1016/j.buildenv.2024.111542
32. **Moncaster, A., Birgisdottir, H., Malmqvist, T., Rasmussen, F. N., Houlihan Wiberg, A., & Soulti**, E. (2018). Embodied Carbon Measurement, Mitigation and Management Within Europe, Drawing on a Cross-Case Analysis of 60 Building Case Studies. In F. Pomponi, A. Moncaster, & C. De Wolf (Eds.), Embodied Carbon in Buildings: Measurement, Management, and Mitigation (pp. 443-462). Springer Publishing Company. https://doi.org/10.1007/978-3-319-72796-7_20
33. **Zong, C., Margesin, M., Staudt, J., Deghim, F., Lang**, **W.** (2022) Decision-making under uncertainty in the early phase of building façade design based on multi-objective stochastic optimization, Building and Environment,Volume 226, 109729, ISSN 0360-1323. https://doi.org/10.1016/j.buildenv.2022.109729
34. **Ascione, F., Bindi, L., Iovane, T., & Mastellone, M**. (2026). Life cycle assessment in industrial buildings: A critical review. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 48(1). https://doi.org/10.1080/15567036.2026.2653706
35. **Lu, K., Jiang, X., Yu, J.,& Tam, V., Skitmore, M.** (2020). Integration of Life Cycle Assessment and Life Cycle Cost using Building Information Modeling: A Critical Review. Journal of Cleaner Production. https://doi.org/10.1016/j.jclepro.2020.125438
36. **Toiabaev, K.D., Agybai, S.S**. (2019) Sandwich Panels—Modern Construction Materials [Sandwich panelder – zamanaui kurylys materialy]. KazBSQA Bulletin, No. 1, , pp. 208–211, URL: https://vestnik.kazgasa.kz/frontend/web/uploads/archive/doc/1608188056_Fd6PuL.pdf (In Kaz.)
37. **Eštoková, A., Fabianová, M., & Radačovský, M**. (2023). Life Cycle Assessment and Environmental Impacts of Building Materials: Evaluating Transport-Related Factors. Engineering Proceedings, 57(1), 5. https://doi.org/10.3390/engproc2023057005
38. **Yalaz, E.T., Dişli**, **G.** (2024) Climate-responsive building façade design: Inspirations from historic buildings in semi-cold climate zone, Sustainable Energy Technologies and Assessments, Volume 69, , 103914, ISSN 2213-1388. https://doi.org/10.1016/j.seta.2024.103914

https://doi.org/10.51488/1680-080X/2026.3-17

39. **Kiss, B., Szalay**, **Z.** (2020). Modular approach to multi-objective environmental optimization of buildings, Automation in Construction, Volume 111, , 103044, ISSN 0926-5805. https://doi.org/10.1016/j.autcon.2019.103044
40. **Sadyrov, R.K., Beksultanova**. **N.N. (**2022). Development of Methodological Foundations for Organizing the Construction of Energy-Efficient Buildings [Formirovanie metodologicheskih osnov organizacii stroitelnogo proizvodstva energoeffectivnyh zdanii]. KazGASA Bulletin. No. 2 (84), https://doi.org/10.51488/1680-080X/2022.2-30 (In Russ.)
41. **Kyriaki, E., Konstantinidou, C., Giama, E., Papadopoulos, A.M**. (2018). Life cycle analysis (LCA) and life cycle cost analysis (LCCA) of phase change materials (PCM) for thermal applications: A review. Int J Energy Res.42:3068–3077. https://doi.org/10.1002/er.3945
42. **Surapaneni, A.** (2021). Environmental Parametric Multi-Objective Optimization to Design High Performance Façades using Daylight, Solar and CFD Analysis. Carnegie Mellon University. Thesis. https://doi.org/10.1184/R1/16623067.v1

https://doi.org/10.51488/1680-080X/2026.3-17

FUNDING

The study was conducted using private sources of funding.

CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

ARTIFICIAL INTELLIGENCE STATEMENT

During the preparation of this manuscript, the authors used artificial intelligence tools (ChatGPT) solelyfor editorial assistance, such as improving phrasing and checking grammar, spelling, and punctuation. All ideas, interpretations, and conclusions are the responsibility of the authors, who take full accountability for the content of the article.

AUTHOR CONTRIBUTIONS

Abzal Malakhanov – conceptualization, methodology, investigation, formal analysis, visualization, writing-original draft.
Masharif Bakiev – supervision, methodology, validation, writing-review and editing.
Galymzhan Karshyga – visualization, formatting and technical editing of the manuscript
Medetbek Kambarov – conceptualization, literature review, comparative document analysis, development of the analytical framework.
Bakhytnur Nukhayeva – scientific supervision, methodology, validation, interpretation of results, writing-review and editing
Daniyar Bazarbayev – scientific supervision, methodology, validation, interpretation of results, writing-review and editing.
Aimash Slyambayeva – collection and analysis of regulatory documents, validation, writing – review and editing.

INFORMATION ABOUT THE AUTHORS

- Abzal Malakhanov
- PhD, Doctoral Student
- M. Auezov South Kazakhstan Research University
- Shymkent, Kazakhstan
- E-mail address: malakhanov.abzal@bk.ru
- ORCID ID: https://orcid.org/0009-0008-6903-2242

- Masharif Bakiev
- Doctor of Technical Sciences, Professor, Chair of the Department of Hydraulic Structures and Engineering Structures
- "Tashkent Institute of Irrigation and Agricultural Mechanization Engineers" National Research University
- Tashkent, Uzbekistan
- E-mail address: bakiev1947@rambler.ru
- ORCID ID: https://orcid.org/0000-0002-8083-5379

https://doi.org/10.51488/1680-080X/2026.3-17

- Galymzhan Karshyga
- PhD
- Institute - Department of Engineering and Technology, Korkyt Ata Kyzylorda University
- Kyzylorda, Kazakhstan
- E-mail address: karchiga.72@mail.ru
- ORCID ID: https://orcid.org/0000-0002-4123-9777

- Medetbek Kambarov
- Candidate of Technical Sciences, Associate Professor
- M. Auezov South Kazakhstan University
- Shymkent, Kazakhstan
- E-mail address: medet_2030@mail.ru
- ORCID ID: https://orcid.org/0000-0001-6397-1451

- Bakhytnur Nukhayeva
- Candidate of Technical Sciences, Senior Lecturer
- L.N. Gumilyov Eurasian National University
- Astana, Kazakhstan
- E-mail address: bakhytnurnukhayeva@gmail.com
- ORCID ID: https://orcid.org/0009-0004-5865-520X

- Daniyar Bazarbayev
- PhD, Associate professor of the Department "Technology of Industrial and Civil Engineering"
- L.N. Gumilyov Eurasian National University
- Astana, Kazakhstan
- E-mail address: daniyar.bazarbayev.86@mail.ru
- ORCID ID: https://orcid.org/0000-0001-8547-5440

- Aimash Slyambayeva
- Candidate of Technical Sciences, Associate Professor, International Educational Corporation (IEC)
- International Educational Corporation
- Almaty, Kazakhstan
- E-mail address: sliambaeva@kazgasa.kz
- ORCID ID: https://orcid.org/0000-0001-8567-2380

Received: 15 July 2026
Revised: 21 August 2026
Accepted: 28 September 2026

https://doi.org/10.51488/1680-080X/2026.3-17