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Comparative Evaluation Model Framework for Cost-Optimal Evaluation of Prefabricated Lightweight System Envelopes in the Early Design Phase

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Abstract: This paper proposes an extended comparative evaluation model framework (ECEMF) that highlights two objectives: (1) a specific economic evaluation method for the cost-optimisation of prefabricated lightweight system envelopes to achieve a greater value of the building, and (2) a comparative evaluation model framework usable by different profiles of stakeholders, when adopting the decision on the most optimal envelope type in the early design phase. Based on the proposed framework, the analysis was conducted for the case study building representing a small single-family house located in Slovenia. The methodology applied is based on the life cycle cost (LCC) including construction, operation, maintenance, and refurbishment costs, but excluding dismantling, disposal, and reuse, for the period of 50 years' lifetime of the building which combines the Building Information Modelling (BIM) with Value for Money (VfM) assessment. To exploit the automated evaluation process in the computing environment, several tools were used, including Archicad for BIM in combination with Legep software for LCC. On one hand, the model confirms the assumption that the optimal value parameters of a building do not only depend on the typical costs related to high-performance buildings. On the other hand, from the stakeholders' view, the model enables the choice of the optimal solution regarding the envelope type to be made in the early design phase. In this view, the model could function as an important decision tool, with a direct economic impact on the value.

Keywords: evaluation model framework; envelope design; cost optimization; life-cycle costs; value for money

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1. Introduction

Research has shown that over a longer life span, the cost of operating the asset could be as much as four times the cost of designing and constructing the building, and 80% that of the operation, maintenance. Furthermore, the replacement costs of a building can be influenced in the first 20% of the design process [1,2]. As Far et al. claim, the initial costs represent less than 30% of the total life cycle costs (LCC), which is a decisive factor in the cost perspective of the investment [3]. Further, according to Hofer, savings of approximately 80% of the savings of all investment and operating costs are determined in the initial design phase, which are called the missing link in LCC [4]. However, after Schade, the main criteria are most commonly the value of the initial construction costs, often set at the minimum value that does not necessarily improve the lifetime performance of a building [5].

In contrast to the finance first approach, Elkington [6] introduces the triple bottom line (TBL) framework, a predominant model of sustainability in which the environmental, social, and financial outcomes are taken into account and where improving social outcomes and ensuring Value for Money (VfM) becomes equally as important as improving environmental outcomes. To enable the success of buildings for sustainable outcomes [7] they should be environmental (i.e., through lower energy and water use), social (i.e., through improved use of the building), and financial (i.e., through a building that provides good value for money now and into the future). As part of the requirements for delivering sustainable building value, the performance mandates should occur within certain limits of acceptability. The limits of acceptability are users' physiological, users' psychological, users' sociological, economic, and environmental implications [8]. Lower design and construction costs, rapid return on investment, increased market value, and lower maintenance and operation costs are some of the determinants of consumers' economical limit of acceptability of a sustainable building.

Since time and efforts spent on the design phase would save a significant amounts of money, the cost-optimal evaluation is not limited to only specific types of buildings but is also usable in the building construction industry [4]. Furthermore, according to Ryghaug and Sørensen, since buildings have much longer lifespans compared to other industrial products, the decisions made in the design stage have long-term consequences [9]. The architectural design process greatly affects the performance of a building, mostly related to the envelope design and the energy system [10]. After Sandberg, during the design phase, objectives often conflict with each other. Therefore, for such problems, the application of multi-objective optimization is beneficial to find optimal solution(s) of design variables and thus solve the existing trade-off between conflicting objectives [11]. The evaluation methodology is connected with consistent performance measurement through a buildings' life-cycle, which is required to ensure the projects are 'future proofed'. This requirement is defined as the ability to continue to be of value in the future. To ensure this requirement to the stakeholders (in the design process these are the owner, architect, contractor, government, and users) the VfM assessment was introduced [12].

1.1. The Link between Value for Money (VfM), Building Information Modelling (BIM), and Sustainability

A holistic approach to project performance provides better VfM with reference to LCC and sustainability, something which is necessary to decide whether or not a system is appropriate [13]. VfM is not only focused on the total lifetime costs of assets at an early-stage quantitative assessment, but also requires the project to achieve a high level of qualitative performance across every aspect of the project [14]. However, a performance-based approach requires a source that allows easy access to and sharing of information and knowledge in real-time. A repository that effectively manages information and knowledge during the building delivery process will enhance the delivery of the required sustainable building value. BIM provides such a repository [15]. Namely, many studies on the cost-optimal methodology where conducted using manual procedures, which may not lead to a high level of accuracy [10]. When looking for the minimum total cost of the building, the automated process could improve the accuracy of the results [16].

Furthermore, BIM tools provide a full and automatic BIM to the Building Energy Model (BEM) workflow that enables designers to fully utilize the building energy modelling capabilities and evaluate building energy performance under any circumstances and locations around the world [17]. BIM applications for energy analysis have been introduced already at the design stage, which can scientifically improve the post-occupancy evaluation process and meet the industry requirements for sustainable buildings [18].

The advantages of the application of BIM-based VfM is that the information extracted from BIM is a vital part of the information initialization providing high-quality data, guaranteeing accuracy and high levels of synchronization in VfM qualitative assessment [19]. BIM, with its extensive support potential, could theoretically maximize the benefits of the VFM process and go one step further with regard to the project life-cycle [19]. Furthermore, even in the early stage, VfM assessment has the potential to start building a support information/reference library for projects. The use of costing tools aligned with BIM could provide a good measure to structure the cost measurement in general [12]. Furthermore, BIM, as seen from an engineering point of view, can be described as providing benefits for management frameworks, tools, standards, and assessment methods through the whole project lifecycle [20], therefore improving VfM and LCC and contributing to sustainability. LCC is a key element in the assessment of environmental sustainability in construction, providing a tool for the economic evaluation of alternative sustainability options exhibiting different capital, operating costs, or resource usage. It also provides methods for evaluating the cost benefits of incorporating more sustainable options into constructed assets [21].

1.2. Local Context

Globally, the buildings operation accounts for about 40% of energy and carbon dioxide emissions [22]. Therefore, sustainability in general and energy efficiency in particular become key measures of building performance. In Slovenia, residential buildings account for approximately 25% of the total primary energy consumption. The majority of them are single-family houses representing 75% of the total residential floor area, and 55% of the entire building sector area [23]. In 2010, the Energy performance of buildings directive (EPBD) were harmonized by the Regulations for the Efficient Use of Energy in Buildings. They incorporate Technical Guidance to achieve minimal standards of sustainable buildings in design, construction, and maintenance [24]. Accordingly, the efforts to increase the overall efficiency of buildings require specific architectural design solutions.

1.3. Research Gap and Aim

In the literature, there are numerous studies that use the LCC assessment for the economic evaluation of buildings and building industry products. According to Lewandowska et al., LCC and LCA tools take the life-cycle perspective into account and can be used universally, for all products and processes, which can differ in terms of construction, manufacturing, function, the mode of fulfilling the function, durability, recyclability, and many other aspects [25]. Most of them use a case study method when assessing the value of different technological systems.

However, the past efforts do not combine VfM and LCC assessment in a comprehensive way. A range of authors, such as Lee et al. [26], Hasan et al. [27], Leckner and Zmeureanu [28], and Matic et al. [29] partly use either the LCC or operational costs parameters. Lee et al. incorporate heating and cooling costs including the energy cost inflation. Hasan et al. simplifies the LCC calculation by taking into account only cost differences in specified parameters between the reference case and other options. They assume the maintenance costs to be constant costs, while the differences in the calculation of the replacement costs depend on the set lifetime span of the building. Further, Leckner and Zmeureanu use the energy-related costs that partly include the LCC, the energy inflation, and the replacement costs of the energy system. In order to reduce the heating energy costs, Matic et al. performed the calculations for savings due to the retrofit.

LCC assessments must be evaluated for a selected period of time. Since the LCC periods in construction are not standardized, they have to be selected. Therefore, the service life of building components must be taken into account. The most common period for major renovations in the residential sector in practice is, according to Zavrl et al., 30–40 years [23]. Gluch and Baumann estimate the lifetime of buildings as 50 years in their LCC approach [30].

Furthermore, residential building represents a specialized industry that differs greatly from the rest of the construction industry. Because residential developments are built with a high degree of repetition, construction has become very standardized. Prefabricated construction guaranties more control over the quality of components, safety of the construction process, and notably faster times at reduced costs [31]. Prefabrication represents repetitive assemblies for a building structure [32]. As Norton [33] identifies, repetitive projects, characterized by the same or similar building type built in different locations, benefit most from the point of view of the value management. Because of the improved value incorporated into all the buildings, the VfM method is very effective in such a case. Moreover, according to Li et al., in the private sector, the two highest risk allocations are the construction time delay at 97.6%, and the higher maintenance costs at 97.5% of the total costs calculation [34].

In order to address the issues discussed in the above-mentioned literature, this paper highlights two objectives, (a) to develop a specific economic evaluation method for the cost-optimisation of prefabricated lightweight system envelopes of a building in the life-cycle perspective (including construction, operation, maintenance, and refurbishment costs) to achieve a greater Value for Money of the building in the scope of the sustainable architectural design, and (b) to develop a comparative evaluation model framework usable by different profiles of stakeholders (in design process these are owner, architect, contractor, government, and users), when adopting the decision on the most optimal envelope type in the early design phase of the project. The VfM method was used for the analysis of four selected types of prefabricated lightweight construction system envelopes, which are characterized by the controlled construction time, and the LCC assessment method with integrated maintenance costs as a key parameter, evaluated for a period of 50 years.

In the following sections, Section 2 discusses the methodology of the comparative evaluation process focusing on the development of the extended comparative evaluation model framework (ECEMF) for prefabricated lightweight system envelopes. Section 3 applies the ECEMF to the case study building of a single-family house including the performance of four selected types of prefabricated system envelopes and emphasizes the results of the energy consumption, the LCC, and the VfM assessment. In Section 4, the results are discussed, and in Section 5 the conclusions of the study are represented.

2. Materials and Methods

As mentioned before, in the first 20% of the design process, 80% of the operation, maintenance, and replacement costs of a building can be influenced [1,2]. This study develops a comprehensive ECEMF usable by different profiles of stakeholders when adopting the decision on the most optimal envelope system in the early design phase. The framework is based on the VfM methodology in the life-cycle perspective.

Figure 1 shows the ECEMF developed in this research. From the point of view of stakeholders, the extended model framework represents an important decision tool, which has a direct impact on the VfM. The overall framework model is based on three main steps of evaluation:

Step 1: BIM GENERATION, gathering and generating the building data.
Step 2: BIM EVALUATION, analysing BEM and communicating the results between tools used.
Step 3: VfM ASSESSMENT, analysing LCC and VfM, and realizing the decision.

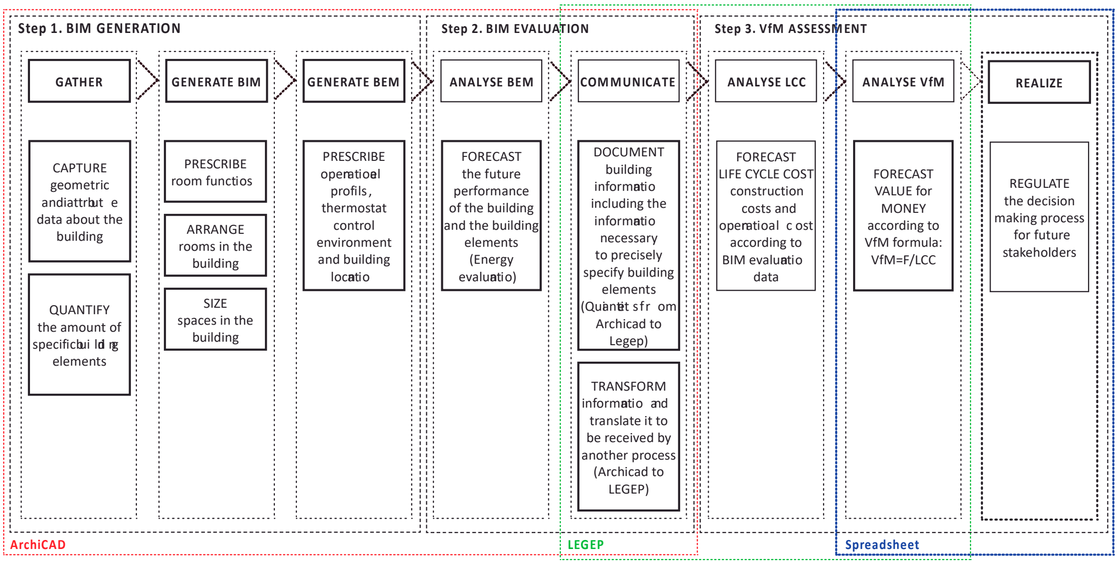


Figure 1. Extended comparative evaluation model framework (ECEMF) for prefabricated system envelopes.

2.1. ECEMF—Extended Comparative Evaluation Model Framework

To simplify the workflow on the case study virtual building, the evaluation of individual types of prefabricated system envelopes refers to the case study building of a small single-family house, and the related BIM with simple functionality. As Love et al. [12] suggested, the use of BIM as a catalyst ensures the monitoring and the evaluation of the building's performance throughout the life cycle. BIM offers not only the digital representation of physical and functional characteristics of a building but also the ability to take the decisions by stakeholders on the complete and integrated information. According to the National Building Information Model Standard (NBIMS) [35], BIM is described as "... the act of creating an electronic model of a facility for the purpose of visualization, engineering analysis, conflict analysis, code criteria checking, cost engineering, as-built product, budgeting and many other purposes." Moreover, Olatunji et al. [36] highlight BIM as a management tool that could aid in achieving the desired VfM by including the LCC analysis, Value Management, Building Information Modelling, and the Lean Construction methods.

In order to develop the ECEMF, the so-called BIM use purposes (Figure 2) were applied for the case study evaluation. After Kreider [37], the BIM use is defined as "... a method of applying Building Information Modelling during a facility's lifecycle to achieve one or more specific objectives." Following this approach, the study includes five BIM use purposes categories: gather, generate, analyse, communicate, and realize.

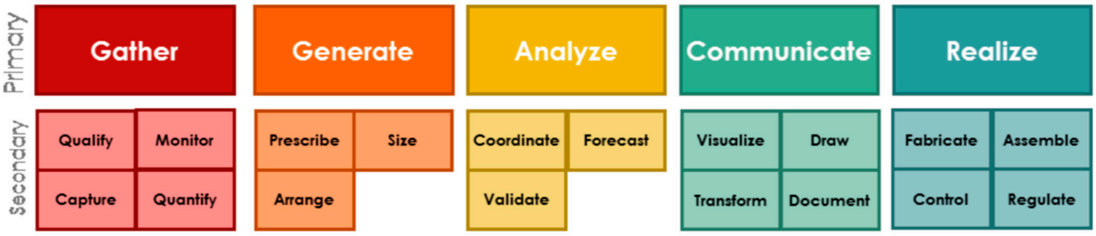


Figure 2. Building Information Modelling (BIM) Use Purposes [37].

2.1.1. Step 1—BIM Generation.

The first step (Figure 1) is based on the BIM Generation, for which the two primary BIM use purposes are used: gather and generate. Firstly, in order to represent the current or wanted status of a building or building elements, the geometric and the attribute data were captured. Secondly, to express and to measure the amount of building elements for future cost breakdown and the LCC (calculations), the amount of specific building elements was quantified. Once the complete information was identified, the Archicad virtual building for the case study with all attributes of building materials was constructed. In Archicad, the virtual materials are not only a graphic presentation but also the simulation of real materials, including all physical properties—thickness, volume, the heat capacity, and thermal conductivity. Building elements are perceived as the combination of different materials in composites representing architectural construction elements such as walls, slabs, and roofs.

2.1.2. Step 2—BIM Evaluation

The second step (Figure 1) presents the BIM Evaluation. Firstly, BIM is analysed, and secondly, the results of the comparison between Archicad as the architectural BIM software for designing and modelling, and Legep software as a tool for integrated life-cycle analysis, are communicated. In order to analyse the construction and operational costs and to estimate the LCC, the future performance of the building and building elements is forecast. For this purpose, the construction cost database or manual input of the data the Legep sirAdos database is used. Further, the quantity information of each building element with all parameters is exported from Archicad and imported into Legep in order to conduct the LCC analysis, and to obtain the final results for the VfM assessment. The final results are calculated by using the data from the quantity take-off list for each element from the BIM virtual construction model by using Archicad. The export of quantity data is presented in the form of schedules and tables and manually imported into the Legep LCC module

2.1.3. Step 3—VfM Assessment

The final step (Figure 1) is the VfM assessment which determines the LCC and VfM. The results are then realized as possible suggestions for the stakeholders. To be able to run the forecast for LCC in Legep software, the thermal blocks for the case study building are defined. Setting this information enables the LCC evaluation. The outcome of the calculation and the evaluation is the LCC forecast which includes the construction, operational (energy, cleaning, etc.), maintenance, and the refurbishment costs.

The final VfM assessment represented in the VfM equation is the result of the calculations for selected system envelope types used for the case study building, compared to the calculation of the reference system envelope. Once all calculations based on the simulation and analysis are completed, the final step enables the possibility of choice for the most optimal envelope. From the point of view of stakeholders, the extended model framework represents an important decision tool, which has a direct economic impact on the VfM assessment.

2.2. VfM and Life Cycle Costs (LCC) Methods

The aim of the study is to propose an ECEMF from the value perspective of the building's system envelope. Therefore, the economic evaluation is performed by using the VfM method. According to Olatunji et al. [36], the VfM method can be defined as the clients' assessment of the project delivered by various project stakeholders as it meets the pre-determined objectives. The clients can assess the VfM when they feel the need to receive a service that was worth the price they paid for. While traditional methods of economic real estate evaluation are mainly focused on the asset's market value, the investors prefer to evaluate the investment's opportunity to assess the correlation between the investment costs and final value of the building or building system [38]. Furthermore, in the early design phase, the project should include the parameters important for the clients to eliminate unnecessary expenditure, and to obtain the optimum balance between parameters of cost, time, and quality of building [39]. The VfM is a further sophistication of an option selection technique. It is calculated by dividing the value score of benefits delivered by the total costs of the option, as shown in Equation (1) [39]:

$$\text{Value for money in construction (VfM)} = \frac{\text{Benefits delivered} \rightarrow \text{Function (Residential)}}{\text{Resources used} \rightarrow \text{Total cost (LCC)}} \tag{1}$$

The calculation helps to differentiate between different options when each has a sufficient value score, but one option costs significantly more than the other. The VfM equation clearly indicates that its main intention is not only to reduce the costs but also to improve the value of the building [40]. The higher VfM is recognized as beneficial for the client and the user of the building [41]. According to Norton [33], there are three major ways to improve the VfM, such as: (i) to provide the required function of the project but at a lower LCC, (ii) to provide improved or additional functions of the project without increasing the LCC, and (iii) to provide an improved function at a lower LCC. The VfM method obviously strives to achieve a balance between the building quality and the LCC [33]. According to Rangelova and Traykova, in building management, the LCC is used as a tool for evaluation, assessing different design alternatives, constructions and skins, considering costs of ownership over the economic lifetime of each alternative, and doing all this in present values. They state that " … life cycle costing is a method for economic evaluation which considers the costs applicable to the total life of the asset" [41].

To improve the VfM, it was decided to provide the required project function and look at the LCC as the parameter that provides greater or lower value. In the study, the function of the building provides the same level of services but with different LCC depending on the system envelope. The function for all cases is set as residential, offering a space for living with the same indoor environment.

2.3. Financial Modelling

From the economic point of view, it is important to consider the long-term financial perspective. For the purpose of LCC analysis, additional data as well as specific rules for evaluating longer time periods were required immediately (i.e., inflation rate). They are integral parts of Legep and are described in the following sub-sections.

2.3.1. Life Cycle Period

Since the lifetime periods for the LCC calculations in construction are not standardized and must be selected, the period for the LCC calculation in this research is based on the rules of the Nachhaltigkeit im Wohnungsbau (NaWoh) certification system, where it is specified at 50 years. Research by Hafner et al. [42] shows that extending the period of observation has no impact on construction and disposal of a building. The main differences come in building operation due to higher exchange cycles of the components. Based on the same usage indicators, the buildings behave similarly during the extended usage phase. Doubling the period under consideration affects the following in particular: facade coatings (15–20 years, replacement of 2–3 times in 50 years), thermal insulation composite exchange (35–45 years, exchange 1 time in 50 years), building technical systems (20–25 years, exchange 1–2 times in 50 years), and windows (40 years, exchange 1 time in 50 years). The primary structures are not affected by an exchange. An extension or shortening of the observation period; however, has a major impact on the energy requirement, however according to research by König [43], the savings potential in relation to the total primary energy demand of the building was determined to be 27% on average for an extension of the observation period from 30 to 50 years, depending on the construction method and the heating technology used. When extending from 50 to 80 years, taking into account major repair work, an additional savings potential of 10% could be achieved on average.

In Slovenian National regulations for maintenance of buildings [23], the lifetime is limited by 60 years. According to Zavrl et al. [23], the average period concerning the need of refurbishment for residential buildings is between 30 and 40 years. Furthermore, Gu et al. [44] assume a lifespan of 50 years, defined by the life cycle green cost assessment method for green building design. Similarly, Gluch and Baumann estimate the lifetime of buildings as 50 years in the life cycle costing approach [32]. According to the NaWoh 4.1.1. Certification, Legep uses a 50 year lifespan as the default value for the LCC calculations of residential buildings [45]. Consequently, the LCC assessment for VfM was carried out for a period of 50 years.

2.3.2. Cost Planning

In this study, a range of data types for cost panning were applied. The LCC cost evaluation was performed with Legep using the expanding and continuously updated sirAdos construction price database, which is a precise, fast, and data consistent tool [46]. After the quantities of elements were extracted from Archicad, the macro-elements were identified and linked with system envelope structures. This approach was suitable for the detailed cost estimation and calculation. Namely, the macro-elements are a compilation of micro-elements created for the given structure, such as roof structure, wall structure, etc. The costs were calculated on the basis of micro-elements' prices as a composition of various service positions calculated automatically. Service positions are precisely described by the specification of individual construction elements, including materials, labour, and the time required. Final costs are based on real prices and are considered as adjustable market margin. In order to adapt the construction costs-related inputs to the project-specific costs, Legep uses the so-called price adjustment factor, added to all construction costs.

2.3.3. Inflation—Dynamic LCC Calculation

Increasing energy and raw material prices lead to different LCC results. Consequently, Legep offers a static and a dynamic LCC calculation method. For this study, a dynamic calculation method was used because it includes the price fluctuations. Since price variations depend on a variety of factors, such as the price variation in international commodity markets, the variation of the exchange rate between the euro and the dollar and the variation of costs for domestic production factors. Therefore, the price evolution can only be considered as an assumed annual price increase rate. [47] This is set in the financial specifications of Legep. According to data obtained from the Statistical Office of the Republic of Slovenia [45], the costs inflation rate of buildings is set at 2%. The average energy price inflation is set at 4%, independently of the price's increase. The inflation of the construction cost could also be set individually. However, according to the Legep Manual, the long-term inflation rate from 2% to 3% per year is expected in the near future. In accordance with the Slovenian tax system in the building construction sector, the fixed tax rate is set at 9.5% of the gross value.

2.3.4. Net Present Value

The present value in the economy, also known as the present discounted value, is the value of the expected income stream determined in compliance with the date of valuation. The present value is always less or equal to the future value because of its money-interest-earning potential, a characteristic referred to the time value of money [48]. In Equation (2) the net present value is calculated:

$$\mathrm{c}_0 = \sum_{t=0}^{T} \frac{c_t}{(1+i)^t} \tag{2}$$

where, C_0 is the cash value, C_t is the sum of payments, t is the current time, T is the viewing horizon, and i is the calculation interest rate.

With regard to the calculation of the net present value, as presented in Equation (2), all deposits and withdrawals are considered as the present value at the time of the investment [49]. Therefore, the net present value is the basis for various applications in the real estate market. The net present value of a payment is reduced when compared to how far in the future the payment is set, and how high the chosen real interest rate is rising [48]. After NaWoh 4.1.1, the total net present value is given for specific life cycle costs used in Legep to determine the usage, predefined discount interest rates, and the given period of 50 years [50]. In the study, default interest rates were set by 2% of the yearly inflation, the capital interest by 5.5%, and the real interest rate by 3.5%.

2.4. Tools and Legislation

To achieve a greater value of a building when adopting the decision on the most optimal envelope type in the early design phase, the VfM method was used. However, to assess the VfM already in the early design phase, a tool that allows easy access to and sharing of information and knowledge in real-time is needed. BIM provides a repository that effectively manages information and knowledge during a building delivery process and enhances the delivery of the required sustainable building value [15]. A BIM model of the building must be created that digitally represents the physical and functional characteristics of a building and also, has the ability to take the decisions by stakeholders on the complete and integrated information [12]. Archicad is used for gathering and generating the information for BIM, since Archicad was recognized as the first CAD product for personal computers that was able to create both two-dimensional (2D) and three-dimensional (3D) geometry, as well as the first commercial BIM product for personal computers [17]. Furthermore, ArchiCAD's extension EcoDesigner STAR was used for energy evaluation in the study, as it provides a full and automatic BIM to BEM workflow that enables designers to fully utilize the building energy modelling capabilities. It is used to evaluate building energy performance under any kind of circumstances and locations around the world, since its analysis engine complies with ANSI/ASHRAE Standard 140–2007 Standard Method of Testing for the Evaluation of Building.

The VfM is calculated by dividing the Residential Function with Life-Cycle Costs. There is no LCC tool currently available that is specific for the Slovenian building sector [51]. Furthermore, SIST

DIN 276-1:2013 (Slovenski inštitut za standardizacijo – SIST, Deutsches Institut für Normung—DIN), a norm adapted from German DIN 276, is used for the planning of construction costs of buildings, especially in the determination and breakdown of costs. Moreover, to determine the cost of building use, German DIN 18960 is used. The standard defines the concepts of cost planning in construction and the characteristics of their differentiation, thereby enabling the comparability of the costing results [52]. Therefore, Legep, a tool for integrated life-cycle analysis that supports the planning teams in the design, construction, quantity surveying and evaluation of new or existing buildings is used. The Legep database contains the description of all elements of a building (Figure 3) based on DIN 276 and their life cycle costs based on DIN 18960 and on the calculation rules of the German DGNB, BNB, and NaWoh Sustainability Certification. Moreover, Legep has an extensive database of materials and composites, which is crucial for such type of evaluations.

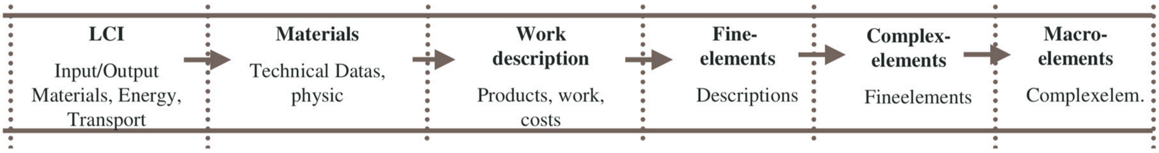


Figure 3. Hierarchical organization of the data "staircase" in Legep software [53].

Further, Kohler et al. [54] used Legep for the life cycle assessment of passive buildings, describing Legep as an assessment tool for the integrated life cycle performance of buildings, adopted in Germany, Switzerland, and France, where Legep supports the planning teams in architectural design, construction, quantity surveying, and evaluation of new and existing buildings and building products.

The Legep program implements the automatic setting of the calculation for the various building certifications. This sets the rules for the calculation of life cycle costs and life cycle assessment for different systems, meaning that many individual settings in the different program modules are made with the setting of building certification. NaWoh certification is developed specifically for housing, for the description and evaluation of the sustainability of new residential buildings [55]. Consequently, the NaWoh setting was used in Legep for the LCC calculation. Selected LCC according to NaWoh certification are presented in Table 1. NaWoh does not include dismantling and disposal of the building.

Table 1. Selected Life Cycle Cost (LCC) according to Nachhaltigkeit im Wohnungsbau (NaWoh) 4.1.1 [55].

Life cycle cost calculation according to NaWoh 4.1.1.	2.4.1 Selected construction costs according to DIN 276	2.4.2 Selected user costs according to DIN 18960							
		2.4.2.1 KG 300 according to DIN 18960: Selected operational costs					2.4.2.2 KG 400 according to DIN 18960: Repair costs		
	300 + 400 Building construction + Technical Building Equipment	KG 310 according to DIN 18960: Selected supply costs (energy and water)		KG 320 according to DIN 18960: Wastewater disposal	KG 330 according to DIN 18960: Cleaning of buildings	KG 350 according to DIN 18960: Operation, inspection and maintenance	KG 410 according to DIN 18960: Repair of the building constructions	KG 420 according to DIN 18960: Repair of the technical building equipment	
Cost categories	Construction	Energy	Water	Wastewater	Cleaning	Maintenance	Replacement investment	Regular repair	Replacement investment

Acronyms: Deutsches Institut für Normung (DIN), Kostengruppen (KG), Nachhaltigkeit im Wohnungsbau (NaWoh).

2.5. Case Study Building and System Envelopes Selection

The VfM assessment was performed for a reference type and for three additional types of system envelopes. For each envelope type, a separate BIM model was created. Independently from the envelope types, all BIM models have an identical floor area and equal internal heated volume. This approach is set as a precondition to obtain the same parameters calculated per m^2 of the net floor area.

The case study building is a two-story single-family house with fixed internal dimensions of 7.20 m × 7.20 m × 6.20 m (w/b/h), heated floor area of 98.77 m^2, and total heated volume of 249.90 m^3. This type of building was selected according to the specific situation in Slovenia. Namely, after the annual report on the Slovenian property market, the residential buildings in Slovenia accounted for approximately 25% of the total primary energy consumption. The majority of them are single-family houses representing 75% of the total residential floor area and 55% of the entire building sector area [23]. Furthermore, approximately 530,000 housing units are single- and two-dwelling-houses, and this is one of the top rankings in Europe. The number of residential units in family houses accounts for 60% of the total housing stock [56]. Furthermore, according to the annual report [56], national average house floor areas (brut) are 120 m^2, excluding basement and/or external storage, and are occupied by a family of four [57].

The development of the ECEMF is based on the idea of evaluating and comparing the options of sustainable prefabricated lightweight system envelopes for future constructions, which are already recognized in the academic and professional community. Therefore, the prototypes of Solar Decathlon Competition Europe 2012 system envelopes (SDE) were analysed. The SDE is aims at the promotion of research and innovation for sustainable and smart architectural design [58]. The main target is a building, which consumes as few resources as possible with special emphasis on the reduction of energy consumption. The energy performance focuses on the reduction of energy consumption and architectural design. To select the SDE system envelopes for the case study building, the jury categories Architecture, Engineering and Construction, Energy Efficiency, Innovation, and Industrialization and Market viability in the Final jury report where analysed and evaluated [58]. According to the analysis of the Slovenian property [56], those five categories should be the most important for the stakeholders. Subsequently, three different system envelopes were selected according to the evaluation: Canopea, Ecolar home, and MED in Italy.

For the reference system, envelope Lumar Primus was selected, because in an independent research “Best Buy Award” the company received “Best Buy Award–Nr. 1” for best price performance in the category of prefabricated houses in Slovenia [59]. The international research for the award was carried out by the Swiss company ICERTIAS (International Certification Association). The research was based on a survey of 1200 samples done in Slovenia and was limited to persons involved in the building sector. Subsequently, their Primus envelope system was used, which according to Lumar, is their highest selling model [60].

3. Case Study

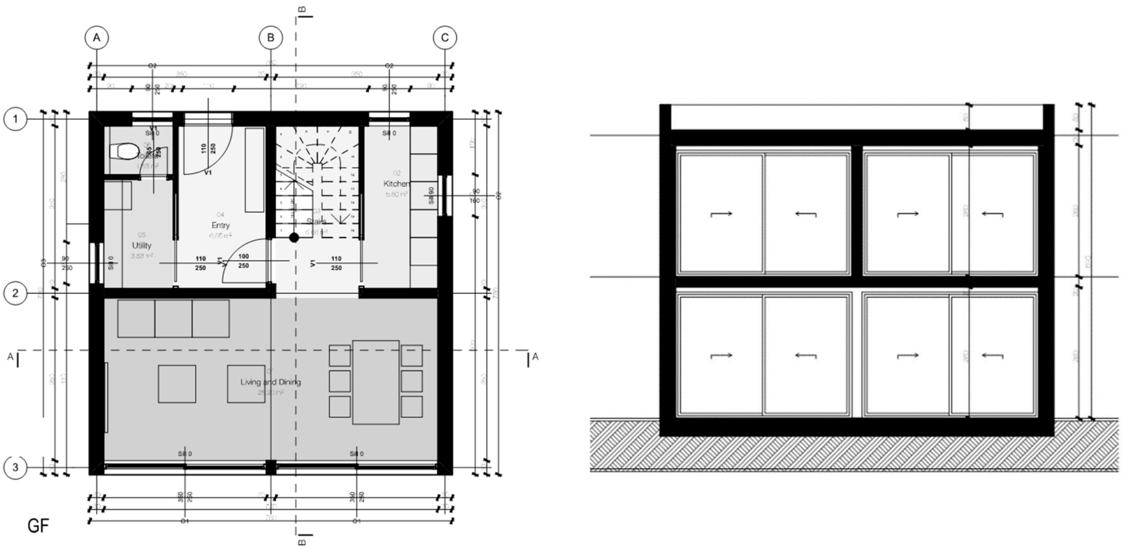
In order to determine the VfM and the applicability of the developed ECEMF for prefabricated system envelopes, it was used on four different types of system envelopes in prefabricated lightweight construction. Canopea, Ecolar, and MED were evaluated for LCC, and compared to the reference system Lumar Primus for the case study building of a single-family in Maribor. Lumar Primus is a timber panel envelope system which is categorized as a very good low energy house in Slovenia and was used as a reference. Canopea is a combination of steel and timber envelope, with a very good thermal transmittance value. Ecolar is a high-tech envelope with a dynamic u-value. MED in Italy is a low-tech solution that adds another cavity to a standardized prefabricated panel system, adding thermal mass with smart use of aluminium pipes and sand. In the following subsections, the application of the three steps (BIM generation, BIM evaluation, and VfM assessment) of the ECEMF on the case study building is presented.

3.1. First Step-BIM Generation

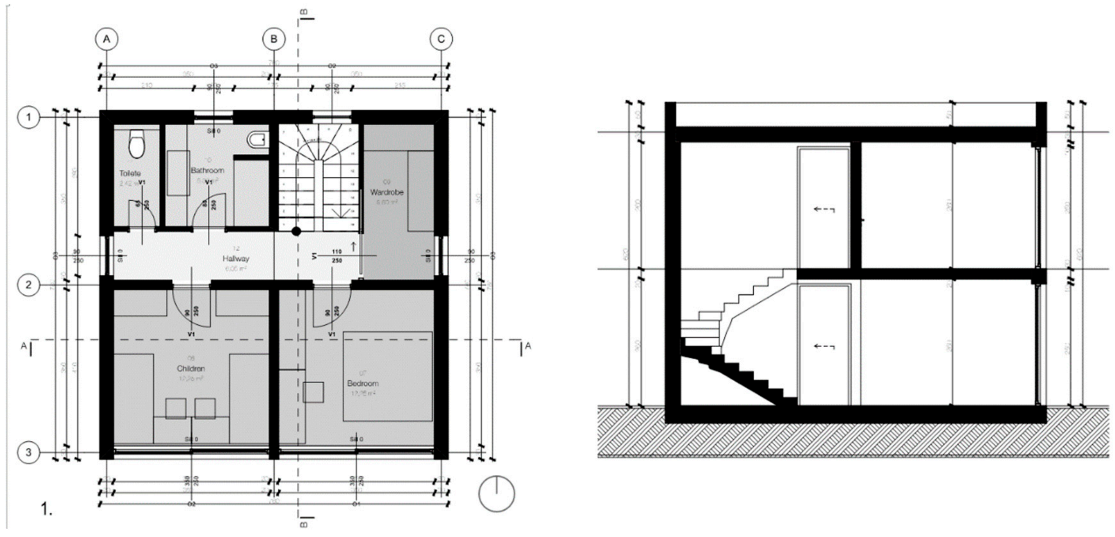
BIM generation is the first step of the ECEMF. In this phase, the information on the building is collected, gathered, and organized.

3.1.1. Gather

In order to gather the necessary data to present the wanted status of the case study building, the geometric data was captured. The case study building is a two-story single-family house shown in Figure 4. According to the annual report [56], the total building size of approx. 116 m^2 was set, depending on the system envelope. Fixed internal dimensions were 7.20 m × 7.20 m. The total heated floor area was 98.77 m^2; the total heated volume is 249.90 m^3. A concrete foundation slab and flat roof construction are set because of the type of selected system envelopes explained in the subsections. Next, the attributes of specific building elements were quantified to measure the amount and cost of building elements for future cost breakdown and LCC calculations.



(**a**) ground floor (**c**) section A-A



(**b**) first floor (**d**) section B-B

Figure 4. Case study building (**a**) ground floor, (**b**) first floor, (**c**) section A-A, and (**d**) section B-B.

Construction

System envelopes of a single-family house are performed in selected types of prefabricated lightweight construction systems for walls and roof construction. The impacts of different thermal capacities are taken into consideration. Walls and roof are considered as system envelopes and are the changing parameters. The foundation slab (U = 0.15 W/m^2 K—recommended by PURES-policy on the efficient use of energy in buildings in Slovenia), first floor slab and internal walls are fixed parameters.

Windows

Windows are considered as fixed parameters in size and energy performance for all cases. The timber window frame has the window's U-value for an energy calculation of 0.87 W/m^2 K [61]. A value lower than 1.10 W/m^2 K is recommended by legislation for timber frame windows [62]. All external openings are, according to legislation, shaded with an external shading device of louvers.

System Envelopes

The development of the ECEMF is based on the idea of evaluating and comparing the options of advanced prefabricated system envelopes for future constructions, which are already recognized in the academic and professional community. Therefore, the select prototypes (as described in Section 2.5) of SDE 2012 and the selected reference system envelopes were analysed to quantify the number of building elements for the LCC. The characteristics of the selected system envelopes are described in the following sub-section, compared in Table 2, and graphically in Appendix A.

Table 2. Comparative table of the four envelope systems (Lumar Primus, Canopea, Ecolar, and MED in Italy) used on the case study building with main properties for this research.

System Envelope	Material	T (mm)	S (mm)	U (W/m^2 K)	Material	T (mm)	Sum (mm)	U (W/m^2 K)
		Wall				*Roof*		
Lumar Primus	Plaster Thin	2	**365**	**0.119**	Polyethylene waterproofing membrane	2	**365**	**0.119**
	Plaster reinforcement	3			Mineral inclined insulation	300		
	Mineral insulation wool	100			bitumen vapor barrier			
	Plasterboard	15			OSB panel	18		
	Cellulose insulation & (Laminated spruce studs)	160			Laminated spruce beams	60/240		
	Vapor barrier	0.2			timber under construction	70/22		
	Mineral wool insulation & (timber studs 60/80)	60			Plasterboard	12.5		
	Plasterboard	15						
	Plasterboard	10						
		Wall				*Roof*		
Canopea	Plaster Thin	2	**344**	**0.08**	Polyethylene waterproofing membrane	2	**370**	**0.07**
	Plaster reinforcement	3			Wood joist + cellulose insulation	60		
	Kerto-Q LVL panel	27			Kerto-Q LVL panel	25		
	Cellulose insulation & (1/2 IPE200 and timber battens 60x40)	200			cellulose insulation (timber 130/60)	130		
	OSB panel	12			Kerto-Q LVL panel	25		
	Vacuum insulation	30			Vacuum insulation (timber 45/45)	45		
	Vapor barrier	0.2			Vapor barrier	0.2		
	Proliferated steel rails	35 × 35			Cellulose insulation (timber 60/40)	60		

Table 2. *Cont.*

System Envelope	Material	T (mm)	S (mm)	U (W/m^2 K)	Material	T (mm)	Sum (mm)	U (W/m^2 K)
	Fibralith panel	25			Reflective insulating screen	10		
	Earth coatin	10			Plasterboard	12.5		
					Earth paintwork (Akterre)	3		
		Wall				*Roof*		
Ecolar	Lucido system	56	**273**	**0.10**	Polyethylene waterproofing membrane	2	**366**	**0.13**
	MDF board	15			OSB	15		
	Thermo-Hemp WCG + Lignotrend U*PSI t 6/170	170			Thermo-Hemp WCG 038 & (timber 160/60)	160		
	OSB panel	19			Thermo-Hemp WCG38 +Lignotrend	135		
	Plasterboard	12.5			Vapor barrier	0.2		
					Clay board	25		
					Plasterboard	12.5		
		Wall				*Roof*		
MED in Italy	Plaster Thin	2	**493**	**0.14**	Stamisol Pack 500	0.7	**386**	**0.14**
	Plaster reinforcement	3			Pavatex Isolair L	22		
	Pavatherm Plus	100			Pavatherm Plus	80		
	OSB	15			OSB	18		
	Pavaflex & (timber battens 200/60)	200			Pavatex & (timber battens 200/80)	200		
	Plasterboard panel	12.5			OSB	18		
	Aluminum pipes (round) + wet sand	80			Cork	20		
	Timber battens 60/60	60			Gypsum Fiberboard (Farmacell)	27		
	Solid wood panel	20						

Acronyms: T—material thickness in mm, OSB—Oriented strand board, S—system envelope thickness in mm, U—u-value of the system composite in W/m^2 K.

Lumar Primus System Envelope

The Lumar Primus system (Figure A1) was chosen as the reference envelope type. It is used for the production of prefabricated lightweight timber houses by the company Lumar which is located in Maribor. Lumar Primus prefabricated houses are categorized as a very good low-energy houses in Slovenia and worldwide [63].

According to Staib et al.'s definitions [64], the Lumar lightweight timber construction system is a timber panel system based on the timber framework construction principle. The external wall of 365 mm has a U-value of 0.12 W/m^2 K and the flat roof construction of 593 mm has the U-value of 0.11 W/m^2 K. All other parameters are considered as fixed values. The thermal insulation is cellulose used for the cavities between construction studs, and mineral wool for the installation and exterior insulation layers. The annual overall energy demand is between 20 and 25 kWh/m^2 a and the floor-heating system is recommended. The Lumar system envelope has very good thermal and soundproofing characteristics and is open to vapor diffusion [65]. The comparative details are shown in Table 2.

Canopea System Envelope

The Canopea system envelope [66] is a high-performance thermal envelope type Figure A2. After definitions provided by Staib et al.'s [64], the primary structure is a steel panel construction is installed on the platform construction principle. The external skin is made of local materials and the prefabricated elements are produced by local companies with controlled costs. The panels are filled with cellulose thermal insulation, combined with innovative insulation materials in the interior as vacuum insulation panels, and as the Kerto-Q LVL panels in the exterior. The final interior skin is earth coating. External walls of 344 mm have an excellent Uwall value of 0.08 W/m^2 K. The flat roof construction of 370 mm has the U-value of 0.07 W/m^2 K. The Canopea system achieves the passive houses standards, with a U-value bellow 0.10 W/m^2 K.

Ecolar System Envelope

With the ambition to combine passive and active solar energy gains, the Ecolar [67] high-energy and high-tech system envelope is based on special opaque facade elements (Figure A3). The primary structure is a timber frame system, designed according to the beam construction principle, while the high-tech infill panels are constructed in the timber panel system according to the timber framework construction principle [64]. The internal layers consist of hemp insulation, a special milled layer with horizontal wooden slats, slightly inclined downwards, and an air gap. The final weather protective layer is the laminated glazing. Additionally, solar beams pass through the 30% translucence warming wooden slats and the spaces in-between. The structure achieves the temperature that is higher indoor than outdoor, and, because of the transmission, the heat losses are intensively reduced. During heating season, even at lower temperatures, the openings on the top and bottom create an unmoved layer of air in-between the glass layers. At high temperatures, these openings prevent facade elements from overheating via convection, with a dynamic U-value of less than 0.01 W/m^2 K during heating season. The external walls of 273 mm make the system as efficient as a conventionally insulated exterior wall of a double thickness. The thickness of the flat roof is 366 mm and the U_{roof}-value is 0.13 W/m^2 K.

MED in Italy Envelope

According to Staib et al.'s definitions [64], the MED in Italy system envelope is a timber panel system based on the timber framework construction principle [68] and an innovative low-tech solution (Figure A4). The panel wall has a cavity filled with sand in order to gain the inertial mass and to optimize thermal behaviour. The lightweight elements built of alloy pipes are transported to the site and filled with humid sand. The total weight of elements is reduced up to 30% compared to a homogenous layer. Due to the ventilation of the mass, the thermal capacity can grow up to 20% because of the increased surface that enables the exchange of the heat. This timber construction system is comparable with traditional insulated brick wall construction. The walls of 493 mm have the Uwall value of 0.14 W/m^2 K. The flat roof of 386 mm has the Uroof-value of 0.14 W/m^2 K.

3.1.2. Generate BIM

Once the complete information with geometric and attribute data of the building and the amounts of specific elements were identified, the BIM virtual building for the case study with all attributes of building materials was GENERATED in Archicad. The prescribed room functions, arrangement of rooms, and size of the building suit a family of four people according to the Statistical office of Slovenia [62]. The architectural drawings consist of floor plans of the ground floor and the first floor, and two sections (Figure 4).

3.1.3. Generate Building Energy Modelling (BEM)

When the specific data for energy evaluation - the environmental data, functional/operational profile, and building systems—was prescribed for the BIM model, it was transformed into a BEM model

(Building Energy Modelling) using the automatic model geometry and material property analysis functionality of Archicad. For running the energy consumption simulation, it was necessary to define the thermal blocks of the case study building that present one or more rooms or spaces in the building that have a similar orientation, operation profile, and internal temperature requirements.

Building Operation Profiles

The case study building operation profile is set as residential. The maximum temperature is limited at 26 °C, the minimum temperature at 20 °C according to TSG-1-004:2010 [64]. Total usage hours are considered as 8760 h per year (365 × 24 h). The lightning for internal heat gain and electricity demands is set as LED (light-emitting diode) lightning. The occupancy count is 4 persons [59]. It is considered that 120 W per person of human heat gain, 150 L of water per person per day, and a humidity load of 10 g per day per m^2 is produced. These default values in Archicad EcoDesigner reflect the Operation Profile specifications of the DIN 18599 Standard-Energy Efficiency of Buildings [69].

Active Technical Systems

The EcoDesigner-calculated HVAC (Heating, ventilation, and air conditioning) design data predicts the heating period of 3639 h per year and the cooling period of 575 h per year. Domestic hot water generation is set for the average temperature of 10 °C for cold water and of 60 °C for hot water, default values reflecting the Operation Profile specifications of the DIN 18599 Standard [70]. Heating requirements and hot water generation by a heat pump with an air-to-water heat exchanger is set for a heat pump with 11,800 W of heating output and a 250 L accumulator tank and a COP (coefficient of performance) of 4.55 (3.0 is the minimum according to TSG-1-004:2010). Such heating source is used as a standard offer for Lumar prefabricated residential houses in Slovenia [71].

Location, Orientation, and Climate Data

The case study building is located in Maribor, the second biggest city in Slovenia, geographically located at the 46°34′53″ N latitude, the 15°38′22″ E longitude, and an altitude of 297 m. The buildings' open glazed elevation is oriented to the south. According to the Strusoft climatic data server used by EcoDesigner for energy evaluation in Archicad, the city of Maribor belongs to the Climate Type A (Moist), identified as a 5A zone, with an average annual temperature 10.55 °C, a minimum temperatures of −9.67 °C in January, and the highest temperatures of +38.17 °C in July. The average annual humidity is 78.82%, and the average solar radiation is 163.80 Wh/m^2. The winds achieve an average speed of 2.38 m/s.

3.2. Step 2—BIM Evaluation

The second step of the evaluation process is the BIM Evaluation, where the BIM was analysed and the results between Archicad and Legep were communicated.

3.2.1. Analyse BEM—Evaluation of Energy Consumption

To be able to analyse the operation costs and the LCC, the future performance of the building and building elements must be forecast. For this purpose, Archicad with its integrated energy evaluation tool to forecast the energy needs of the building was used. This enables an accessible workflow for performing dynamic building energy calculations.

The evaluated case study building always has the same interior heated volume of 249.90 m^3, a net floor area of 94.44 m^2, and the glazing ratio of 23%. The results (Table 3) of the energy consumption are evaluated for different categories, such as heating, service hot water, cooling, and lighting and equipment by using the Archicad EcoDesigner Star software module. The average U-value rating is the combination of walls, roof, and openings. The total electricity amount for lighting and equipment is 609.90 kWh/a and uses the same parameters and residential function the same for all four systems.

Table 3. Building Energy Modelling (BEM)—Energy consumption results.

System Envelope	Average U-Value (W/m² K)	Heating (kWh/a)	Service Hot Water (kWh/a)	Cooling (kWh/a)	Light. And Equip. (kWh/a)	Net Heating Value (kWh/m² a)
Lumar Pr.	0.31	3103.6	2765.3	355.8	2366.0	36.33
Canopea	0.28	2653.6	2765.3	314.2	2230.0	31.53
Ecolar	0.31	2991.3	2765.3	346.6	2331.0	35.00
MED	0.31	3167.6	2765.3	274.0	2348.0	35.80

3.2.2. Communicate

To perform the LCC analysis, the quantitative information of each element with all of its parameters is exported from Archicad into Legep. The final results are the quantity take-off list of each element from the BIM model. The export of quantity data is presented in the form of schedules and tables and manually imported into the Legep LCC module.

3.3. Step 3—VfM Assessment

The final step is the VfM assessment, in which the LCC and VfM were analysed and then the results in the form of suggestions for future stakeholders were realized.

3.3.1. Analyse LCC—Life Cycle Cost Evaluation

Once the thermal blocks for the case study building where defined in Legep, the LCC evaluation was performed. The results of the LCC forecast include construction, operational (energy, cleaning etc.), maintenance, and refurbishment costs.

Construction costs for all four system envelopes are evaluated according to the Cat. 300 and 400 of the DIN Standard described in Section 2.4. As presented in Table 4, the differences in construction costs arise from the alterations among categories of material, labour, toll, and processing costs. The Lumar Primus system is characterized by the lowest construction costs. Due to the high-tech external wall envelope and façade material, the Ecolar system construction costs are the highest. Because of the low-tech based insulations, the other two systems of Canopea and MED possess very good U-values and low construction costs, with the exception of the expensive vacuum insulation panels of the Canopea. As shown in Table 5, the LCC operational costs vary due to the differences between the construction and operational costs.

Table 4. Construction cost evaluation according to Legep.

	Lumar Primus	Canopea	Ecolar	MED in Italy
building construction (300) in €	80,211.61	90,937.44	115,963.85	88,176.44
foundation	14,495.04	14,495.04	14,495.04	14,495.04
floor slab	6480.82	6480.82	6480.82	6480.82
exterior wall with windows and shading in €	44,378.86	48,123.12	74,856.15	50,676.33
>Windows	14,437.84	14,437.84	14,437.84	14,437.84
>Shading	6631.26	6631.26	6631.26	6631.26
interior walls	6655.14	6655.14	6655.14	6655.14
roof in €	7402.43	14,589.82	12,849.40	9069.79
technical equipment (400) in €	28,552.62	28,523.47	28,523.47	28,523.47
Construction cost net in EUR (300 and 400) in €	108,764.67	119,459.53	144,487.68	116,728.76
Difference (%)	0	+8.9	+24.7	+6.8

Table 5. Comparison of the Supply and Disposal Costs, Cleaning Costs, Maintenance Costs, and Service and Repair Costs.

System Envelope	Supply and Disposal in EUR	Diff. in Supply and Disposal in (%)	Cleaning Cost in EUR	Diff. in Cleaning (%)	Maintan. Cost in EUR	Diff. in Maintan. (%)	Service and Repair Cost (KG300/400) in EUR	Diff. in Service and Repair Cost (%)
Lumar Pr.	16,718.39	0	5792.52	0	16,747.35	0	43,792.02	0
Canopea	16,214.44	−3.11	5792.52	0	17,011.07	1.57	45,883.56	4.78
Ecolar	16,634.80	−0.5	11,266.79	94.51	17,625.88	5.25	58,794.84	34.26
MED	16,674.43	−0.26	5792.52	0	16,952.89	1.23	50,046.58	14.28

Acronyms: Diff.—Difference, Maintan.—Maintenance, KG—Kostengruppen.

The lowest LCC is the characteristic of the Lumar Primus system envelope and the highest of the Ecolar. With regard to supply and disposal costs, the highest rates are evaluated for the Lumar Primus, and the lowest for the Canopea. As expected, due to the smart use of low-tech aluminium pipes, the LCC value of the MED system envelope is lower than the other three types. The highest operational costs are incurred in the Ecolar system envelope due to the high-tech external wall that reduces the annual supply and disposal costs by approximately 1%. The Ecolar system envelope's maintenance and service costs are 20.4% higher than the costs of the Lumar Primus.

The comparison of the cost evaluation among four envelope types clearly demonstrates that the advanced technology (high-tech) equipment and materials are reducing supply costs that include energy consumption related costs. However, due to higher maintenance and service costs during the buildings' lifetime, the operational costs are increasing. When observing the results in the users' and owners' perspective, the perception of costs varies heavily. In view of the user, a building with lower supply costs is more suitable. In contrast to that, the maintenance and service costs are more important for the owner. For the Slovenian housing market conditions, the findings regarding the owner's perception are especially significant, since according to statistical data, 77% of residential homes are privately owned [69].

3.3.2. Analyse VfM

After the LCC forecast was gathered, the results were imported into Excel for the final VfM evaluation. It was evaluated for three system envelopes and compared to the reference system envelope for the case study building. The VfM evaluation indicates the efforts to reduce the costs and improve the residential value of the building, in parallel. The case study buildings' functionality of services is estimated to be at the same level for all four system envelopes (residential), while the LCC values vary due to their different characteristics, as shown in Table 6. The highest VfM value of the Lumar Primus system envelope is set as a reference value of 100%. The Canopea system envelope indicates the value of 94%, and the MED system envelope, the value of 93%. The lowest VfM value of 77% is achieved in the case of the Ecolar system envelope.

Table 6. Comparison of Construction cost, Operational costs, LCC, and VfM.

System Envelope	Const. Cost Net in EUR (300 and 400) Building Construction (300) and Technical Installations (400)	Operational Cost (NaWoh) in EUR	Diff. in Operational Cost in %	LCC (Const. Cost Net 300 and 400 + Operational Cost NaWoh) in EUR	Diff. in LCC in %	Value for Money in %
Lumar Pr.	108,764.67	83,060.28	0	191,824.95	0	100
Canopea	119,459.53	84,901.59	+02.17	204,361.12	+06.13	94
Ecolar	144,487.68	104,322.31	+20.40	248,809.99	+22.90	77
MED	116,728.76	89,466.42	+07.16	206,195.18	+06.97	93

Acronyms: Diff.—Difference, Maintan.—Maintenance, KG—Kostengruppen.

3.3.3. Realize VfM

Once all calculations based on the simulation and analysis were completed, the information generated through the ECEMF can be used by stakeholders in the decision-making process to choose the most optimal construction system envelope.

4. Discussion

The study on the development of ECEMF provides a range of interesting outcomes with regard to various aspects of analysing prefabricated system envelopes.

When observing the construction costs and BEM analysis, it must be emphasized that all evaluated system envelopes achieved very good U-values, reaching from 0.07 to 0.14 W/m^2 K, which are far below the minimum of the Slovenian energy efficiency standards. The BEM analysis presented that Canopea, with a high-performance thermal envelope, has the best results of the net heating energy, whereas the simplest envelope system of Lumar primus has the worst value. These values vary by up to 13%. Differently, in the Supply and Disposal costs that include the energy-related costs, the difference is merely 3.11% in 50 years. However, the net values of the initial construction costs vary up to 25% for reasons identified in the case of the high-tech-prototype-like envelope design. For this type, the high increase in initial construction costs can only be partly repaid by the expected lower supply and disposal costs. When observing only the construction costs, the initial construction costs of the Canopea system envelope with the best U-value are higher than the construction costs of the Lumar Primus system envelope. The Ecolar system envelope with a high-tech dynamic U-value was expected to achieve good results due to the highest initial construction costs. Surprisingly, the Ecolar system Supply and Disposal costs were evaluated as being only 0.5% lower than the Lumar Primus system, while the initial construction costs are 24.7% higher than those of the reference case. It can be concluded that the high-tech system envelopes reduce energy supply costs; however, due to very high maintenance and service costs these systems produce additional operation costs up to 22.9%. Nevertheless, supply and disposal costs represent only 16% to 20% of the total LCC net present value. This is important as LCC is a key element in the assessment of environmental sustainability in construction, providing a tool for the economic evaluation of alternative sustainability options and methods for evaluating the cost benefits of incorporating more sustainable options into constructed assets [21].

Regardless of the higher initial construction costs that are often perceived as an investment to avoid future operational costs, the net present value of the Lumar Primus system envelope proved a different conclusion. Namely, lower supply and disposal costs, including the energy consumption costs, do not compensate for higher replacement and maintenance costs in the 50 years' lifetime. In Slovenia, where 77% of the housing fund is privately owned [69], lower initial construction and operational costs result in a superior VfM, and therefore, a better decision in terms of the owner's perspective. Improving social outcomes and ensuring VfM is equally as important as improving environmental outcomes in the predominant model of sustainability [6]. Moreover, a building providing good VfM now and in the future in addition to being social and environmental, is a sustainable outcome [7].

Additionally, BIM combined with Legep and its use of pre-set macro-elements in the frame of the developed ECEMF, creates an automation process that enables the LCC analysis in the early design phase. For a model of VfM evaluation, only the values of different layers of system envelopes are needed.

The study has implicated that the developed ECEMF can be used in an earlier design phase, which according to Hofer [4], determines approximately 80% savings of all investment and operating costs.

This study differentiates from other studies of cost optimal strategies for stakeholders in the following aspects. The researched studies [26–29] did not include thorough life cycle costs and mostly considered energy supply costs over the lifetime as LCC. Some of them [26] approached operational costs as a sum of energy consumption over the lifetime with a static calculation method that does not include inflation or interest rates. Additionally, a dynamic LCC calculation method was used, taking into account the following values: building cost inflation of 2%, energy price inflation of 4%, real interest rate of 3.5%, and capital interest rate of 5.5% [69].

It is important to consider a range of limitations of the study. The first one is the consideration of the systems with advanced prefabricated system envelopes in lightweight construction systems. To simplify the workflow, the case study building was limited to a single-family house of approximately 100 m^2 heated net floor area with simple functionality. The next limitation was that all system envelopes meet the quality standards of residential buildings providing healthy and comfortable living conditions for the dwellers. The selected system envelopes ensure that the size of the floor area and internal volume stay the same. Furthermore, the climate settings for the location in Maribor are in line with the mid-European climate conditions. The LCC analysis for this study was performed according to the DIN 18960 standard which does not include the End-of-Life-Phase (including the dismantling and disposal of the building and reuse of materials).

5. Conclusions

The decisions made in the design phase have long-term consequences for stakeholders, who currently make decisions mostly on initial construction costs and typically overlook life cycle costs of the building. The main goal of this study was to develop a specific economic evaluation method for the cost-optimisation of prefabricated lightweight system envelopes of a building in the life cycle perspective to achieve a greater VfM of the building in the scope of the sustainable architectural design and to develop an ECEMF that is usable by different profiles of stakeholders, when making the decision on the most optimal envelope type in the early design phase of the project. The primary findings from this study provided insights for ongoing discussions around cost-optimal design of a building envelope in the early design phase:

1. Creating an extended evaluation model with functionality to enable automated workflows of evaluation is an enabler for early design optimization and decision making and this paper contributes to explaining how this can be done.
2. With the use of BIM in Archicad and Legep pre-set macro-elements, the VfM evaluation is already possible in the early design phase before final detailed planning is developed, since only values of different layers of system envelopes are needed. This implicates that ECEMF can indeed be used by stakeholders in the earlier design phase.
3. When looking at the functional dependence of VfM from service and repair costs, these are approximately three times higher than the maintenance costs and up to two times higher than the supply and disposal costs. This indicates that to get an accurate value for money evaluation of a building case study, it is important to asses it thorough life cycle costs and not merely supply and disposal costs that include the BEM analysis with energy-related costs.
4. The ECEMF is enhancing the building's sustainability performance by optimizing the VfM and subsequently LCC when choosing its system envelope, therefore, contributing to sustainability outcomes.

It is often claimed that high-tech external system envelopes of building provide substantial benefits in terms of energy consumption and operation costs. However, the results of the study clearly defied this statement in the identification of cost-optimal parameters and their interdependence.

To generate a general evaluation model for different building designs utilizable in the early design phase, there is a need for more case studies exploring different parameters (different geographical location, etc.), to allow further assessment of the subject. Follow-up research should involve (1) inclusion of the dismantling and disposal and reuse into the ECEMF, (2) comparison to non-prefabricated technologies, and (3) production cost reduction through industrialization.

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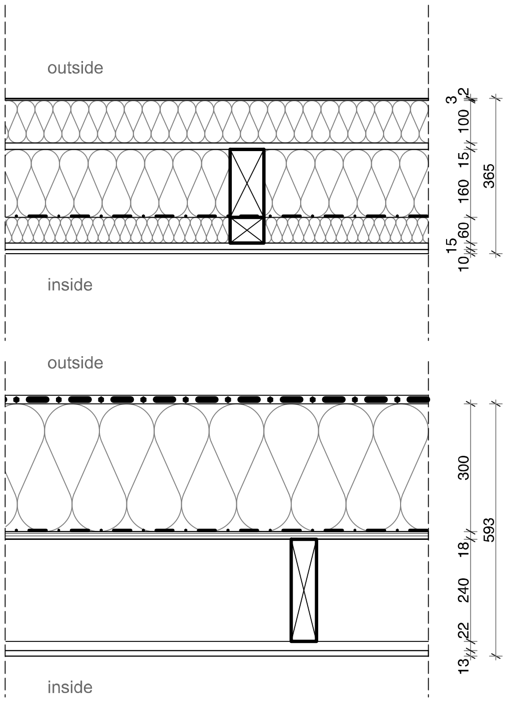
Appendix A



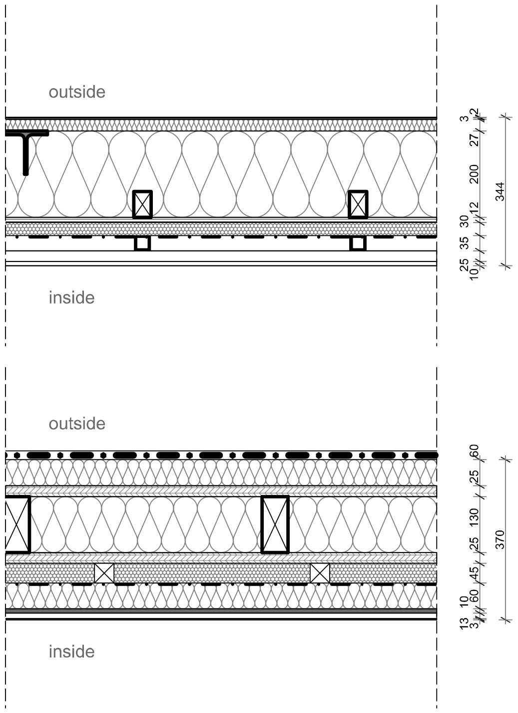
LUMAR PRIMUS WALL

material	**thickness** (mm)
Plaster Thin	2
Plaster reinforcement	3
Mineral insulation wool	100
Plasterboard	15
Cellulose insulation & (Laminated spruce studs 160/60)	160
Vapour barrier	0,2
Mineral wool insulation & (timber studs 60/80)	60
Plasterboard	15
Plasterboard	10
Wall thickness (mm)	**365**
U_{wall}-value (W/m2K)	**0,119**

LUMAR PRIMUS ROOF

material	**thickness** (mm)
Polyethylene waterproofing membrane	2
Mineral inclined insulation	300
bitumen vapour barrier	
OSB panel	18
Laminated spruce beams	60/240
timber under construction	70/22
Plasterboard	12,5
Roof thickness	**593**
U_{roof}-value (W/m2K)	**0,11**

Figure A1. Lumar Primus system envelope for walls and roofs.



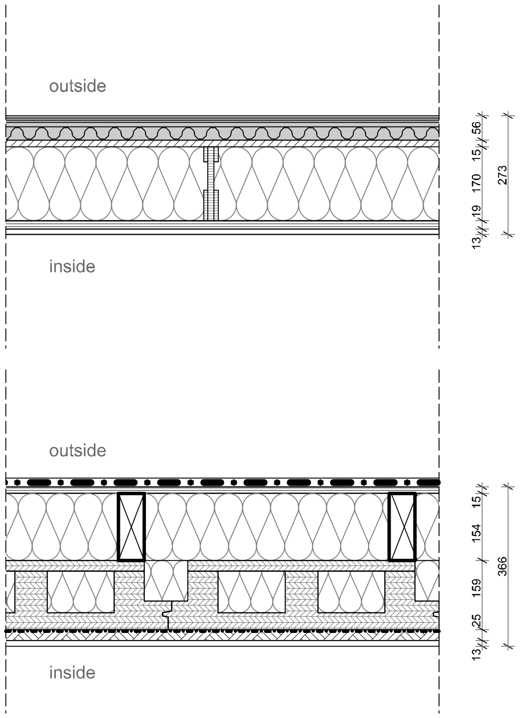
CANOPEA WALL

material	**thickness** (mm)
Plaster Thin	2
Plaster reinforcement	3
Kerto-Q LVL panel	27
Cellulose insulation & (1/2 IPE200 and timber battens 60x40)	200
OSB panel	12
Vakuum insulation	30
Vapour barrier	0.2
Proliferated steel rails	35x35
Fibralith panel	25
Earth coating	10
Wall thickness	**344**
U_{wall}-value (W/m2K)	**0,08**

CANOPEA ROOF

material	**thickness** (mm)
Polyethylene waterproofing membrane	
Wood joist + cellulose insulation	60
Kerto-Q LVL panel	25
cellulose insulation (timber 130/60)	130
Kerto-Q LVL panel	25
Vakuum insulation (timber 45/45)	45
Vapour barrier	0.2
Cellulose insulation (timber 60/40)	60
Reflective insulating screen	10
Plasterboard	12.5
Earth paintwork (Akterre)	3
Roof thickness	**370**
U_{roof}-value (W/m2K)	**0,07**

Figure A2. Canopea system envelope for walls and roofs.



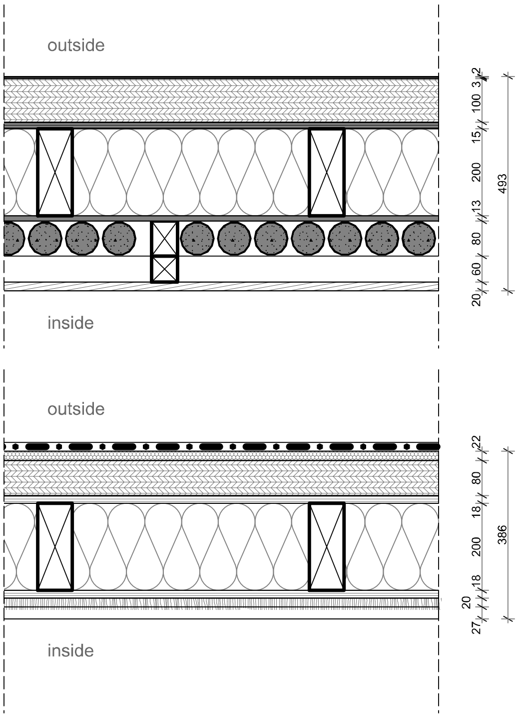
ECOLAR WALL

material	**thickness** (mm)
Lucido system	56
MDF board	15
Thermo-Hemp WCG (between Lignotrend U*PSI t 6/170 elements)	170
OSB panel	19
Plasterboard	12,5
Wall thickness	**273**
U_{wall}-value (W/m2K)	**0,10**

ECOLAR ROOF

material	**thickness** (mm)
Polyethylene waterproofing membrane	
OSB	15
Thermo-Hemp WCG 038 & (timber 160/60)	160
Thermo-Hemp WCG 038 & (between Lignotrend elements)	135
Vapour barrier	
Clay board	25
Plasterboard	12,5
Roof thickness	**366**
U_{roof}-value (W/m2K)	**0,13**

Figure A3. Ecolar system envelope for walls and roofs.



Wall (04 Med in Italy)

material	**thickness** (mm)
Plaster Thin	2
Plaster reinforcement	3
Pavatherm Plus	100
OSB	15
Pavaflex & (timber battens 200/60)	200mm
Plasterboard panel	12,5
Alu pipes (round) + wet sand	80
Timber battens 60/60	60
Solid wood panel	20
Wall thickness	**493**
U_{wall}-value (W/m2K)	**0,14**

Roof (04 Med in Italy)

material	**thickness** (mm)
Stamisol Pack 500	0,7mm
Pavatex Isolair L	22mm
Pavatherm Plus	80mm
OSB	18mm
Pavatex & (timber battens 200/80)	200mm
OSB	18mm
Cork	20mm
Gypsum Fibreboard (Farmacell)	27mm
Roof thickness	**386**
U_{roof}-value (W/m2K)	**0,14**

Figure A4. MED system envelope for walls and roofs.

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