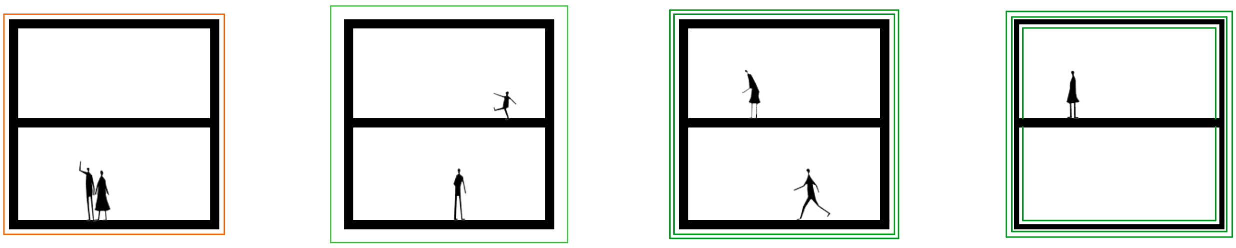
SMART ARCHITECTURE IS MORE THAN JUST TECHNOLOGY



COMPARATIVE EVALUATION METHOD FOR DIFFERENT PREFABRICATED RESIDENTIAL HOUSE ENVELOPES

Case studies of Solar decathlon Europe 2012 envelopes
compared to the reference construction system used in Slovenia

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Abstract

Technical solutions, while certainly vital, are just one of many aspects that define architecture. Technology is therefore not the principle impulse in architectural design.[1] As Le Corbusier roughly described; building is always a composite of building elements, everything is available, but it is the architect who makes the choice and is therefore responsible for architecture. He or she selects the elements and decides how they will be combined to create an architectural entity.

The residential sector in Slovenia accounts for approximately 25% of total primal energy consumption. Furthermore, single-family houses in Slovenia represent 75% of the residential sector floor area and 55% of the entire building sector[2]. Therefore, it was required to develop an appropriate design of the envelope for sustainable housing. To develop a sustainable house, means designing and using the right mix of economic, social and environmental solutions for today and for tomorrow. Therefore, the stakeholders (in residential building construction these are the owner, architect, contractor, government, and users) in the process have to decide for an appropriate envelope system that will reduce energy consumption, eliminate wastage and particularly reduce life cycle costs.

In Slovenia several companies are enhancing efficiency in residential construction by developing constructions using standardized lightweight frames and materials. These construction methods are rapidly changing construction practices in Slovenia especially due to economic, structural and environmental benefits. Since the construction of lightweight prefabricated buildings is not dependent on weather conditions and, due to the prefabrication, they can be executed extremely quickly. These construction systems are lightweight they and therefore need less materials and the result is lower environmental loads and also enhanced seismic resistance.[3] One question always remains. Which technologies will emerge from a flood of different solutions and which solution has the greatest value for stakeholders?

The purpose of this study was to use a specific economic evaluation method for construction, to evaluate the prefabricated lightweight systems and to elaborate their suitability for Slovenian residential property market. The goal was developing a comparative model for evaluation, to be used in the design phase by the stakeholder when adopting an envelope system.
Most of the researches and inventors in the field of architecture, structure, energy and cost efficiency come from Universities. For this study we wanted to evaluate future construction systems that connect research, knowledge, praxis and PR effect. Therefore, we decided to evaluate the envelope systems used for the Solar Decathlon competition and compare them to a reference system used in the Slovenian property market. The SDE is a competition

[1] Staib/Dörrhöfer/Rosenthal 2008, 10.
[2] Zavrl/Gjerkeš/Tomšič 2012, 163.
[3] Najia a.o. 2014, 727.

between solar houses, that arose with the aim of promoting sustainable development in architecture through research and innovation.
To develop an evaluation model for the envelopes, we did a research of recent studies in the field of construction system evaluation, regarding the suitability for a purpose. In general, different methods have been applied for economic evaluation or comparative analysis of different construction systems for buildings. Life cycle costing is typically used for economic evaluation of buildings and building related industry. When assessing different systems most authors apply and compare their cases to a reference basic model. From the research we could summarize that the most suitable method for a comprehensive evaluation method is the value for money method (VfM), which incorporates function and life cycle cost. Our general critic remark on existing studies is that they do not use thorough life cycle costing evaluation. They use parts of the operational costs which mostly include energy related costs, but exclude other costs like repair and replacement costs, cleaning and demolishing costs which add a considerable net value in the lifetime period of a building.

For the study we evaluated a case model, on which we applied specific envelopes chosen from Solar Decathlon competition houses and compared them with the reference prefabricated lightweight construction house system that is used on the Slovenian property market.
For the evaluation method we combined the BIM use purposes consistent with Kreider Figure 4-7 with Value for money evaluation method.
Value for money (VfM) as a concept, relates to the optimum balance between the benefits expected of a project and the resources expended in its delivery. The ratio shown in Figure 0-1-1, between benefits delivered and resources used is called the Value ratio.

$$\text{Value} \propto \frac{\text{Benefits Delivered}}{\text{Resources Used}}$$

Figure 0-1-1: The value ratio.[4]

Because in construction the use of resources often translates in use of money, is this ratio often referred to as Value for money – VfM[5].
Two kinds of software where used for the research. Initially to gather in, generate and analyze information we used BIM Software Archicad[6]. Next, further case study analysis and evaluations where done with the integrated life cycle analysis software Legep[7]. BIM software enables us to model and simulate the real construction process and its cost in a virtual environment. Energy evaluation was done directly inside the BIM program (Archicad), in which the analysis of the parametric model in terms of environmental behavior and energy consumption was done. Based on the total cost per year based calculations, resources used

[4] Dallas 2006, 14.
[5] Dallas 2006, 14.
[6] Graphisoft Inc.
[7] Weka Bausoftware Gmbh.

for the building where evaluated using Legep. This software provides the total utility of all costs.
To simplify the workflow of the case studies, we limited ourselves to a small residential house with simple functionality.

Improvements of cost effectiveness and lifetime quality of buildings is consequently of common interest for the owner, the user and society. Value for money method for buildings can therefore be an important tool for involving the construction client better in early stage design decisions.
The Value for money evaluation was done for different LCC periods. The evaluation showed how value for money of evaluated cases changes through different life cycle periods. The evaluation was done for a period of 50 years in 5 year steps, starting with the initial construction costs. The results show that in the early period after the construction, the value of the reference case is the highest. The high tech envelope with a dynamic U-value that also presented the highest investment costs had the lowest value because of the extremely high initial construction costs. The value is reduced by 26%. Our data indicates that none of the MEP (mechanical, electrical, and plumbing) variants has a higher value than reference case with the gas stove heating. From the perspective of owners/investors the reference case with the gas stove can be considered most valued. From national resources management and user perspectives we would rather suggest the reference case with the pellet stove, especially up to 20 years of usage.
The Value for money analyses, that where done according to LCC calculation based on “Steckbrief 4.1.1 (NaWoh)” with 3 different MEP systems, showed that operation costs are not dependent only on energy supply costs. The results show that supply and disposal costs for a 50-year life cycle period for evaluated cases, represent only between 18% to 28% of total operational costs.

As described the discoveries of this study were set out to explore a specific economic evaluation method for construction, to evaluate the prefabricated lightweight systems used for residential houses and to elaborate their suitability for Slovenian residential property market. The study also developed a comparative model for evaluation, to be used in the design phase by the stakeholder when adopting an envelope system to their building.

Contents

1 INTRODUCTION

This dissertation is based on case model study and deals with the influence of applying different contemporary external envelopes on a case model. Based on the analysis and findings of different cases, using a combination of Building Information Modeling (BIM) Uses and Value for Money (VfM) analysis, the aim of the dissertation is to evaluate the suitability of Solar decathlon Europe 2012 projects for use in the Slovenian residential prefabricated house market, using Value for Money method. Furthermore, we want to develop an innovative model for value assessment of different construction envelopes when being adapted to a house model in the design phase.

1.1 Problem background

Nowadays our planet is facing major environmental problems: global warming, ozone layer, waste, etc. According to research all over the world the climate is changing[8] and will continue to change. So to save our environment we have to adapt changes also and especially in construction industry, since it is a major economic and energy consumption factor in developed and developing countries[9].

The residential sector in Slovenia accounts for approximately 25% of total primal energy consumption in is required to develop an appropriate design approach for sustainable housing for current and future generations. Single-family houses in Slovenia are representing 75% of the residential sector floor area and 55% of the entire building sector[10].

Reducing energy consumption and eliminating wastage are among the main goals of the European Union. In recession times, for EU to stay competitive and to still meet the commitments made under Kyoto protocol, energy efficiency is very important. To reach this goal, more energy efficient buildings must be produced as well as energy efficient improvements must be performed on the existing building stock. With 40% of overall energy consumed in buildings, the EU has introduced legislation to ensure that they consume less energy.

A key part of this legislation is the Energy Performance of Buildings Directive (Directive 2002/91/EC, EPBD), first published in 2002, which required all EU countries to enhance their building regulations and to introduce energy certification schemes for buildings. The original Concerted Action EPBD came to a close in June 2007, but, with an implementation deadline of 2009 for Certification and Inspections, a second phase running until 2010 was launched immediately after the end of the first Concerted Action[11].

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[8] Sharma a. o. 2011, 871-5.
[9] Ortiz/Castells/Sonnemann 2009, 28-39.
[10] Zavrl/Gjerkeš/Tomšič 2012, 163.
[11] Energy performance of buildings, 09.01.2014, http://www.epbd-ca.eu, 26.9.2014

In Slovenia the adaptation of EPBD directive was brought to life with PURES 2010 (Legislation for efficient use of energy in buildings in Slovenia), which was adopted on 30th of June 2010 when the test fazes begun and is in full use since 1.1.2011. The use of this legislation is obligatory. A part of the legislation is also a technical guidance for achieving minimal demands of PURES 2010. It covers all 3 fazes: building design, construction and maintenance.[12]

With the adoption of the recast EPBD in 2010 (Directive 2010/31/EU), EU Member States faced new tough challenges. The Directive 2010/31/EU (EPBD recast) Article 9 namely requires that “Member States shall ensure that by 31 December 2020 all new buildings are nearly zero-energy buildings; and after 31 December 2018, new buildings occupied and owned by public authorities are nearly zero-energy buildings”. Furthermore, Member States shall “draw up national plans for increasing the number of nearly zero-energy buildings” and “following the leading example of the public sector, develop policies and take measures such as the setting of targets in order to stimulate the transformation of buildings that are refurbished into nearly zero-energy buildings”.

A nearly zero-energy building is defined in Article 2 of the EPBD recast as “a building that has a very high energy performance. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby”[13].
A very important part of such directive is the exchange of experiences with already existing high performance buildings (ranging from low energy buildings to passive houses, zero-energy and zero-emission buildings, and even to energy surplus houses).

One question always remains. Which technologies will emerge from a flood of different solutions for energy efficient buildings and even more for “Zero energy” and “Plus energy” buildings? This is not only success dependent, mostly it depends on budget and politics. Politicians make funding happen, so they actually decide which technology will have a market advantage. At the moment wooden construction is heavily promoted by the Slovenian government.

However, technical solutions, while certainly vital, are just one of many aspects that define architecture. Technology is therefore not the principle impulse in architectural design.[14] As Le Corbusier roughly described; building is always a composite of building elements, everything is available, but it is the architect who makes the choice and is therefore responsible for architecture. He or she selects the elements and decides how they will be combined to create an architectural entity.

[12] Glusic, Anja: Pravilnik o energetski učinkovitosti stavb, 22.08.2011, http://www.enforce-een.eu/slo/pures-2010/pravilnik-o-energetski-ucinkovitosti-stavb, 26.9.2013
[13] Maldonado et.al. 2013, 47.
[14] Staib/Dörrhöfer/Rosenthal 2008, 10.

Several companies in Slovenia are enhancing efficiency in residential construction. They have developed constructions using standardized lightweight frames and materials. These construction methods are rapidly changing construction practices in Slovenia especially due to economic, structural and environmental benefits.

The construction of lightweight prefabricated buildings is not dependent on weather conditions and, due to the prefabrication, are executed extremely quickly. The large wood panel elements which are the basic building elements of such houses are produced in production halls in all seasons of the year and also in winter. This type of construction does not require a drying phase and allows very precise planning, a clear determination of the duration of the individual construction phases and therefore also the exact date of clients to move in. Since these construction systems are lightweight, they need less materials and therefore result in lower environmental loads and also enhanced seismic resistance.[15]

Moreover, quickness means economic efficiency because moving in quickly will reduce or even dissolve numerous costs. It is also possible to adapt the level of completion of such buildings. The building can have a finished shell, which allows the owner to gradually complete the interior with more participation of the owner. It is common to get a turn-key house ready for occupation, which enables the client to move in quickly without major commitment and additional work.

State of the art research

The purpose of this study is to use a specific economic evaluation method for construction, to evaluate the prefabricated lightweight systems used in SDE2012 houses and to elaborate their suitability for Slovenian residential property market. The goal is developing a comparative model, to be used in the design phase by the stakeholder when adopting an envelope system. Therefore, a research of recent studies in the field of construction system evaluation, regarding the suitability for a purpose, is done.

Tam et.al.[16] provided a feasibility analysis in adopting prefabrication in construction activities in their study Towards adoption of prefabrication in construction. They state that the current implementation of prefabrication is unable to provide satisfactory results to the construction industry. Based on a questionnaire survey, the advantages, hindrances and future development on prefabrication's applications are provided. They also analyzed the suitability of prefabrication of various project types. Furthermore, they did a financial analysis on a local case study. To examine the significance of benefits in applying prefabrication they considered that the benefits have different levels of significance to construction businesses. The main focus of the survey was to identify the level of recognition of these beneficial aspects. Authors applied five significance levels for their survey: least significant, fairly significant, significant, very significant and extremely significant. The survey results are

[15] Najia a.o. 2014, 727.
[16] Tam et.al. 2007, 3642-3654.

summarized in Figure 1-1. Their results show that for the respondents the most valued benefit of applying prefabrication are better supervision and frozen design at the early stages.

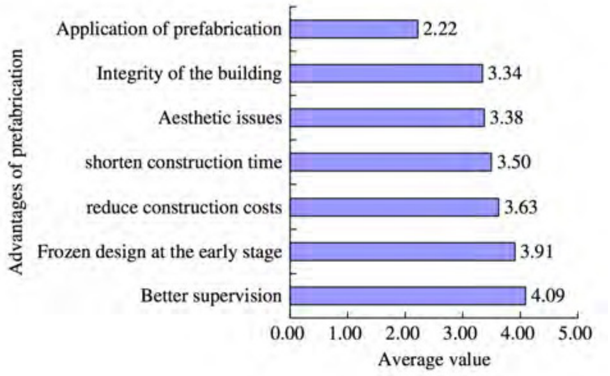

Figure 1-1: Advantages of applying prefabrication.[17]

They conclude that waste management is becoming an important issue in the construction industry and prefabrication provides a better solution to the problems of huge waste generation on site. They claim that with adaptation of prefabrication the wastage generation can be reduced up to 100%, in which up to 84.7% can be saved on wastage reduction. Furthermore, the state that the adoption of prefabrication has potential in the construction industry and that it can lead to achieving better environment and quality. Moreover, according to authors, even if the initial construction cost is higher, long-term construction costs can be reduced.

A research to determine the sustainability of prefabricated buildings by studying the economic, environmental and social impact of the methods of prefabrication used in their construction, was preformed by Pons in 2014.[18] The study used the integrated value model for sustainable assessment (MIVES), a multi-criteria decision-making method that includes value functions for assessment of prefabricated schools. Finally, they presented recommendations and future trends. According to the study[19], despite the environmental challenges, only some new buildings have reflected the new environmental awareness, and even fewer have taken into account other types of economic and social impact. Therefore, they state that buildings constructed using prefabricated technologies, have a rationalized life cycle process and therefore have less environmental impact, due to reduction in consumption. Further they claim that prefabricated technologies are a part of industrialized construction, produced by the industry. For the research a classification of structural prefabricated technologies was done as shown in Figure 1-2.

[17] Tam et.al. 2007, 3644.
[18] Pons 2014, 434-456.
[19] Pons 2014, 434.

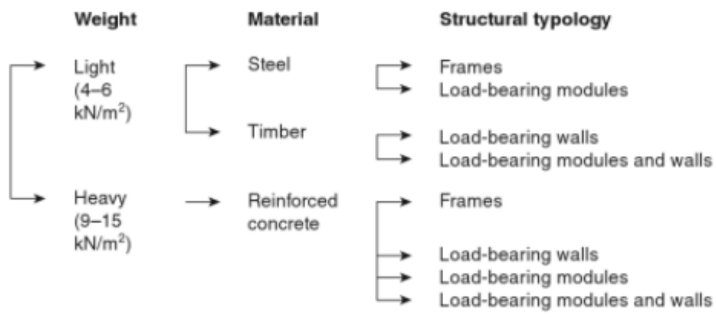

Figure 1-2: Classification of the structural prefabricated technologies for the case studies in research.[18]

Finally, the authors recommend following when considering prefabricated or non-prefabricated system for a construction:

- The most sustainable prefabricated technology will critically depend from the distance between factory and construction site
- Some non-prefabricated technologies are more suitable than prefabricated ones (e.g., if construction time is not critical, if main parameter is initial cost)
- In the future it is expected that industrialized technologies will be most sustainable as long as their costs and logistics of production are rectified.

Rakshsan[20] et. al. evaluated the sustainability impact of improved building insulation on a case study in the Dubai residential built environment. Although the “cradle to grave” analysis increases understanding an environmentally sustainable building creation, in commercial real estate the focus is generally on reducing cost, while long term operational and end-of-service considerations remain unconsidered. Consistent with authors the balance between initial costs and operational costs is directly reflected in the building energy use. For the method the study evaluated the trade-off between the operational CO2 emissions saved by improved thermal efficiency from additional wall insulation thickness, and the CO2 entered to the atmosphere for the production, transportation and disposal of the same amount of insulation. They indicate that due to typically short building lifetime and lack of comprehensive waste management strategies, the overall impact of using insulation materials within the full lifecycle of the Dubai built environment requires special consideration to end-of-service treatment.

Another study by Mateus et. al.[21] assessed the sustainability of innovative lightweight building technology for partition walls, which were compared with conventional technologies. According to the study the growing necessity to save resources, the environmental issues and uncertainties on the evolution of the economy, have impelled minimalist approaches to Architecture and Engineering. The paper presents a sustainability assessment with the use of a methodology that comprises the environmental, functional and economic life-cycle analysis. The comparative evaluation of new technologies is based on a standard Life-cycle

[20] Rakhshan 2013, 105-110.
[21] Mateu et. al. 2013, 147-159.

Assessment method and a multi-criteria decision support method for an integrated analysis of the used sustainability indicators. According to authors to be able to identify the advantages of the building technology under development, the design approaches assessment had to be compared to reference in conventional technologies. Although they conclude that new technologies are more sustainable, they propose to include other life-cycle stages, like the maintenance, and the use of the specific Life Cycle Inventory (LCI) data from the chosen producers, for future evaluation.

Matic[22] et.al. did an economical feasibility study on energy refurbishment of prefabricated building in Belgrade, Serbia. The main objective of the research was to evaluate the integrated design strategies applied in refurbishment of the prefabricated residential housing, erected in ′ 70 in the New Belgrade. According to authors, the investment in energy efficiency retrofitting, can improve macroeconomic stability and contribute to the sustainable economic growth. They preformed economic analyses for each case study, considering present economic situation in Serbia and availability of funds for refurbishment. Feasibility of refurbishment was perceived and analyzed within the existing economic outlook of Serbia. The study applied two distinct financing models. One where owners bear the entire cost of the retrofit and the other where a commercial loan facility is used. Furthermore, they also considered a government subsidy. The calculations that were done for savings as the outcome of the retrofit, were calculated solely as the reduction in the heating energy bill. The authors used following economic methods for analysis of the retrofit measures: The Net Present Value (NPV), the Simple Payback period (SPB) and the Depreciated Payback Period (DPB). The results of the study demonstrate that according to economic analysis of the presented model, their proposed energy-efficient actions are all feasible.

Cabeza[23] et. al. did a review of Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector. As they state in the research, LCA methods have been applied in the development process in building sector as state of the art method for the last 10 years (2014) opposed to LCA application in other industries. As they further present, a growing body of literature is developing and employing LCA methods in performance evaluation of buildings, in their design and construction. As said by authors also the life cycle cost analysis (LCCA) method is widely used for assessing total cost of facility. They quote the National institute of Standards and Technology, which defines life cycle costs (LCC) as “the total discounted dollar cost of owning, operating, maintaining and disposing of a building or a building system” over a period of time. LCC is considered an economic evaluation technique, which can be performed on large or small buildings or isolated building systems. They further state that many apply the LCC method in decisions regarding construction or improvements to a facility. One of the most important finding of their research for our study is that they conclude that the operational phase contributes more than 80-85% share in the total life cycle energy of buildings. Therefore, they suggest that future efforts should focus on reducing the operational phase, even on the cost of other less significant

[22] Matic 2015, 74-81.
[23] Cabeza et. al. 2014, 394-416.

phases. LCCA of buildings are according to authors more difficult to evaluate. They are large in scale, complex in materials and function. Moreover, they are temporally dynamic due to limited service life of building components and changing user requirements. Additionally, their production processes are much less standardized than most manufactured goods, because of uniqueness. They conclude, that though the LCA and LCCA methods usage for buildings is scattered in literature, both methods have recently been used for similar purposes in building sector.

Leckner and Zmeureanu[24] analyzed life cycle cost and energy consumption of a Net Zero Energy House with a solar combisystem, for a climate in Montreal, Canada. The total annual energy use was estimated using TRNSYS simulation software. As presented in the study the life cycle cost method looks at the economics over the life of a product. According to authors, for such an analysis it is very important to make every effort to compile accurate and realistic prices. To evaluate the financial payback for different changes to the house model they used two methods. First was the simple payback method which does not consider the time value of money, the effective interest rate, rising energy prices or the replacement cost. Second method used was cumulative cash flow method, which is similar to the life cycle costs method. They compared the results of both methods. The authors concluded that there are financial benefits of making the house more energy efficient. However, they claim that it is unlikely that average homeowner would accept the additional expanses for the construction of a NZEH presented in their study.

Hasan et. al.[25] did a research on minimization of life cycle cost of a detached house using combined simulation and optimization. For the minimization method they used an implemented approach in coupling the IDA ICE 3.0 building performance simulation program with the GenOpt 2.0 generic optimization program. The goal was to find optimized values of five selected design variables in the building construction and HVAC system. These variables are insulation thickness of the external wall, roof and floor, U-value of the windows and type of heat recovery. According to authors the designers should increasingly use simulation tools instead of guessing, when deciding on building envelope improvement. For their energy calculations they considered their house model as a single zone, which was still accurate enough, but simplified the simulation. Further they used a reference case for their case study, with a typical Finnish construction and initial U-values in accordance with the Finnish National Building Code C3 of 2003. As said by authors, when the objective is to reduce total building cost during its lifetime, the life cycle cost of the building is to be studied. For their study they simplified the LCC calculations, by including only the difference produced by the variation of specified parameters between the reference case and any other case. Moreover, they assumed that the maintenance cost is constant, nonetheless they considered different replacement costs depending on the life span of a system. They calculated the LCC to the present value. For the lifespan the authors used two variables, 50 years and 20 years. For the energy price inflation, they used two values 1% and 5% and studied two real interest

[24] Leckner/Zmeuranu 2011, 232-241.
[25] Hasan/Vuolle/Siren 2008, 2022-2034.

rates, 2.94% and 4.90%. Additionally, they used two different locations. Furthermore, for the investigation they used fixed internal dimensions of the house. Adding exterior layers did not affect the interior volume of the study. They came to conclusion that a significant reduction of 23–49% in the space heating energy for the optimized house is obtained compared with the reference case. However, the results depend on interest rate and energy price inflation values.

Najia[26] et. al. evaluated structure, energy and cost efficiency during useful life of three different lightweight construction systems used in low-rise residential buildings in Turkey. The three system are wood light frames (WLF), lightweight steel frames (LGSF) and 3D sandwich (3DSP) panels. The main objective of the study was to evaluate, as stated by authors, three main efficiency aspects: structural behavior, energy consumption and constructional cost for three main materials for residential building (wood, steel and concrete). For the method of the study, they used a residential sample building with two floors and applied all three construction systems to it. For the structural analysis and design the authors used ETABS software while for the analysis of the energy consumption EnergyPlus was used. For the energy model Sketchup 3D drawings of the sample building were transferred into EnergyPlus. They studied the annual energy demands for all three systems for their energy evaluation. According to authors the economic issues and saving money are among the most important challenges in all aspects of human life. Therefore, it was important for them to discuss the construction cost of each structural system and to acknowledge that the construction and energy costs are based on local aspects. Consequently, the cost for each alternative structural system differs and depends on the country in which it is constructed. They conclude their economic evaluation with the outcome that cost of construction for 3DSP construction is 34.6% lower than WLF and 27.7% lower than LGSF. Moreover, the 3DSP designed building requires 11% less energy for total heating and cooling during one year. As an overall evaluation for for Istanbul the study recommends the usage of 3DSP, due to high seismic risks in Istanbul. As said by authors, 3DSP provides seismic resistance, its thermal convenience is easier and more economical.

In 2015 Lee[27] et. al. did a comparative analysis of energy related performance and construction cost of external walls in high-rise buildings. The research was intended for stakeholders, when deciding to adopt the proper external wall system by considering energy performance. The purpose of this study was to evaluate the energy related performance and construction cost of external walls in high-rise residential buildings. The different external walls were staple external walls, using reinforced concrete (RC), glass fiber reinforced concrete (GFRC) and cellulose fiber reinforced cement (CFRC). All the wall systems had the same doors and windows in their bodies for equal comparison of energy efficiency and construction cost. This study was most influential for the method of our research, because it uses value for money method for the evaluation. The research used the function of a residential building space that provides same level of service to inhabitants however, this

[26] Najia et. al. 2014, 727-739.
[27] Lee/Kim/Na 2015, 67-74.

service has different costs of creating and maintaining the space, depending on construction material used, which results in change of value. According to authors, the value for money evaluation, was done in three phases. First the function setting was implemented (a space with same level of function, cooling and heating services). Second, a cost analysis was performed to compare the construction cost of each reference. Third, operational costs where quantified (heating and cooling, energy cost inflation). Finally, they compared and evaluated overall results. To analyze the energy performance, they created Model IT to create basic model building configuration, then they calculated the heating and cooling loads with the Apache-sim and used IES_VE software for the energy performance simulation. As already explained function and cost were needed to determine the VFM of each external wall type. According to the research the functions of space of a residential building are identical, they provide space for rest and safety. The construction and operation costs incurred in creating space differ among external wall types applied to the case study. The difference in construction costs is because of the difference in material and labor costs. For the operation cost, heating and cooling costs vary depending on the energy performance of the external walls. Therefore, the VFM analysis was carried out by first evaluating the function of the space, next determining the LCC of each wall, and then evaluation. The value assessment considering the LCC revealed that different stakeholders (in residential building construction these are the owner, architect, contractor, government, and users) had different opinions with regard to value depending on their phase of involvement, regardless of material efficiency. According to authors, the development of materials that satisfy LCC requirements and minimize the amount of energy used will be encouraged in considering the energy performance and cost of external walls. They state that their study can be used as the basis for further simulation studies to easily and quickly calculate the LCC or VFM in cases of design change.

1.2 Statement of the problem

To answer the question, which technologies will emerge from a flood of different solutions for energy efficient buildings, in our study we want to evaluate future construction systems that connect research, knowledge, praxis and PR effect. One competition that connects all these topics and combines researches and investors is Solar Decathlon. This competition between solar houses arose with the aim of promoting sustainable development in architecture through research and innovation, and raising public awareness about the importance of protecting the environment and fostering sustainability in construction work and also being market viable. Its origins come from America where the department of Energy of the North American government created the US DOE Solar Decathlon competition in 1999, and its first edition was held on the National Mall in Washington DC in 2002. It is a biannually event. Furthermore, the main objective for the houses built for Solar decathlon competition is to design and build houses that consume as few natural resources as possible and produce minimum waste products during their life cycle. Particular emphasis is put on reducing energy consumption and on obtaining all the necessary energy from the sun. The houses also have to be prefabricated and built on site by students in 3 days. The prototypes must upon others have efficient construction with simple joints, future proof an energy performing skin, architectural appeal and also must be market viable. The focus of the energy performance analysis of the houses is on reduction in energy consumption, and not on the analysis of the energy production systems or the strategies of the houses.

For clients most commonly, initial construction cost is the main aspect in construction. This initial cost is often set to the minimum, which does not necessarily improve the lifetime performance of buildings[28]. However, it is estimated that initial costs of a building represent less than 30% of the total life-cycle cost of a building[29]. This is significantly important for the investors in perspective of total cost and the value of investment[30]. For the Value for Money method, a higher production cost might decrease total life cycle cost (LCC) and so increase Buildings Value. Therefore, it is important to show the client, already in design phase, the relationship between design choices and the resulting Value for Money. Additionally, Value for money method is not restricted to specific types of projects[31] and is recommended to be implemented in building construction[32]. Nevertheless, Norton[33] identified different types of projects that benefit the most from value management and one of them is *repetitive projects*. For repetitive projects it is common that same or similar type of building or construction needs to be build in many different locations. Here the utilization of value for money method becomes very effective, because improved value can be incorporated into all buildings to be built later on.

In general, different methods have been applied for economic evaluation or comparative analysis of different construction systems for buildings. Life cycle costing has been used for economic evaluation of buildings and building related industry (including construction systems) through a very scattered literature. Most recently LCC in construction has been used for evaluation purposes of different systems. When assessing different systems most authors apply and compare their cases to a reference basic model. From the research we can summarize that the most suitable method for a comprehensive evaluation method would be the value for money method, which incorporates building function and life cycle cost. However, no study has combined both concepts in a comprehensive way. Although some of the studies Lee[34] et. al., Hasan et. al., Leckner and Zmeureanu[35] and Matic[36] et.al. used either LCC partly or operational costs partly, this existing studies did not use thorough LCC including all operational costs. They have used parts of the operational costs which mostly include energy related costs, but excluded other costs like maintenance, service and replacement costs, cleaning and demolishing costs which add a considerable net value in the lifetime period of a building. This study will therefore seek to fill the gap by studying LCC and VfM evaluation methodology and develop a comprehensive evaluation method.

[28] Schade 2012, 321.
[29] Far/Pastrana/Duarte 2015, 1.
[30] Far/Pastrana/Duarte, zit. n. Schulte 2008
[31] Rangelova and Traykova 2014, 432.
[32] Oke/Aghimien/Olatunji 2015, 55.
[33] Norton et al. 1995, 18.
[34] Lee/Kim/Na 2015, 67-74.
[35] Leckner/Zmeuranu 2011, 232-241.
[36] Matic 2015, 74-81.

According to the survey done for research VFM and Risk Allocation Models in Construction PPP projects, two highest risk allocations in Private sector are Construction time delay (97,6%) and Higher Maintenance costs (97,5%)[37]. Therefore, the aim of this research to assess value using Value for money method, with Life Cycle Costs (maintenance costs) as the main parameter, and to evaluate prefabricated construction envelopes (controlled construction time) is additionally confirmed.

1.3 Research objectives

In order to address the problem statement discussed above; the objectives of the study are as follows:

1. To use a specific economic evaluation method for construction to determine if the prefabricated future lightweight construction systems and envelopes used in SDE2012 for residential houses are feasible for Slovenian residential property market.
2. To develop a comparative model for evaluation, to be used in the design phase by the stakeholder when adopting an envelope system to their building.

1.4 Research questions

To achieve the set objectives of this research further questions are being asked to guide the literature review, information gathering and the rest of the research activities:

1. Are future construction systems and envelopes that connect research, knowledge, praxis and PR effect in form of Solar decathlon Europe 2012 competition suitable for the Slovenian prefabricated house property market?

2. Can stakeholders, already in the design phase, use an effective economic evaluation method when deciding for a construction system?

1.5 Significance of Study

Improvements of cost effectiveness and lifetime quality of buildings is consequently of common interest for the owner, the user and society. Value for money method for buildings can therefore be an important tool for involving the construction client better in early stage design decisions and consequently improving the value of a building by reducing life cycle costs.

[37] Li/Akintoye/Hardcastle 2002, 20.

1.6 Research methodology

The purpose of this study is that future stakeholders can apply our developed method already in the design phase when deciding for an economically suitable envelope for their house. Since the evaluation process itself is very complex, several research steps have to be performed.

First step is a preliminary study, a research and analysis of Slovenian residential market, energy concepts in Slovenia and its legislative framework, energy efficiency classifications and basic principles of prefabricated construction systems.
Solar Decathlon Europe 2012 competition, its selected case models and the reference model for Slovenian property market, are analyzed in the *second step*.
Third step is a research of the Value for Money (VfM) method in construction, basic principles of the Life Cycle Costing and the overview of the BIM use purposes used for this study. It is followed by the development of the evaluation model which can easily be applied, to value future prefabricated lightweight construction systems for residential houses, according to VfM.
If feasible in *fourth step*, the final aim of the dissertation has to be attained, which is the VfM evaluation of the SDE2012 construction systems and their feasibility for Slovenian property market.

1.7 Outline of the dissertation

The dissertation consists of six chapters.

In **Chapter 1**, the base concept of the thesis with the up-to-date data of existing research in the field of construction system evaluation, regarding the suitability for a purpose, is introduced. The main aims and objectives of the thesis are introduced as well.

In **Chapter 2** Slovenian property market is researched through the analyses of the yearly report[38] which is done on a six-month basis by the Surveying and mapping authority of the republic of Slovenia. The first goal is finding input parameters for the residential house case study model. Since LCC costs are main parameter for value for money evaluation in construction and almost 30% of all buildings operating costs represent the energy costs[39] legislation framework relating to energy efficiency of buildings in EU and Slovenia is shortly presented and different classifications or definitions of energy-efficient houses. Further we describe the difference between industrialization and prefabrication and present an overview of prefabricated lightweight construction systems.

Envelope case studies and Solar decathlon competition are introduced in **Chapter 3.** Following contests out of ten are evaluated for the analysis of SDE2012 houses:

[38] Annual report on the Slovenian property market for 2014
[39] Bright Green Builings 2008, 6.

architecture, engineering and construction, energy efficiency, industrialization and market viability and innovation. For the research it is important that the houses have an architectural appeal, that is why architecture as category is considered the most important parameter. Five projects which scored highest in the five categories are further evaluated for the use as case study envelopes. Further we present the prefabricated lightweight construction house system that is used as a reference model for the researched case studies.

Research methodology is presented in **Chapter 4**. First we present Value for money method usage in construction and life cycle cost evaluation. For the methodological approach of this study, the BIM Use method and its BIM Use Purposes[40] are used as presented in Chapter 4.2. Five primary categories of the purposes and objectives are used[41]: gather, generate, analyze, communicate, and realize. Further it is developed into an innovative method using LCC software and VfM for assessment of prefabricated lightweight construction envelopes. Supplementary the base case-study model is described with all parameters: plan, construction, windows, location, orientation and climate data, shading, internal gains, active technical systems, parameters varied and the object of the research. Further, we also present the software (Legep and Archicad) that is used for this research. Finally, the economy aspects that are used for this study, are described.

Value for Money evaluation of selected systems on a case study simulation model is done in **Chapter 5**. To elaborate the value of construction systems, a BIM model of the sample house is created with Archicad. Each of the construction systems of selected SDE2012 houses is applied on the simulation model with following fixed parameters: Foundation plate, Roof, Interior walls, Openings, Location (Climate), Orientation and Function. A BIM model is created for each of them and then upgraded to BEM. Following life cycle costs are estimated using LCC method in LEGEP software. Results are then evaluated according to Value for money and compared to determine the value of each system.

The conclusion with thoughts on future practices and researches are summoned up in **Chapter 6**.

[40] Kreider/Messner 2013, 6.
[41] Kreider 2013, 6.

2 PRELIMINARY STUDY

In this chapter the currents situation in the Slovenian residential market is presented with a research of the Statistical yearbook of the republic Slovenia. The goal is to find parameters for the case study residential house. Next the legislation framework relating to energy efficiency of buildings in EU and Slovenia is shortly presented and basic principles of energy efficiency are introduced. As our research is devoted to prefabricated houses, we describe the basic principles of lightweight construction systems used for residential houses in the final subchapter.

2.1 Slovenian property market

In following chapters Slovenian property market is researched through the analyses of the yearly report[42] which is done on a six-month basis by the Surveying and mapping authority of the republic of Slovenia.

2.1.1 Analysis of the Statistical Yearbook of the Republic Slovenia

The data that is analyzed for this chapter is taken from the the Surveying and Mapping Authority of the Republic of Slovenia who writes regular semi-annual and annual reports with statistical indicators of real estate prices and real estate transactions in the Slovenian real estate market. These reports are in accordance with the Real Estate Mass Valuation Act – ZMVN[43] and the Rules on the method of calculating annual real estate price indices and on the method of determining real estate value indices[44].

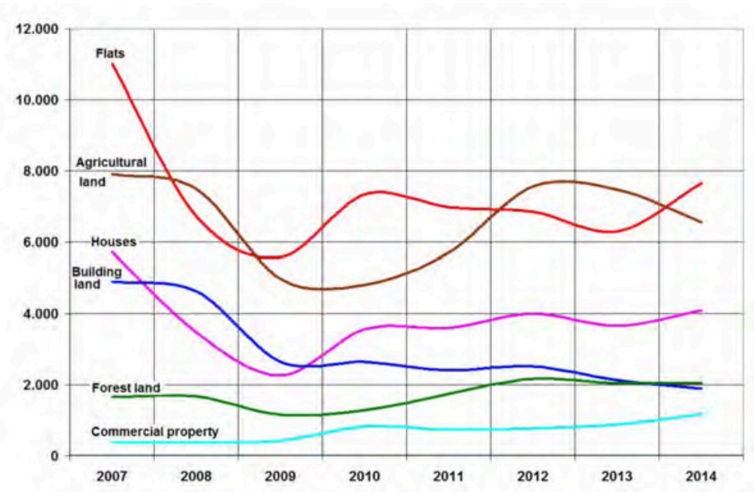

Figure 2-1: Number of recorded property sales, Slovenia, 2007–2014[45]

[42] Annual report on the Slovenian property market for 2014
[43] Official Gazette of the Republic of Slovenia, nos. 50/2006, 87/2011 and 40/2012 – ZUJF (Fiscal Balance Act)
[44] Official Gazette of the Republic of Slovenia, no. 4/2013
[45] Annual report on the Slovenian property market for 2014, 8.

As seen in Figure 2-1 since 2007 the property market decreased rapidly in Slovenia including the house market. The total number of recorded sales of flats and houses was in 2014 still 30% lower compared to the pre-crisis year of 2007. At the end of 2013, it appeared that the downward trend in the sales of residential property was intensifying and that in 2014 the crisis of the Slovenian property market would hit a second nadir[45]. However, the opposite happened. Sales of flats and houses rose substantially and even reached the highest point since 2009. In 2014 82% more houses where sold than in 2009 after the property bubble burst. However, the sales of houses were still 28% lower than in 2007.

For the fifth year in the row the prices for flats were falling in Slovenia in 2014 and according to GURS data the average price per square meter of usable area for a flat was 1460 EUR in 2014. This is the smallest value since 2007 and is 20% lower than the highest level in 2008.

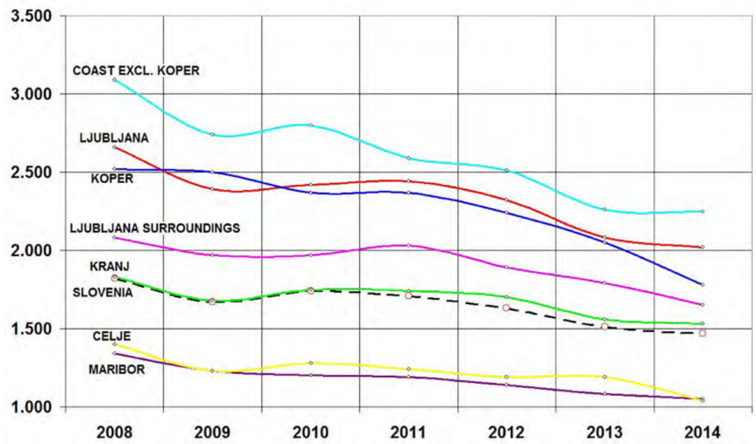

Figure 2-2: Movement oft he average prices of flats (EUR/m^2), Slovenia, 2008-2014[46]

The highest prices for flats are in Ljubljana (2020 EUR/m2) and in costal area – excluding Koper (2250 EUR/m2). Maribor, which was used as location for the case study is slightly under average with prices holding at around 1050 EUR/m2 which is 22% below the highest value in 2008. In the past two years, Maribor has seen the smallest fall in prices among all areas considered.

The number of submitted building permission is showing a big decline of big property projects wit record lows. New buildings are risky and not market viable in current economic conditions. All of this is understandable because of the current global but especially domestic economy situation, with purchasing power declining and credit crunch looming over investors.

Looking at the value declination in last period we can establish that the price has stabilized in the smaller markets like the cities of Maribor and Celje, however on high priced property markets like Ljubljana and costal area there is still room for the property prices to drop.

[46] Annual report on the Slovenian property market for 2014, 23.

2.1.2 Maribor and surroundings

After two years of decline in Maribor, which was used as location for the case study, the sales of flats finally slightly picked up. The average price of a resale flat was EUR 1,050/m2, which indicates that the prices are gradually stabilizing. There is almost no supply of new flats in Maribor. However, the sales of one- and two-dwelling houses increased considerably compared to the year 2013. In 2014, nearly 30%[47] more transactions were recorded in Maribor. In the surrounding areas, where sales almost came to a halt in 2013, they increased by almost three-quarters. The downward trend in the prices of houses with associated land, which started after 2008, was halted in Maribor but continued in the surrounding areas.

An important parameter for this research is the fact that the number of submitted building permissions for one-dwelling houses is increasing significantly. This fact is directing us to the assumption that in current harsh economic times people are vastly turning them into self-investors or even do-it-yourself builders which is also showing in the decline of the flat market.

2.1.3 Houses

At the end of 2014, approximately 530,000 housing units in single- and two- dwelling houses were recorded in Slovenia. This is a top ranking in Europe (houses per habitants). The residential units in houses accounted for 60%[48] of the housing stock and those in multi-dwelling buildings for 40%. The houses being sold are mostly detached houses (79%)[48], 12% of them are terrace houses and 8% semi-detached houses.

Analytical region	Indicator	2008	2009	2010	2011	2012	2013	2014
SLOVENIA	Size of sample	1688	1293	1964	2059	2162	1750	2144
	Average contract price (EUR)	144.000	128.000	124.000	120.000	119.000	114.000	105.000
	Year of construction (median)	1969	1972	1971	1970	1970	1971	1971
	House floor area (m²)	143	142	141	141	145	147	151
	Land area (m²)	1050	1140	930	1090	1110	1050	1050

Figure 2-3: Average prices and structures of houses sold, 2008-2014[49]

The case study for this research is a one-dwelling house. According to the data presented in Figure 2-3 in the last 18 months the houses which were sold on the property had a price average of 105000 EUR. The values are 37% lower then the highs from 2008. In Maribor, the price of an averagely maintained 160 m^2 house with over 500 m^2 of associated land, built around 1970, was slightly less than EUR 110,000, i.e. around the same level as the year before. In the surroundings of Maribor, the price of a 35-year old house of 155 m^2 with 1,250 m^2 of associated land was on average EUR 88,000.[50]

[47] Annual report on the Slovenian property market for 2014, 18.
[48] Annual report on the Slovenian property market for 2014, 25.
[49] Annual report on the Slovenian property market for 2014, 26.
[50] Annual report on the Slovenian property market for 2014, 28.

As shown in Figure 2-4 Ljubljana (Central Slovenia) has the highest valued property, which is much higher then the rest of Slovenia excluding coastal area. Even though the prices in the house market tend to fluctuate we can still see a trend off falling values in all urban central areas around the country.

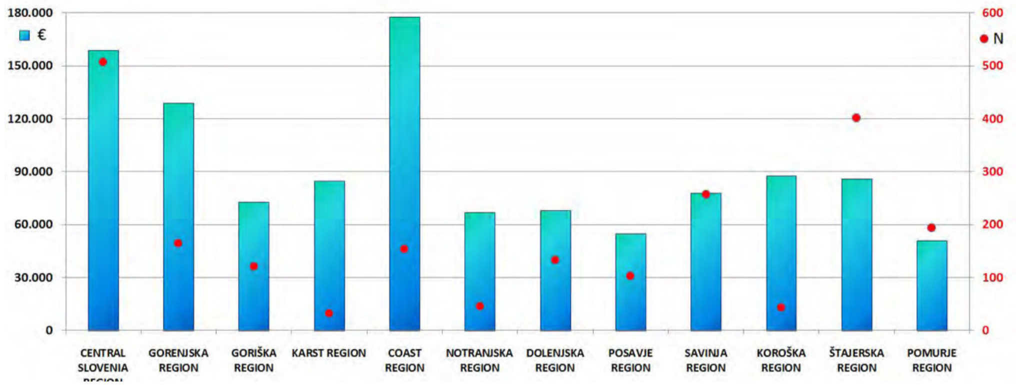

Figure 2-4: Average prices of houses with associated land (in EUR) and the number of sales taken into account by analytical region, 2014[51]

The average floor area of the sold houses was 151 m2 with an average area of associated land of 1050 m2. Both area sizes are staying mostly unchanged over last couple of years.

According to report evaluation we are coming to a conclusion that in the near future Slovenian market will be open for small self-investors or DIY builders concentrated towards low budget houses that due to legislative energy demands have to be good low energy houses. National average house floor areas (brut) are 150 m2, including storage spaces (basement and/or external storage). For further research it is important that the average price paid for a house, with an average of 560 m^2 of land, is 108000 EUR in Maribor and 88000 EUR in its surroundings.

2.2 Towards nearly zero energy concept in Slovenia

Buildings account for around 40% of total energy consumption and 36% of CO2 emissions in Europe[52]. For reducing energy dependency and greenhouse gas emissions important measures have to be taken in the building sector. Up to 80% of the operational costs of standard new buildings can be saved through integrated design principles, often at no or little extra cost over the lifetime of the measure. The Directive on the energy performance of buildings (EPBD) demands that by 2020 all new buildings constructed within the European Union after 2020 should reach nearly zero- energy levels. That is why all new buildings will have to demonstrate very high energy performance. Their reduced or very low energy needs will be covered by renewable energy sources.

[51] Annual report on the Slovenian property market for 2014, 27.
[52] Boermans et.al. 2011, 3.

2.2.1 Legislative framework

Reducing energy consumption and eliminating wastage are among the main goals of the European Union (EU). To meet the commitments on climate change made under the Kyoto protocol EU has introduced legislation to ensure that buildings consume less energy than they do now (accounting to 40% of energy use).[53] The improvement of energy efficiency has to succeeded with cost-effective measures.

A key part of this legislation is the Energy Performance of Buildings Directive (Directive 2002/91/EC,EPBD)[54], first published in 2002, which required all EU countries to enhance their building regulations and to introduce energy certification schemes for buildings. National laws were introduced to meet the EU requirements which was very challenging, as the legislation had many advanced aspects.

The original Concerted Action EPBD came to a close in June 2007, but, with an implementation deadline of 2009 for Certification and Inspections, a second phase running until 2010 was launched immediately after the end of the first Concerted Action. When initiated in 2005, most countries were still at the planning stage. After stimulating advancement and convergence across the EU, the approach was enhanced in 2007.

In 2009 the EU adopted a wide-ranging package on climate change. The package focuses on three areas: emissions cuts, renewables and energy efficiency. The overall 20-20-20 targets have been kept: a 20% cut in emissions of greenhouse gases by 2020, compared with 1990 levels a 20% increase in the share of renewables in the energy mix and a 20% cut in energy consumption. The climate and energy package is a set of binding legislation which aims to ensure the European Union meets its ambitious climate and energy targets for 2020 (Citizens' summary EU climate and energy package).

The adoption of the recast EPBD in 2010 (Directive 2010/31/EU), all EU Member States faced new tough challenges. Foremost among them, moving towards new and retrofitted nearly-zero energy buildings by 2020 (2018 in the case of Public buildings), and the application of a cost-optimal methodology for setting minimum requirements for both the envelope and the technical systems. [55]

2.2.2 EPBD implementation in Slovenia

"In Slovenia, the implementation of the Energy Performance of Buildings Directive (EPBD) is the overall responsibility of the Ministry of Infrastructure and Spatial Planning. The EPBD was transposed into the national legislation by the Building Construction Act, the Environmental Protection Act, and the amended Energy Act (on the 17th of November 2006).

[53] Energy performance of buildings, 09.01.2014, http://www.epbd-ca.eu, 26.9.2014
[54] Young 2012, 21.
[55] Maldonado 2013, 37, 47.

The secondary regulation on new minimum requirements, calculation methodology, feasibility studies and regular inspection of air-conditioning (AC) systems was promulgated in 2008, while the regulation on Energy Performance (EP) certification was accepted in 2009. The training and licensing of independent experts working on the building EP certification and AC systems inspection, as well as the protocols related to the certificates registry, were defined in detail in the 2010 Regulation. The regular inspection of boilers was implemented by an existing scheme, upgraded in November 2007.
Slovenia implemented the first EPBD in 2002 based on minimum requirements for energy-efficient buildings. These requirements have been revised in the 2008 and in 2010 Building Codes."[56]

In the 2002 Regulation on the efficient use of energy in buildings (PTZURES 2002), the minimum requirements for new buildings and major renovations were expressed by the maximum energy needs for heating (useful energy), and were complemented by the maximum U values for the building envelope, the envelope components and the windows.

In the 2008 Regulation (PURES 2008), an intensive reduction of transmission losses through the building envelope, as well as new requirements on the obligatory 25% use of Renewable Energy Sources (RES) in the final energy use, were introduced.

As a part of the implementation of the recast EPBD, the 2010 Building Code (PURES 2010) placed the focus also on the calculation of primary energy and CO2 indicators and set additional minimum requirements for the primary energy for heating, limited the heating and cooling needs, both in terms of useful and primary energy, and added many new minimum requirements for energy systems.

The minimum requirements at the end of 2012, in line with the recast EPBD, were defined in the revised Regulation on the efficient use of energy in buildings (PURES 2010)[57] in force since January 2011. Minimum requirements are expressed using performance-based requirements, energy-related requirements, and detailed technical requirements for building components and systems.

Performance-based minimum requirements are focused on bioclimatic architectural concepts and on low energy losses in building envelopes with high airtightness. They also treat thermal bridges by limiting the linear thermal transmission coefficients. Before the design of Heating, Ventilation and Air-Conditioning (HVAC) systems, the potential of shading, passive cooling and night ventilation must be utilized to reduce the energy needs below the required levels. Mechanical ventilation with heat recovery is not a mandatory technology (natural ventilation is also allowed) but if mechanical ventilation is used, then heat recovery is mandatory. Public buildings must comply with 10% more strict requirements.

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[56] Zavrl/Potočar 2013, 329.
[57] Official Gazette of the Republic of Slovenia no.52/2010, 7840-7843.

The use of renewable energy sources (RES) is mandatory in all new buildings since 2008, i.e., min. 25% of the total final energy use for the building energy systems operation must be covered by them.

The additional minimum requirements refer to the maximum U-values of building envelope (as shown in Figure 2-5) and windows, and to the airtightness of the envelope.

Minimum requirements of PURES 2010 building code	
Element of building envelope	Umax (W/m².K)
WALL	0.28
WALL BETWEEN APARTMENTS.	0.90
WALL AGAINST GROUND	0.35
CEILING BETWEEN APARTMENTS.	0.90
FLOOR ON THE GROUND	0.35
CEILING AGAINST UNHEATED ATTICS	0.20
CEILING ABOVE UNHEATED CELLAR	0.20
CEILING, OPEN PASSAGE	0.30
FLAT ROOF	0.20

Figure 2-5: Minimum requirements of the PURES 2010 Regulation for the building envelope elements in case of new buildings and renovation of existing buildings, U_{max} (W/m^2K).[58]

A comprehensive list of requirements refers to energy efficiency characteristics of installations. Heat recovery in ventilation must be used due to the strict requirements for maximum allowed ventilation heat losses. Low temperature heating systems (max.55 °C), as well as condensing gas boilers, are obligatory in new buildings. Additional requirements for cooling refer to obligatory shading of the envelope, and to efficiency requirements for cooling systems. The total shading factor must be lower than 0.5 ($g < 0.5$). Internal shading devices are not considered as solar protection.
The minimum requirement for lighting defines the maximum allowed specific power of lighting devices per building category. Energy-saving lamps are obligatory.

At the design stage, it is obligatory to prepare a 'summary of the building thermal characteristics', where the main building and system characteristics, as well as the energy and CO2 indicators are given. Fulfilment of the minimum requirements are to be applied to all new buildings, as well as to all major renovations regardless of size (if at least 25% of the surface of the building envelope is subject to renovation) in order to obtain a building permit. Once the construction process is completed, the independent expert prepares the Energy performance certificate (EPC), which is a precondition for issuing the building's use permit. In

[58] Zavrl-Šijanec/Potočar 2013, 329.

the energy performance certification process, the designer's calculations and a building survey are used in order to analyze the real status of the building and the building systems.

The calculation of the building energy performance was updated in July 2010 (PURES 2010) along with the obligatory technical guidelines for construction TSG-1-004[59]: 2010 Efficient use of energy. The calculation methodology is based on the SIST EN ISO 13790 and nationally adjusted set of CEN EPBD standards.

2.3 Cost optimization in energy performance parameters

Single-family houses in Slovenia represent 75% of the residential sector floor area and 55% of the entire building sector.[60] That is why in 2012 a national[60] study was done with the focus on optimal minimal cost at financial level of end user perspective for new single-family houses. The most common period for major renovations in the residential sector in practice is 30-40 years, so 30 years (60 years is national regulation) was taken as calculation period and a boundary condition. The other boundary conditions are based on the National Energy Program (NEP 2030). This defines the energy scenarios (assumption on the energy price increase, anticipated increase of CO2 prices based on the emission trading system) for the calculation at the macroeconomic level. The categorization of the building stock was done according to the type of use, period of construction, main architectural characteristics and implemented renovation measures. The selection of reference buildings was based on the typology of the Slovenian national residential building stock, elaborated in the IEE project TABULA. They are characterized by architectural type (single-family buildings, terraced houses, small apartment buildings, and high-rise apartment buildings), and by the construction period reflecting the energy efficiency level (until 1970, 1971-1980, 1981-2002, 2003-2010, 2011 and beyond). The climate in central Slovenia was considered relevant for the majority of settlements in the country.

At the end of 2012 the preliminary results for a single-family reference building where given. A group of 130 variants was defined for a single-family house with a useful floor area of 150 m^2. The different variants where done considering following parameters:
- different insulation thickness (5 – 35 cm)
- windows with thermal transmission between 1.2 W/m^2K and 0.8 W/m^2K
- natural and mechanical ventilation
- heat recovery energy systems with gas boiler, wood pellet biomass boiler, ground/water heat pump, air/water heat pump, solar collectors for DHW and/or space heating

The results of the research as shown in Figure 2-6 demonstrate clearly that the minimum requirements set for new residential single-family houses are stricter in the PURES 2010 Building Codes than the minimum requirements corresponding to the cost-optimal level. This

[59] Žarnić 2010, 14.
[60] Zavrl/Gjerkeš/Tomšič 2012, 163.

is mainly due to the national energy and climate policy objectives in our building sector.

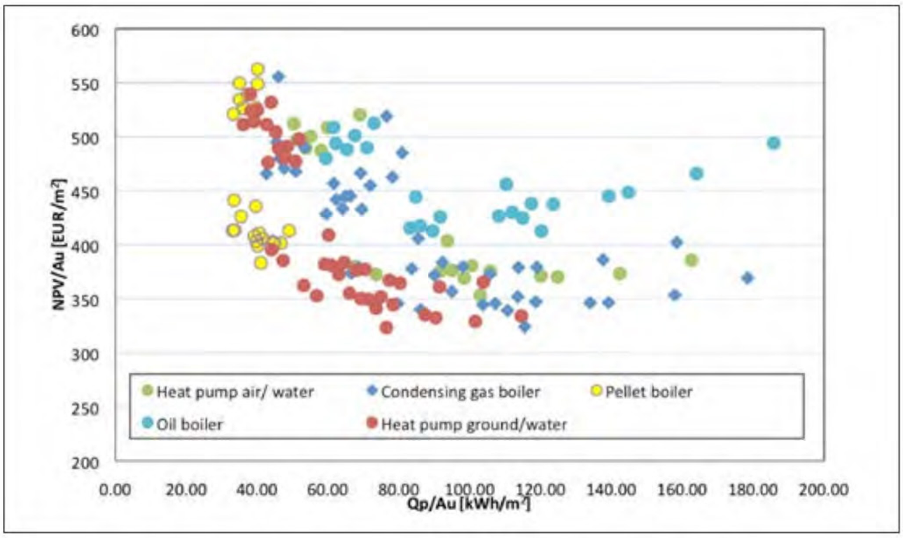


Figure 2-6: Net present value of the energy related investment, running and maintenance costs for a typical new single family building with various energy e ciency levels, energy systems and energy sources (discount rate 3%, 30 years life-time). Net present value (NPv/Au) is presented depending of the primary energy use (Qp/Au) to enable to identi cation of cost optimal building design.[61]

2.3.1 NZEB implementation in Slovenian legislation

The implementation of NZEB principles into Slovenian legislation and integration of building design and energy planning is needed. The increasing energy demand in buildings will be composted with on-site RES and a share of green energy in the national energy networks. The process of setting national minimum requirements was based on the advanced but market available technologies for energy efficient buildings and defined in accordance with the national targets and obligations set by the 20-20-20 policy. “Slovenia has adopted a target to achieve a 1% annual energy savings or 9% in the period from 2008 to 2016 (Slovenian NEEAP, in line with ESD directive). Furthermore, a very ambitious target (binding by RES directive) to achieve a 25% share of renewables in gross final energy use (currently 15%) by 2020 and 10% share of renewables in final energy consumption in transport, was accepted.”[62]
The most appropriate RES for power production in Slovenia as presented in Figure 2-7 seem to be wood biomass and hydropower. This is due considering the development of RES technologies and available natural resources. Wood is already a strategic resource and is used in wood industry for high valued products, as well as a byproduct for energy production. The sun is also a source widely used, but even though solar power plants in Slovenia take 6% of RES capacity they only produce 1.4% of RES produced electricity. Municipal waste and fermentation of organic matter for biogas are both very promising. Hydropower is already well used and its potential is almost exploited.

[61] Šijanec-Zavrl 2012, 13.
[62] Šijanec-Zavrl 2012, 162.

	year 2009			year 2010			
Power plant	Power generation [kWh]	Share in RES [%]	Share in total production [%]	Power generation [kWh]	Share in RES [%]	Share in total production [%]	Index 2010/2009
Hydro (up to 10 MW)	430.239.719	66,612	2,981	483.033.860	67,247	3,472	112,3
Biomass	97.943.961	15,164	0,679	100.756.071	14,027	0,724	102,9
Wind	218	0,000	0,000	10.666	0,001	0,000	4892,7
Solar	2.528.978	0,392	0,018	10.305.110	1,435	0,074	407,5
Biogas	78.276.053	12,119	0,542	96.269.047	13,402	0,692	123,0
Biomass co-burning (5 % to 90 %)	6.403.404	0,991	0,044	0	0,000	0,000	0,0
Municipal waste	30.501.352	4,722	0,211	27.918.645	3,887	0,201	91,5
Total RES	**645.893.685**	**100,000**	**4,476**	**718.293.399**	**100,000**	**5,162**	**111,2**

Figure 2-7: Installed capacity of RES power plants in Slovenia[63]

The cost-effective energy optimization and the potential of unexploited RES should become one of the focal points for sustainable buildings and the development of Slovenia.

2.3.2 Energy Performance Certificates (EPC)

In Slovenia all public buildings and all residential and non-residential buildings in case of sale or rental need to be certified. The certification protocols and methodologies where defined in 2009 and were revised in December 2012. The regulation determines in which cases certificates are to be applied (calculated or measured), how the indicators should be obtained, as well as the responsibilities for the provision of data. All EPC certificates have to be public.[64]

For all new buildings a ‘calculated’ certificate is reviewed and for all existing non-residential buildings a ‘measured’ one.

The ‘calculated’ EPC uses four calculated parameters according to SIST EN ISO 13790:

- energy needs for heating > **kWh/m²a** (quality of architectural concept thermal building envelope)
- final energy (delivered energy) use for HVAC systems and lighting > **kWh/m²a**
- primary energy use > **kWh/m²a**
- related CO2 emissions > **kg/m²a**

Seven classes are defined from A to G (A and B further subdivided). A, B1 and B2 may be considered in line with the recast EPBD objectives (main aim of investors). In the figure bellow the energy classes are shown with basic data.[65]

[63] Gjerkeš, Rapler, Šijanec-Zavrl 2011
[64] Regulation on the EP certification, (2014), Official Gazette RS, 17/2014
[65] Zavrl-Šijanec/Potočar 2013, 336.

Energy class or energy indicators (Qnh / Au) in Slovenia:

• class A1:	0	<	10	kWh/m^{2}a
• class A2:	> 10	<	15	kWh/m^{2}a
• class B1:	> 15	<	25	kWh/m^{2}a
• class B2:	> 25	<	35	kWh/m^{2}a
• class C:	> 35	<	60	kWh/m^{2}a
• class D:	> 60	<	105	kWh/m^{2}a
• class E:	> 105	<	150	kWh/m^{2}a
• class F:	> 150	<	210	kWh/m^{2}a
• class G:	> 210	<	300 & more	kWh/m^{2}a

Classes A and B are attributed to passive and almost zero energy buildings. Low energy buildings are regarded to have following indicators, from 15 to 35 kWh/m2a.

A single- family house EPC, costs between 300 € to 500 € (one day of expert's work), depending on complexity of the building and technical documentation.

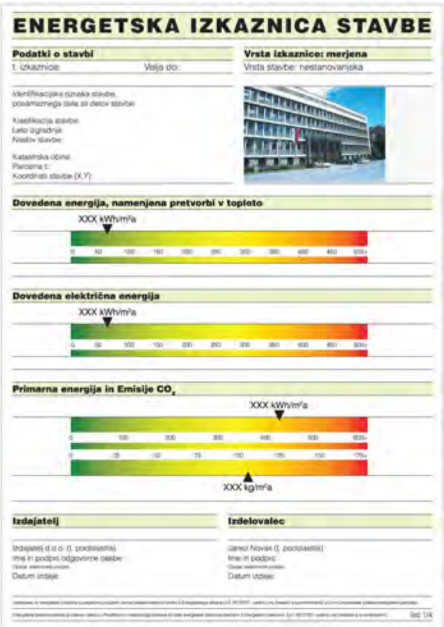


Figure 2-8: Example of a 'Calculated' energy certificate for a building[66]

2.4 Energy efficiency classifications/definitions

EPBD (Energy Performance of Buildings Directive) demands drawing up national plans for nearly zero-energy buildings according to specific national and regional conditions. To successfully implement the Directive, it is important to have feasible country definitions and EU standards. Realization of saving potentials and maximization of social and economical benefits are very important.

There are different classifications or definitions of energy-efficient houses that differ from each other regarding energy demand. For example, definitions for low energy houses with their energy demand being less than 50 kWh/m^{2}a, but they slightly differ from country to country. For passive house the parameter is 15 kWh/m^{2}a and is strictly defined. But heating energy demand is not the only parameter for classifications, there are additional parameters

[66] EP certificate sample, http://energetskaizkaznica.si, (19.9.2016)

which have to be met: minimum U-value of external building elements, the air tightness of the building's envelope, window energy values, building form etc.

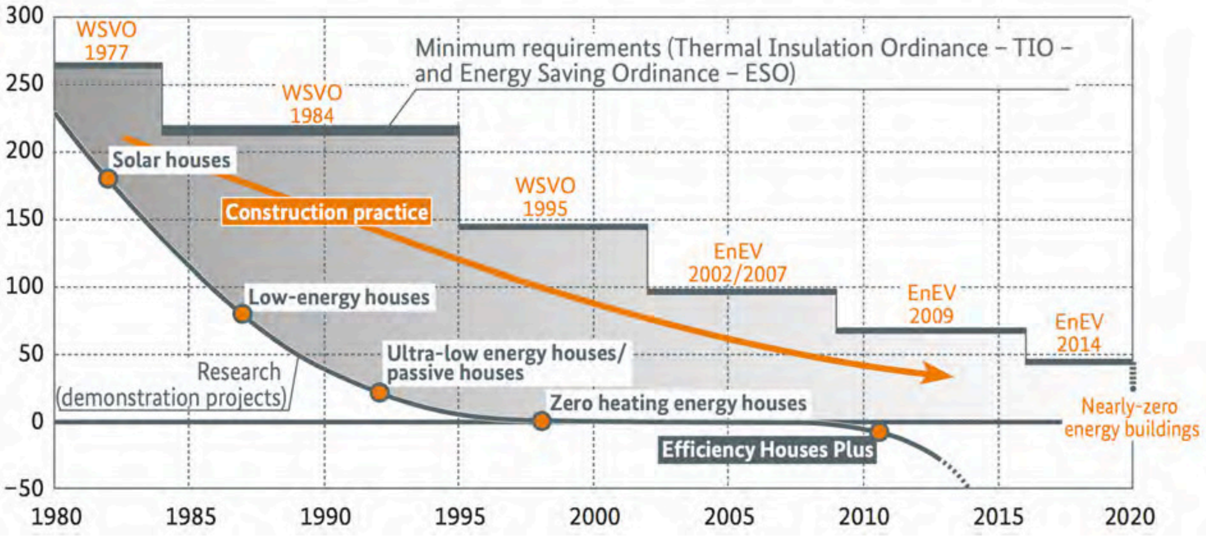


Figure 2-9: Primary energy demand for a semi-detached house – heating (kWh/m^2a)[67]

Slovenian legislation is mostly implementing German standards therefore they where researched in this chapter. For reducing Energy consumption and emissions in building sector, Germany has developed different Building standards and assessment methods. The goal was to reduce the energy consumption even further than the EnEV regulation demands.

The Figure 2-9 shows how the primary energy demand for semi-detached houses has developed over the last 30 years. The bottom curve shows exemplary research projects that were investigated for the research "What makes an Efficiency House Plus?" done by The Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR) within the Federal Office for Building and Regional Planning (BBR) in Germany. This monitoring was done to introduce a better energy level to the market. The top curve records the statutory minimum requirements and presents the German energy efficiency standards. The Innovative construction practice is somewhere between these two curves. The graph shows that a market launch phase of 10 to 15 years between different standards being piloted and becoming a legal requirement is common.[67]

In the following sub-chapters, the most important Building standards and assessment in German speaking areas are presented according to Hegger.[68]

2.4.1 KfW Efficiency House (KfW Effizienzhaus)

Germany wanted to stimulate energy efficient buildings, therefore the KfW promotional programs for the KfW Efficiency House where developed. They provide funds in the form of either a grant or a loan to anyone investing in the energy-efficiency refurbishment of an older residential building or the construction or initial purchase of new or newly refurbished KfW-efficient home. The energy standards for a "KfW Efficiency House" are laid out in the Energy

[67] Erhorn/Bergmann 2014, 6.
[68] Hegger 2013, 84-97

Conservation Ordinance (Energiesparverordnung / EnEV) and apply to new buildings. There are currently 6 efficiency categories. The number next to each category indicates the percentage of the maximum primary energy requirement specified by the EnEV that the house consumes. The highest support is received by the best standard (lowest number). KfW Efficiency House 100 is now the standard and was former Low-energy house according to EnEV 2007.

	Berechnungsbasis EnEV 09, Anforderungen bezogen auf den Neubauwert*	Berechnungsbasis EnEV 07 oder älter, Anforderungen Primär- und Endenergie
Effizienzhaus 40	max. 40% Neubau und Sanierung	max. 30 kWh/(m²a)
Effizienzhaus 55	max. 55% Neubau und Sanierung	max. 40 kWh/(m²a)
Effizienzhaus 70	max. 70% Neubau und Sanierung	max. 50 kWh/(m²a)
Effizienzhaus 85	max. 85% nur Sanierung	max. 60 kWh/(m²a)
Effizienzhaus 100	max. 100% nur Sanierung	max. 70 kWh/(m²a)

Figure 2-10: Dena Efficiency House, Energy requirements [69]

Energy Efficient Refurbishment is promoted, if after refurbishment the houses do not exceed a specific energy requirement (Figure 2-10) for a comparable new house. The five levels of support for a "KfW Efficiency House" have been defined as follows:
KfW Efficiency House 55, KfW Efficiency House 70, KfW Efficiency House 85, KfW Efficiency House 100, KfW Efficiency House 115. For new houses or initial purchase of a KfW Efficiency House 85, 70, 55, 40 and passive house is supported.
Crucial categories, besides a heat insulation without thermal bridges are: efficient heating, water heating and ventilation (with heat recovery), shape of the building, position, orientation, window insulation and other parameters as shown in Figure 2-11.

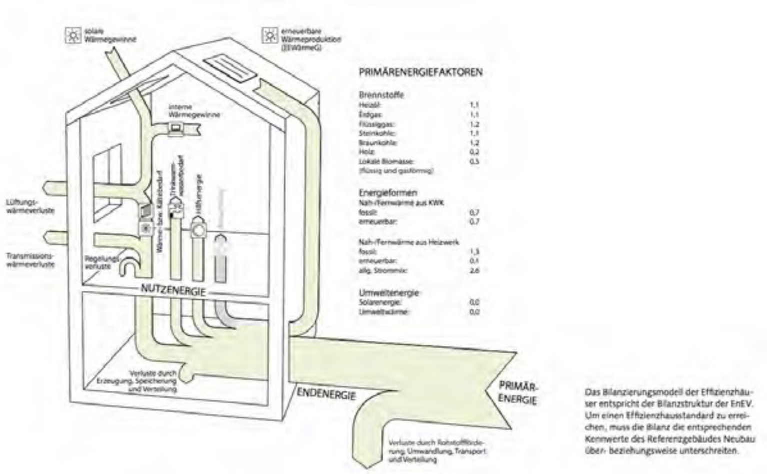


Figure 2-11: Balance model „Effizienzhaus“ – Efficiency house [70]

[69] Energetische Anforderungen, https://effizienzhaus.zukunft-haus.info/guetesiegel-effizienzhaus/energetische-anforderungen/, 4.6.2015
[70] Hegger 2013, 85.

2.4.2 Passive house

Passive house concept was established in the beginning of 90s by Dr. Wolfgang Feist. The basic concept was to optimize the thermal balance of buildings by introducing a thick thermal insulation of the outer layer and minimizing thermal losses caused by ventilation with airtightness and heat recovery systems. A standard heating system is not required because heating is done by inlet air.

Main objective is to keep the Heat inside the building which is done by:
- heat transmission standards for roof, outer walls, ground slabs and windows (20 - 50cm thermal insulation, triple glazing, thermally independent window frame, optimized details etc.)
- no thermal bridges in the construction
- compact building design
- good wind and air tightness
- minimizing ventilation thermal loses (mechanical ventilation with efficient heat recovery system, fresh air preheating)
- internal heat gains
- smart window positioning and sizing (Big opening in the south smaller in the north)
- warm-air heating (for extreme temperatures) and supporting heat elements for temporary used zones (Bathrooms, Office, Guest rooms)
- error free designing and building construction

Passive buildings should be certified and evaluated. In Germany this is done by PHPP or EnEV analysis.
When calculating the analysis following single parameters are taken into calculation:
- designing windows
- designing the ventilation
- calculating thermal balances, U-value calculation for all construction components inclusive thermal bridges
- rating the heat load
- summer comfort prediction
- rating for heating and warm water preparation
- certification for passive house promotion (i.e. through KfW)
- simplified analysis through EnEV (“Energieeinsparverordnung”)

The primary energy demand inclusive electricity demand for lighting, housekeeping and service must not exceed predefined maximal values (Figure 2-12). With this values, the building’s concept balance sheet is better than the legislation values. The air tightness is checked mechanically on the building site.

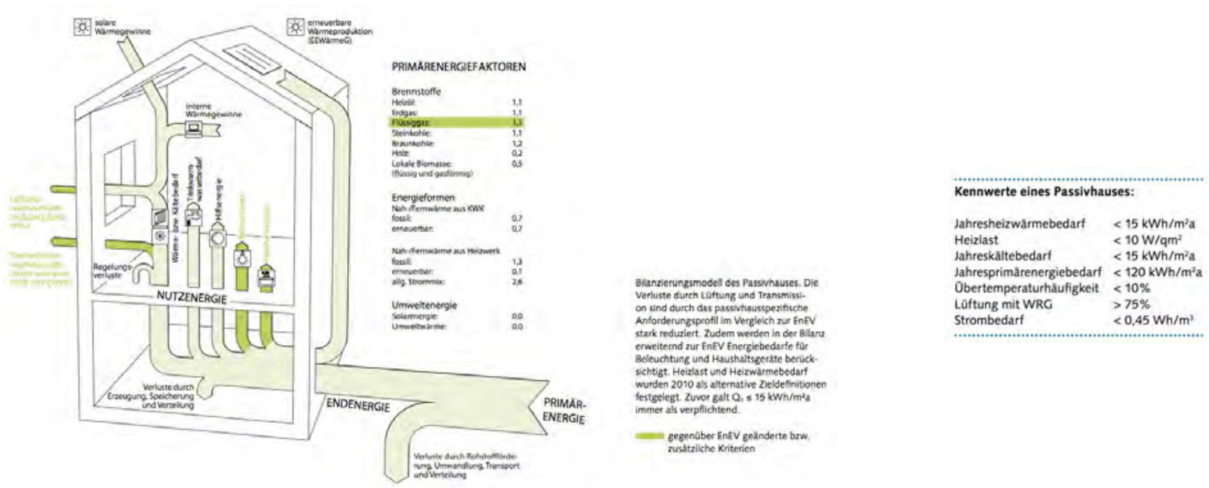


Figure 2-12: Balance model for a Passive house with main parameters.[71]

2.4.3 Nearly-zero-energy and zero-energy house

Zero-energy house is a building which produces as much energy as it consumes. The energy is produced by renewable energy sources. This means that there is no external energy application and that is why such house is a zero-energy house. The energy balance-sheet is theoretically zero. The balance model presented in Figure 2-13 is not detailed. The renewable on-site energy production has to be the same as the energy consumption. Which consumers are accounted by the balance model, has to be clarified with the development of national standards.

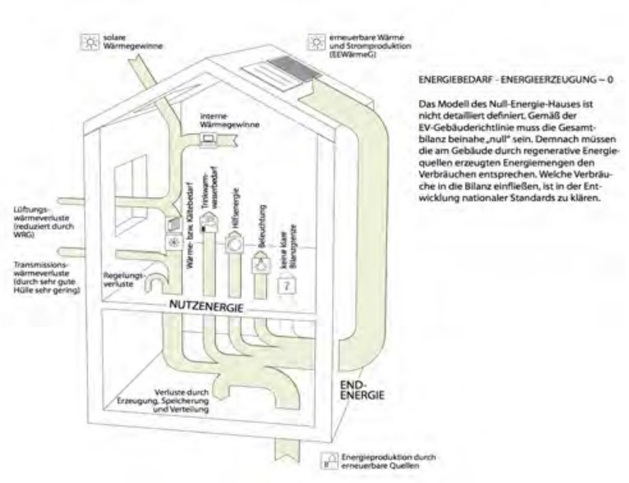


Figure 2-13: Zero energy house balance model.[72]

In 2010 the EU Directive on Energy Performance of Buildings (EPBD) was introduced. According to this directive all buildings after 2021 should be nearly-zero buildings. But the main problem remains, how to credit the excessive energy mainly in summer period, to get most realistic results. It is mostly suggested that the overproduced energy should be transformed into electricity and be fed into public electricity grid with the possibility of using

[71] Hegger 2013, 87.
[72] Hegger 2013, 89.

that energy when needed. This means that such houses would be net-zero-energy-buildings on yearly period but not on monthly basis.

Until 2015 all EU countries should have suggested their national legislation framework standard for EPBD.

2.4.4 Efficiency house plus

In 2011 Germany introduced the first Plus-energy building standard. The ‘efficiency house plus’ produces more energy than it is demanded so it is surpassing the zero-energy concept.

The efficiency house plan is a state funding program. An important part of the program is building monitoring for 24 to 30 months so the implementation into legislation would bring best possible results.

The energy balance sheet (Figure 2-14) evaluates following energy parameters: HVAC, building operations and electrical appliances (lighting, household appliances, cooking, other). The calculations are done corresponding to monthly balance system (energy demand and energy yield are compared). Building property is set as the assessment limit. This means that all renewable energy being produced on corresponding property can be taken into consideration (opposing to EnEV).

Figure 2-14: Balance Model for the Efficiency-house Plus.[73]

In practice most such buildings get extensive electricity from photovoltaics produced in summer credited for getting the winter energy from outside. Looking only at primary energy the plus-balance is easy to achieve, because electrical energy is highly evaluated. The difficult part is achieving a positive End-energy balance. For this target mostly heat-pumps are being used.

[73] Hegger 2013, 91.

The yearly Primary-energy demand (Q_p) and End-energy demand (Q_e) must be lower than zero (0 kWh/m2a) and all other EnEV requirements (like summer heat-protection) must also be complied.
Additional demands suggest using Appliances with highest energy-efficiency (A++ or better) and monitoring of energy usage and production.

2.4.5 Active House

Active House is residential building standard that creates healthier and more comfortable lives for their occupants without negative impact on the climate. An Active House is evaluated on the basis of the interaction between energy consumption, indoor climate conditions and impact on the environment. It is designed as an open source model and has a corresponding Online[74] platform.

Following the active house principles are presented:
a) Comfort
Improving the quality of the indoor climate is achieved through abundant daylight and fresh air. Also the thermal environment is of high quality. This has a considerable impact on our health and comfort. A good indoor climate is a key quality. It must be an integrated part of the house design. In order to evaluate each building's indoor climate, four levels of ambition are to be utilized. Architects and engineers can use these levels to work towards creating their own specific levels for a building.
Key factors for comfort:
- a building that provides an indoor climate that promotes health, comfort and sense of well-being
- ensuring a good indoor air quality, adequate thermal climate and appropriate visual and acoustical comfort
- providing an indoor climate that is easy for occupants to control and at the same time encourages responsible environmental behavior

b) Energy
The energy supply concept is to minimize the energy demand of the building. This is accomplished using energy-efficient solutions and architectural measures (orientation, materialization and shape of the building). The remaining energy requirement is sourced as much as possible from renewable and CO2-free energy sources (on the building, the plot or from the nearby energy systems). Any remaining energy demand may be met by using fossil fuels through highly-efficient energy conversion processes.
The designing and building process includes monitoring and evidencing and a user friendly building management is demanded, which should allow users a good control of the house.
Because 'active house' is an international standard the specified levels, evaluation policies, primary-energy demands and emission calculation parameters are to be considered according to national legislation. The main value is primary-energy demand which consists

[74] Active house online platform, www.activehouse.info, 14.4.2015

of: building energy demand for building operation (Heating, Cooling, Ventilation, Hot-water preparation), energy demand for home appliances and credit value of self-used and regenerative produced energy.
Key factors for energy:
- energy efficient and easy to operate
- it substantially exceeds the statutory minimum in terms of energy efficiency
- exploits a variety of energy sources integrated in the overall design

c) Environment
It should have a minimal impact on environment and this means that any harm to environment, soil, air and water should be minimized or to have a positive impact on the environment. Consideration should be given in the design phase for how Active Houses use building materials and resources. Also considering the local building culture and behavior in and around the local buildings as well as traditions, climate and ecology, must be done. This is relevant when working on improving the building's exterior and interior relations to the cultural and ecological site-specific context.
The key parameters to consider within resource and emissions are:
- Consumption of non-renewable energy resources
- Environmental loads from emissions to air, soil and water
- Freshwater consumption

When evaluating the performance of an Active House, it is important to consider the consumption of energy resources and the emissions to air, soil and water through a Life Cycle Assessment (with EN 15643 or ISO 14040).

The building's life cycle is considered at the following stages:
- Production of building materials
- Construction processes
- Operation of the building and maintenance of the building construction and fabric
- End of life of building materials
- Transport and site processes may be omitted

All major building components should be considered:
- Outside walls, roofs, slabs, foundations, windows and doors
- Inner walls, floors and ceilings
- Major technical components (heat generators etc.)

The estimated service life of the building and building components should be in accordance with local standards. Active House suggests 50 years as benchmark.
The following impact categories are to be evaluated:
a) Resource consumption:
- Primary energy consumption (non-renewable)

- Primary energy consumption (renewable)
b) Impact categories (emissions):
- Global warming potential (GWP)
- Ozone depletion potential (ODP)
- Photochemical ozone creation potential (POCP)
- Acidification potential (AP)
- Eutrophication potential (EP)

A synopsis of all presented impact categories for an active house says that an active house is a building that has a minimum impact on environmental and cultural resources, is avoiding ecological damage and is constructed of materials with focus on re-use.

The Active House Radar as presented in Figure 2-15 brings together the three main Active House criteria and describes for each criterion the level of ambition of how 'active' the building has become.[75]

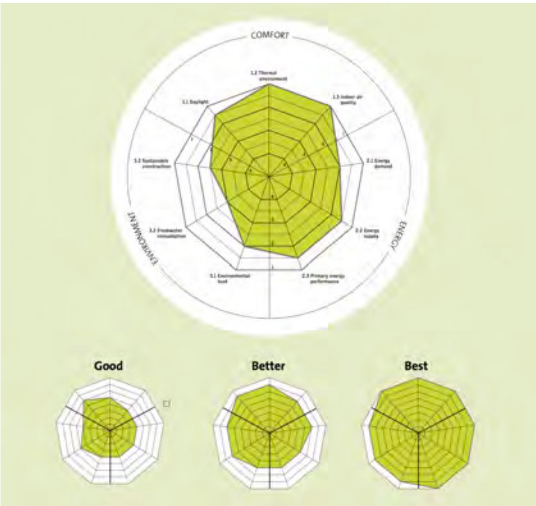


Figure 2-15: Active house radar[75]

2.4.6 Minergie standard

Minergie® is a registered quality label for new and refurbished buildings. This trademark is supported by the Swiss Confederation, the Swiss cantons and the Principality of Liechtenstein along with trade and industry. The trademark is firmly protected against unlicensed use. Within the framework of the Minergie® registered trade mark, several products are offered (Figure 2-16).

Regular Minergie® Standard for buildings requires that general energy consumption (Heating, warm-water, electricity, mechanical ventilation, cooling) must not to be higher than 75% of that of average buildings and that fossil-fuel consumption must not to be higher than 50% of the consumption of such buildings. A residential house energy yearly consumption must not exceed 38 kWh/m^{2}a. Regular Minergie standard is considering only parameters

[75] Eriksen 2015, 70.

regarding interior building conditions without household electricity. But it is suggesting use of energy efficient household appliances as well as a mechanical ventilation with heat recovery to ensure greater comfort.

Minergie- energy consumption factors:

0 > sun, solar radiation and environmental temperatures, geothermal energy

0,6 > bio-mas (Wood, Biogas, Sewage Gas)

0,7 > district heating (min. 50% renewable energy, waste heat, cogeneration)

1 > fossil fuels (Oil, Gas)

2 > electricity

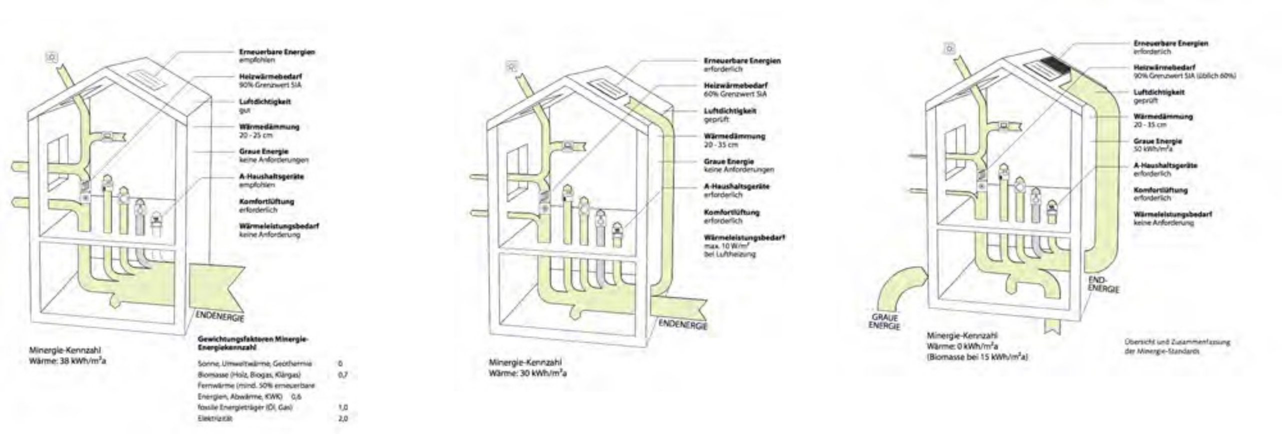


Figure 2-16: Overview and summary of Minergie standards (Minergie, Minergie-P, Minergie-A).[76]

The **Minergie-P**® Standard defines buildings with a very low energy consumption, it is especially demanding ins regard to heating energy demand wich must not exceed 30 kWh/m2a. The heating energy demand must not to be higher than 40 % of that of average buildings. This standard corresponds to the passive house standard. This means that such building systems are highly optimised and sensible and must correspond to even more requirements for comfortable and error free operation (thermal comfort in summertime, airtightness of building envelope, integration of comfort ventilation).

The **Minergie-A®** Standard was the first available label standardizing a zero-balanced type of building. The standard prescribes an annual net zero primary energy balance for heating, domestic hot water and ventilation. Electricity consumption for appliances and lighting is excluded. Additionally, Minergie-A is the first standard worldwide which includes a requirement in regard to embodied energy. The basis of all Minergie-A buildings is a well-insulated building envelope. On- site energy generation is typically covered by the installation of a sufficient amount of photovoltaic collector modules.

The three central requirements for a Minergie-A standard are:

- a heating demand which is at least 10% lower than what is allowed according to the Swiss building regulations (SIA380/1:2009)
- an annual net zero energy balance for space heating, domestic hot water, ventilation and auxiliary electricity is required. If the energy carrier for heating is wood and more than 50% of

[76] Hegger 2013, 95-97

the space heating and domestic hot water is covered by solar thermal collectors, a credit of 15 kWh/m^{2}a is given

- the embodied non-renewable primary energy must not exceed 50 kWh/m^{2}a. If the embodied energy exceeds this requirement, the difference can be compensated by electricity production with a photovoltaic system.

The Minergie-ECO® Standard adds ecological requirements such as recyclability, indoor air quality, noise protection etc. to the regular Minergie® requirements.

According to Hegger, it is not possible to compare all standards in their numbers because of different input parameters (i.e. nationally different primary energy factors or different methods of calculation). But they all have the same objective which is an efficient energy supply for buildings. operating energy. The main focus is operating energy.
But it is important for the standards to go beyond operating energy. Some of them already look at the life cycle of the buildings, which includes energy needed for building production, building material production and the influences of buildings to the environment. This parameter should become even more important in the future.

2.5 Prefabricated constructions systems

In this chapter a preliminary study of industrialization and prefabrication is presented. Furthermore, we offer an overview of prefabricated lightweight construction systems according to Components and Systems: Modular Construction: Design, Structure, New Technologies.[77]

2.5.1 Industrialization and prefabrication

Because our study assesses, if the houses designed for the SDE competition can be successfully transferred onto the Slovenian property market, we looked into correlation between construction cost and prefabrication.

A limitation for this research is the question of the production cost reduction through industrialization and repetition because the research is based on prefabricated residential houses. Industrialization includes a rapid transformation in the significance of manufacturing in relation to all other forms of production and work undertaken within national or regional economies.
A reduction of the production process time, means because of labor costs, a reduction in construction costs. According to Smrkolj[78], from Chamber of Commerce and Industry of Slovenia, a single house in Slovenia takes up to two years to be built and settled in classic construction method, where it takes approximately only five months for the same house in prefabricated lightweight construction.

[77] Staib/Dörrhöfer/Rosenthal 2008
[78] Mihajlovic, Stela: Hiša: klasična ali montažna?, 13.7.2010, http://www.finance.si/284674, 15.4.2014

Corbusier describes in his book Towards the new architecture the process of industrialization "a new era has begun; a new spirit is abroad in the world. Industry as forceful as a river surging towards its destiny, gives us the new solutions appropriate to the new era. The law of economy dictates our actions. The problem of housing is a problem of our times; the balance of our social order depends upon solving it. Re-evaluation of essential elements of the house. Serial construction relies on analysis and experimental research. Large industry must address building and produce individual building elements in series. The intellectual requisites for serial production must be created."[79]

Although "production and connection of the prefabricated parts" should according to Paxon[80] "function like a machine", we cannot consider residential homes as industrial products. According to authors of Canopea project manual[81] "they are mainly cultural goods that participate to cultural identity". Consequently, it is our assumption that houses cannot be produced in the same way that car industry produces its products. An industrialization process based only on standardized prefabrication should be avoided. Each building should architecturally and constructively be adapted to the context and technologies of its location. Nevertheless, standardized industrialization remains a solution to cut costs for technical elements, because when bought in block purchase the prices can be lowered. A good prefabrication building is based on a dry assembly system that rationalizes producing costs, shortens assembly time and improves quality control in order to guarantee performance.

According to Staib et.al.[82] the industrial prefabrication of buildings today, means the production of building products by way of industrial techniques. Site work is transferred into controlled environments (site plants), where building elements can be produced independent of weather conditions and under optimal production and quality control. In this plants materials are processed to produce building elements. According to authors the proportion of industrially manufactured products in conventionally constructed buildings nowadays is between 50 to 60%. Furthermore, the application of systems, based on prefabricated building components is increasing. The aim of prefabrication is reduction of construction time on site. It is still a standard practice to combine prefabricated building units with elements produced in-situ, which can lead to delays and quality losses. This leads to the assumption that the greater the degree of prefabrication, the shorter the construction time. The most commonly used system for prefabricated residential houses, the panel construction system, has a prefabrication level of approximately 60% as shown in Figure 2-17. Modular systems have a prefabrication degree of 85% and the highest level have fitted-out room modules, with a factor of 95%. Furthermore, since the buildings can be created out of linear, planar or spatial elements, which determine the construction principles characteristics of system building: the frame, the panel and the room module, it is important to also look at the levels of flexibility and its correlation to degree of prefabrication. The frame is the most flexible, followed by

[79] Le Corbusier 1969 (Deutsch), 166.
[80] Kohlmeier/Sartory 1988, 415.
[81] Project Manual #5 2012, 629.
[82] Staib/Dörrhöfer/Rosenthal 2008, 40.

panel systems and the modular building methods. However, the level of prefabrication is in reverse order.

Type of building	Level of prefabrication [%]
Rationalised housing	25–35
Industrial building site processes	20–30
Standard ready-built (rein. conc., steel, timber)	40–60
Ready-built housing (timber panel system)	50–80
Modular units/sanitary blocks (rein. conc., steel, timber)	60–90
Mobile modular units (steel, timber)	95–100
Automobiles (for purposes of comparison)	100

Figure 2-17: Levels of prefabrication for different types of buildings.[83]

The authors of SDE2012 winning project Canopea, did an extensive evaluation on industrialization possibilities of their prefabricated house. They evaluated the cost of the prototype for 1/10/100/1000 units. For their standard apartment they evaluated following costs as shown in Figure 2-18:

- A prototype costs 2 485 €/m^2 SHON (Gross area).
- For a 10 units production, they estimate that the cost of a housing unit could go down to 2 372 € /m^2 SHON (Gross area).
- For 100 units production they estimate that the cost of a housing unit could go down to 2 142 € /m^2 SHON (Gross area).
- For a 1000 units production they estimate that the cost of a housing unit could go down to 2000 € /m^2 SHON (Gross area).

TOTAL FOR A STANDARD APARTMENT LEVEL			357 877,80 €	VAT free	341 683,01 €	VAT free	308 521,22 €	VAT free	290 594,87 €
Measurable Area	75,00	m2	4 771,70 € /m2		4 555,77 € /m2		4 113,62 € /m2		3 874,60 €
Gross Area	144,00	m2	2 485,26 € /m2		2 372,80 € /m2		2 142,51 € /m2		2 018,02 €

Figure 2-18: Canopea standard apartment cost evaluation for 1/10/100/1000 units after cost of prototype's evaluation.

Since they consider their Skin as a low-tech part of their project, which can be produced and assembled locally, we also looked into their evaluation of skin cost for industrialization purposes. The skin of their prototype is described in detail in Chapter 3.1.4 in this study. It is made of locally produced components: steel structure, prefabricated load bearing wood panels for floors, prefabricated and insulated wood panels for walls including windows, prefabricated bay windows with rolling screens and interior finishing. It can be delivered "ready to use" or "ready to finish". Buyers who want to spare some financial resources can even conduct the interior finishing by themselves. For the envelope of their standard apartment they evaluated following values:

[83] Staib/Dörrhöfer/Rosenthal 2008, 40-42.

- A prototype envelope for 1 unit has a cost factor of 100%.
- For a 10 units production, they estimate that the cost gain factor for the envelope would be 96%.
- For 100 units production they estimate that the gain factor would be 87%
- For a 1000 units production they estimate that the gain factor of envelope could be 82%.

Parallel to cost evaluation they also preformed a study of the degree of industrialization for a repeated production of 1/10/100/1000 units. The global strategy for the Canopea project was for the Core and Shell parts components to be industrialized and pre-assembled. For this two parts the authors evaluated that for more than 100 units all of the pieces could be 100% industrialized. However, the Skin part is an element that according to authors, adapts to local context, and locals building cultures and therefore should be flexible. They designed it in a way that it can be built on site by local building companies using a workforce with average qualification. Therefore, level of industrialization is lower than for the other two parts:
- Prototype: 62% of pieces of the Skin are standardized,
- 100 units: 70% of pieces the Skin are standardized,
- 1000 units: 84% of pieces of the Skin are standardized.

2.5.2 Lightweight structural systems

Building systems define the relationships between the individual elements within a geometrical organizational principle. The design phase of a building determines the quantity, dimensions, combination and coordination of elements in it.

2.5.2.1 Frame systems

These are systems used in buildings, where load-bearing structure is designed as frame and is structurally in functionally clearly separated from external envelope which is not load-bearing. The load-bearing frame can be located either outside or inside the building envelope. Frame systems are formed by linear building elements like columns and beams as shown in Figure 2-19[84]. When they are braced, they combine for a construction, which becomes a stable construction, that is capable of withstanding both vertical and horizontal loads.

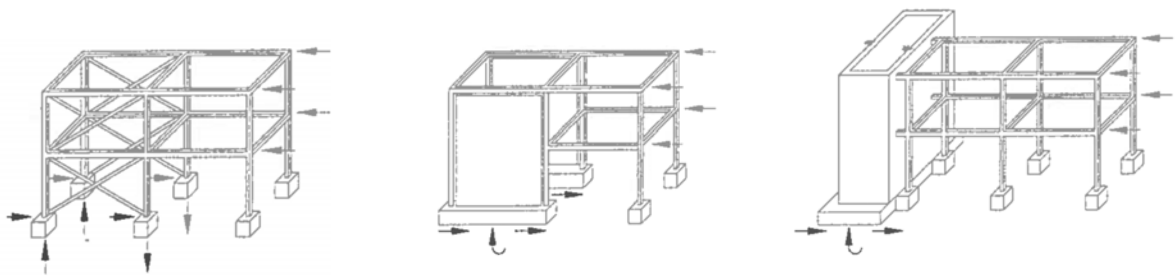


Figure 2-19: Bracing systems in frame construction[84]

[84] Staib/Dörrhöfer/Rosenthal 2008, 54.

2.5.2.1.1 Steel frame systems

Columns and beams are made of prefabricated steel sections that create a frame of linear elements with minimal weight. Steel frame allows large spans because it has high load bearing capacity. Though very long spans can be achieved with few construction elements the most economic spans are 6 - 18m. Bracing elements ensure the stability of the construction horizontal and vertically, where horizontal bracing is provided by slabs or horizontal girders (support beams) and vertical bracing by rigid corner joints, girders or solid wall plates.

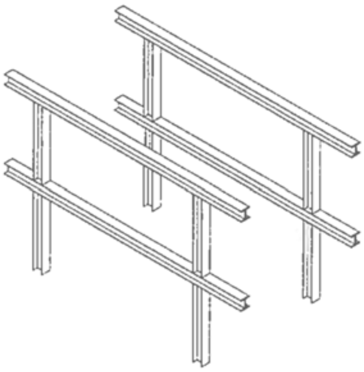


Figure 2-20: Frames with continous beams[85]

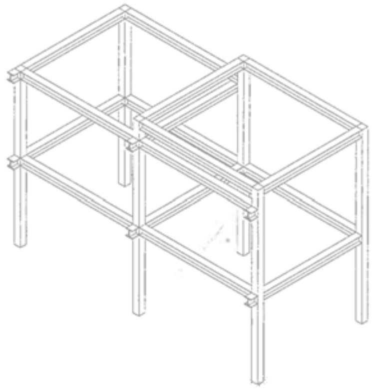


Figure 2-21: Frames with continous columns[85]

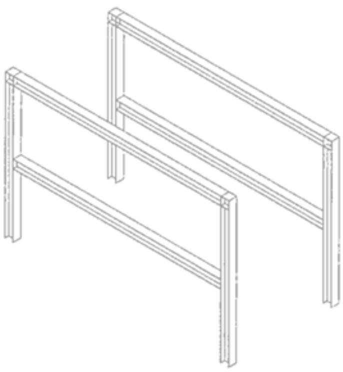


Figure 2-22: Non-directional frame[85]

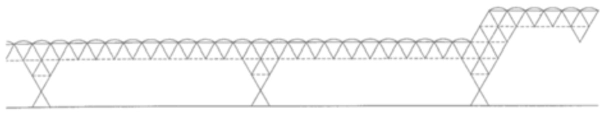


Figure 2-23: Space frame - elevation[85]

For steel frame systems following construction principles are used[86]:

a) Frames with continuous beams where structural system is formed by frames that are erected at defined distances to one another (Figure 2-20).
b) Frames with continuous columns have a structural system where the beams are fixed between the columns (Figure 2-21).
c) Non-directional frames: continuous columns are positioned at the intersections of regular square grids in this structural system (Figure 2-22)
d) Space frames: two basic elements construct a space frame structural system, this are hollow tubes and spherical nodes which are connected to form a three dimensional system (Figure 2-23).

[85] Staib/Dörrhöfer/Rosenthal 2008, 60.
[86] Staib/Dörrhöfer/Rosenthal 2008, 60.

2.5.2.1.2 Timber frame systems

Timber frame building systems are made up of columns and beams. The difference to other timber building systems is the load-bearing structure, which is independent of the envelope enclosure. There are many construction methods that differ in the system how the beams and columns are made and connected. The construction is stiffened by diagonal tension or compression members, wall panels connected to the frame or solid cores extending the full height of the building.

Different construction principles are common for timber frame systems (Figure 2-24). These are defined by the layout and form of the columns and beams.[87]

a) Post and beam: columns in this system extend through entire height of the building. The beams can be fixed to all sides of the column and are regarded as simple beams (Figure 2-25).

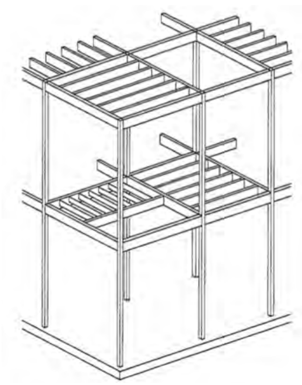


Figure 2-24: Frame construction[88]

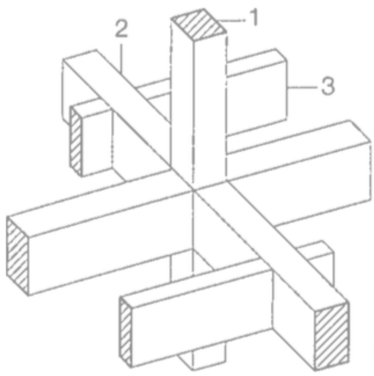


Figure 2-25: Column and rail junction point[87]

b) Beam and column: primary beams are supported by story height columns in this system (Figure 2-26). The beams can be continuous or simple. Secondary beams for the substructure of the slabs can be beams or planks.

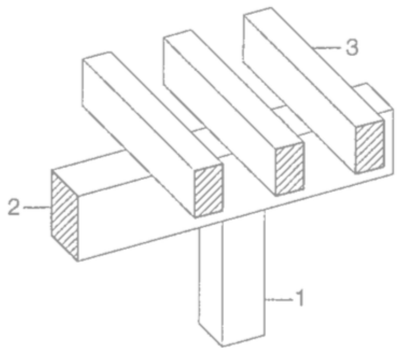


Figure 2-26: Column with double beams junction point[87]

c) Column and double beam - double column and beam: in this construction principle each beam consists of two members that are fixed to either side of the column (Figure 2-27). The

[87] Staib/Dörrhöfer/Rosenthal 2008, 65.
[88] Deplazes 2009, 98.

secondary beams can be made as beams or as planks. The systems can also be designed in the opposite way, where we have double columns and single beams (Figure 2-28).

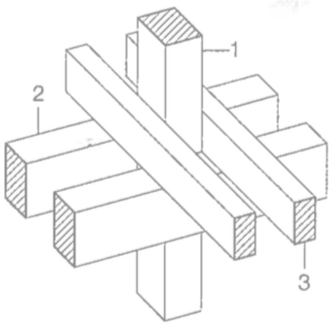


Figure 2-27: Column with double beams junction point[87]

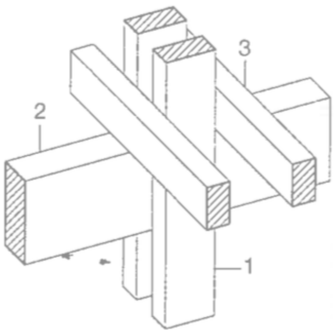


Figure 2-28: Double columns with beams junction point[87]

d) Timber space frame: these are composite constructions of rod-like glues laminated timber members (Figure 2-30) and spherical steel nodes (Figure 2-29). Nods and steel tubes that are set into timber rods together create a structural frame.

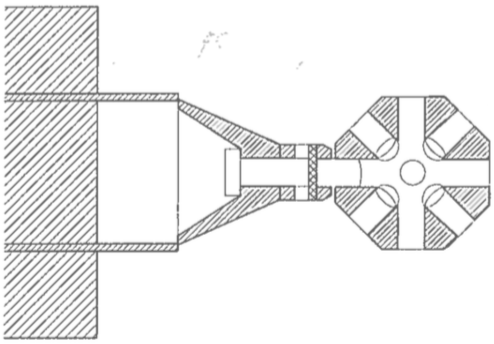


Figure 2-29: Timber space frame section through node[87]

Figure 2-30: Timber space frame roof structure[87]

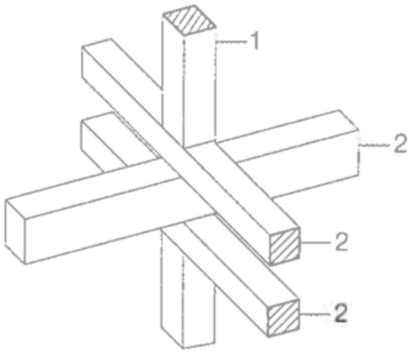


Figure 2-31: Frame connection (1 column, 2 beam)[89]

Figure 2-32: Timber-frame construction[90]

e) Timber frame constructions: are frame constructions (Figure 2-31) usually externally clad with timber-based panels, internally with plaster boards and filled with insulation in the cavity. The sill plate forms the base of the system and is the connecting element between floor and the wall. The frame is braced by diagonal struts (Figure 2-32) which are always placed in

[89] Staib/Dörrhöfer/Rosenthal 2008, 67.
[90] Deplazes 2009, 96.

pairs running in opposite direction to each other. They transfer the horizontal loads from the posts and sill plate.

f) Timber stud construction: is a principle where the frame is made of studs, which provide the structure for both, the wall and the floor. The studs are in standardized dimension and are positioned close to each other. The bracing is done with cladding, horizontal boards or wood-based panels. The timber stud constructions are subdivided into platform frame constructions and balloon frame constructions.

f1) Platform frame construction (Figure 2-34): is a structure where floor rests on top of the story-height studs (Figure 2-33). In this system the building is erected story by story. Timber panel construction evolved out of this principle.

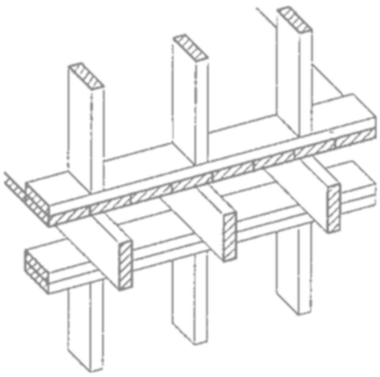


Figure 2-33: Platform construction[89]

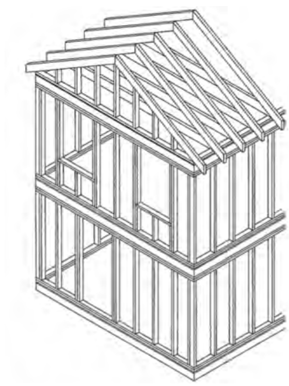


Figure 2-34: Platform frame construction[91]

f2) Balloon frame construction (Figure 2-36): in this construction principle the vertical timber members of external walls continue through several stories (Figure 2-35). The horizontal floors can be directly fixed to the wall studs or onto traverse members connected at the level of each story.

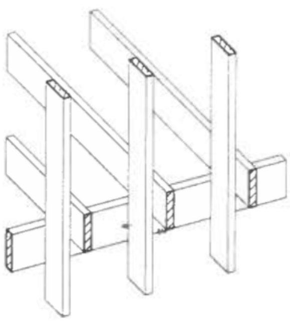


Figure 2-35: Balloon frame construction[89]

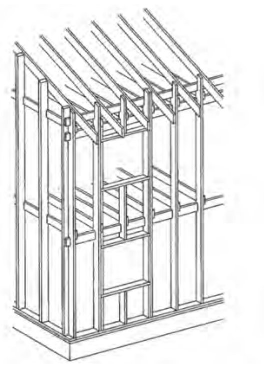


Figure 2-36: Balloon frame construction, timber stud construction[92]

[91] Deplazes 2009, 97.
[92] Deplazes 2009, 96.

2.5.2.2 Panel systems

Structural systems where planar wall and slab elements form an enclosed space are called panel construction systems. These panels can be constructed of steel or timber construction (for a lightweight construction). All narrow or large panels are self-supporting elements.

There are three construction methods used for panel systems (Figure 2-37):
a) Small panel construction
b) Large panel construction
c) Crosswalk panel construction

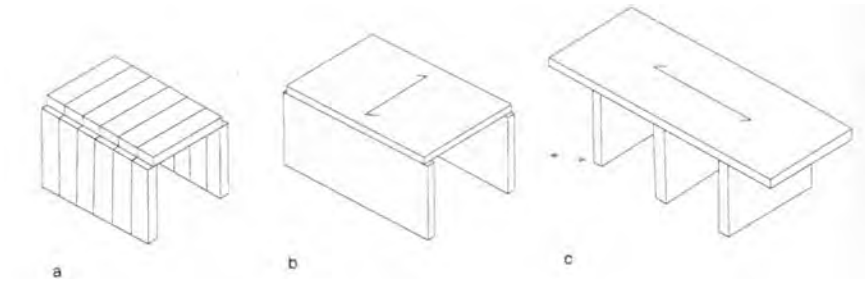


Figure 2-37: Construction principles of panel systems: Small-panel (a), Large panel (b) and Cross wall construction (c).[93]

Figure 2-38: Panel construction[94]

2.5.2.2.1 Steel panel systems

In steel panel systems the steel frame in conjunction with the cladding acts as a plate. The steel frames and cross ribs are prefabricated and the panels are delivered to the site either as framework or complete with cladding. Basic principle employed for steel panel structures is framework construction. The weight saving of steel, compared with timber framework construction is approximately 30% and about 66% when compared with solid wall constructions.

Steel framework construction is the form of construction where load bearing panel elements are constructed out of cold rolled steel sections as rough elements for walls, slabs and roofs of a building. The frame is made of vertical studs that are connected with a U-profile at the top and the bottom. The double sided cladding provides the stability for the wall or slab panel. The loads are transferred with panels to the adjacent building elements. The cavity is insulated according to needs. Steel framework systems are divided in two construction principles:

Platform construction (Figure 2-39): this building is erected story by story. Story slabs rest on the story height walls.

[93] Staib/Dörrhöfer/Rosenthal 2008, 110.
[94] Deplazes 2009, 97.

Balloon frame construction (Figure 2-40): is a principle where walls have the full height of the building. The slab construction is not directly connected to the walls, instead it is connected to console elements that are welded to the studs.

Figure 2-39: Platform building method (steel-frame construction)[95]

Figure 2-40: Balloon frame building method (steel-frame construction)[95]

2.5.2.2.2 Timber panel systems

The load bearing in timber panel systems is a wall or a slab and not a linear member. The construction principle makes it possible to rationalize the layered assembly. Single components can play a multifunctional role, that reduces the number of layers. For example, a load bearing solid timber panel no longer needs a surface finish internally, instead it only needs coat paint. Timber panel construction systems are subdivided into panel construction, framework construction, block construction and building with timber modules.

a) Timber panel construction: is a principle, where load bearing elements can be small or large panels of timber building materials. They function as booth partition and as structure. The loads are transferred to the concrete foundation floor slabs via panels. Timber panel construction is further divided into construction with timber block panels and solid timber units.

a1) Timber block panels are exceptionally stiff and dimensionally stable elements as shown in Figure 2-41. They are made of processed timber construction materials and stabilized with cross ribs, which prevent bending. The cavities can be used for installation lines or they can be insulated. The elements can carry loads in one direction.

a2) Solid timber panels are completely prefabricated elements that are produced by laminating solid timber (Figure 2-42), processed timber construction or timber shavings under pressure. They can carry loads in two directions. Window openings, installations and cavities are pre-cut. The insulation is applied to the exterior.

[95] Staib/Dörrhöfer/Rosenthal 2008, 111.

Figure 2-41: Timber block panels[96]

Figure 2-42: Solid timber panels[96]

b) Timber framework construction (Figure 2-43) is a principle where timber frame elements act as non-load-bearing infill members in frame construction, however they function as load-bearing in panel construction. The cladding is done with processed timber construction panels (Figure 2-44). The load bearing structure consists of frames of strut-like scantlings. The vertical scantlings transfer the vertical loads from the roof, while processed timber planes absorb the horizontal loads.

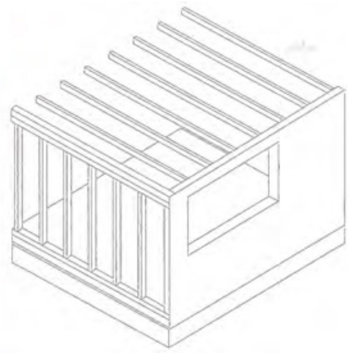


Figure 2-43: Timber frame structural system (isometric diagram)[96]

Figure 2-44: Shell, timber frame construction[96]

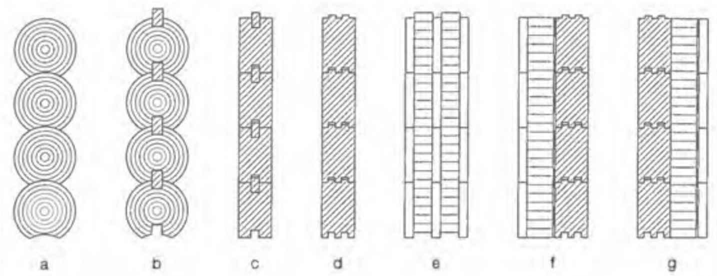


Figure 2-45: External wall in block construction (historical development): round timbers (a), notched round timbers (b), notched scantlings (c), tongue and grooved scantlings (d), prefabricated sandwich elements (e), block-construction wall with external insulation (f), block-construction wall with internal insulation (g)[97]

c) Timber block construction: is a timber construction where walls are constructed of horizontal beams that are fixed at the corners and have load-bearing and partitioning function (Figure 2-45). Solid timber walls function as a plate, which with corner detailing braces these constructions. A variety of different systems with thermal insulation, installation cavities and cladding have been developed.

[96] Staib/Dörrhöfer/Rosenthal 2008, 114.
[97] Staib/Dörrhöfer/Rosenthal 2008, 117.

d) Timber modules is a contemporary timber construction principle, based on cross-wise lamination of solid timber slats, which form timber modules (Figure 2-46). In a specialized, interlinked course, these modules form load bearing walls. The structural systems function as a planar one, so it can absorb vertical and horizontal loads. The cavities can be used for installation or for insulation.

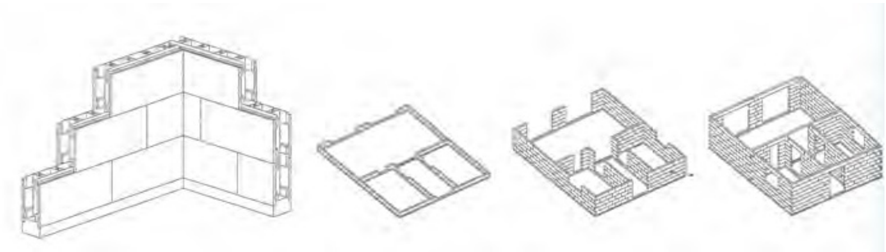


Figure 2-46: Steko timber module connector system, showing corner connection and the construction process.[98]

2.5.2.3 Room module systems

Room modules are load bearing or non load bearing building units, that can be interconnected on the site to form a building (Figure 2-47). A high level of prefabrication can be achieved with all necessary installations, internal fittings and also built in furnishing. Doors and windows can also be included. Most common construction materials for room modules are steel, wood or concrete.

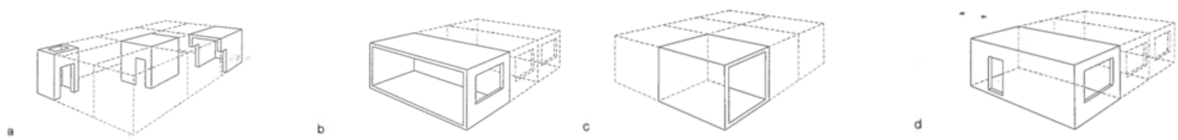


Figure 2-47: Different room module construction systems: combined with large panels (a), with long sides open and load-bearing external walls (b), with one open transverse end (c), all sides closed (d).[99]

2.5.2.3.1 Steel room module system

Room module system is a three dimensional structure which primary construction is formed by welded or bolted steel frames and steel sections (Figure 2-48) or hollow sections. The basic principle of this construction is a frame structure, but when the individual modules are connected, it is capable of forming a load bearing structure of entire building. The infill panels are usually already incorporated by the prefabrication. The cavities are filled with fire resistant thermal insulation as shown in Figure 2-49. The exterior cladding can be done by various materials.

[98] Staib/Dörrhöfer/Rosenthal 2008, 118.
[99] Staib/Dörrhöfer/Rosenthal 2008, 160.

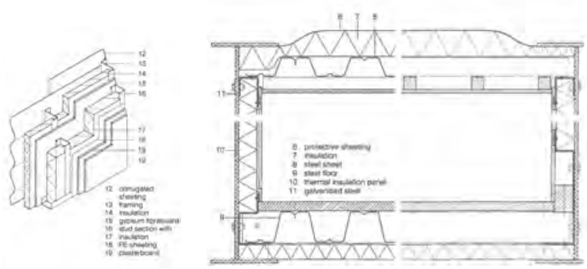


Figure 2-48: Example of a wall construction and a section through a steel room module.[100]

Figure 2-49: Production of steel room modules in a factory.[100]

2.5.2.3.2 Timber room module systems

Timber room module systems are constructed by vertical wall panels and horizontal roof panels that are modularly combined. Various forms can be constructed. The prefabrication can be done complete with installations and internal fittings. Due to low weight, especially comparing to concrete modules, they can be easily transported (Figure 2-50). Double sided cladding with panels of processed timber or alternatively with plaster, is used for bracing. Bracing with rigid corners is also possible. The assembly is done according to principles of solid timber construction, with timber wall, slab and floor panels.

Figure 2-50: Transport and assembly of timber building modules and a section through the module.[101]

[100] Staib/Dörrhöfer/Rosenthal 2008, 161.
[101] Staib/Dörrhöfer/Rosenthal 2008, 162.

3 ENVELOPE CASE STUDIES

In this chapter Solar Decathlon competition houses and the case study house that are used for this study are presented. Further we present the prefabricated lightweight construction house system that is used as a reference model for the researched case studies

3.1 Solar decathlon Europe 2012 case studies

Solar decathlon presents competition houses that are affordable, attractive, and easy to live in, maintain comfortable and healthy indoor environmental conditions, supply energy to household appliances for cooking, cleaning, and entertainment, provide adequate hot water and produce as much or more energy than they consume.

3.1.1 Introduction

Main objective for this research are the projects which have been built for the second edition of SDE, which took place from the 14th to 30th September 2012 in Madrid, Spain. 18 teams from 12 countries (Germany, Brazil, China, Denmark, Egypt, Spain, France, Hungary, Italy, Japan, Portugal and Romania), built 18 energy efficient houses.[102]

Solar decathlon Europe (SDE) is an international competition among universities which promotes research in the development of efficient houses. The objective of the participating teams is to design and build houses that consume as few natural resources as possible and produce minimum waste products during their life cycle. Particular emphasis is put on reducing energy consumption and on obtaining all the necessary energy from the sun.
The teams are competing in ten contests, that is why it is called 'decathlon'. These categories decide which one is the winner of that edition. All of the teams are supported by one or more universities and have the economic and technical support from institutions and companies. The main figures during the whole process, from the design to the last phase of the competition are the students, known as 'Decathletes', who are guided by one or more professors from their Faculties.

The event has a twofold purpose: educative and scientific. The Students learn how to work in multidisciplinary teams and how to face the challenges of the future of building by developing innovative solutions. The SDE is very important for the public so they can see and become aware of the real possibilities of reducing the environmental impact and at the same time keeping quality of the design and the comfort in their homes. For professionals it is even more important to have access to techniques and processes that we can study and use. Moreover, universities, companies and public institutions have access to a new way of collaborating, for example, by trying scientific projects in real conditions to launch them later onto the market or by improving and using in a creative way existing products.

[102] Solar decathlon Europe 2012 Professional Brochure 2011

Solar Decathlon origins come from United States where the department of Energy of the North American government created the US DOE Solar Decathlon competition in 1999 with its first edition being held on the National Mall in Washington DC in 2002. It is a biennial event. First edition of Solar Decathlon Europe was held, with great success, in 2010, in Madrid, with over 200,000 people visiting the sustainable houses of the participating teams. In 2013 first Solar Decathlon China took place. The three competitions have similar principles and objectives, but they are independently organized and have some differences regarding regulations and contests, adapting in this way to their own circumstances and contexts.

The participants of the competition are post-secondary educational institutions, mainly universities. Out of the proposals the Organization selects a limited number of participating teams. The teams are composed of the Team Members and the Team Crew. The first ones are people linked to the educational institution or institutions which lead them, such as professors, graduate/postgraduate students or recent graduates, among others; the second group are collaborating companies, volunteers, sponsors, etc. The role of the 'Faculty Advisor' is especially important. They are the professors who act in the name of the educational institution and guide the team during the development of the project. The final phase of the competition held on site is exclusive for the Decathletes, who are the Team Members (students or recent graduates).

3.1.2 Parameters for the competing buildings

The dimensions of the lots for the teams and their houses are 20 x 20 meters. The buildings also comply with three parameters:

- They had to stay within a Solar Envelope in the shape of a truncated pyramid with a base of 20 x 20 meters (the size of the lot), a superior plane of 10 x 10 m and 6 meters high. In this way, it is implicitly said that the houses can have one or two floors.

- They had to have an architectural footprint of less than 150 m2, considering the exterior perimeter of the house, cantilevers, and moveable components, but not interior open spaces such as courtyards.

- They had to have a measurable area between 70 m2 and 45 m2. The interior space is the thermal envelope, without walls, pillars, closets, and storage from ground to ceiling; considering courtyards at 50% and observing the limits mentioned in any position of the hypothetic moveable elements the project includes. In case the house has two floors, only the biggest one would be considered; and, in any case, the area of the smallest which overlaps with the biggest one shall not be bigger than the 50% of the area of the latest one.

3.1.2.1 Energy parameters

All the energy consumed by the houses had to come from the solar radiation incident upon their lot. At all times during the competition, the house could consume that energy simultaneously (from the production of their PV or thermal panels), or later, obtaining it either from their own storage systems, which may have previously stored that kind of energy (electricity or heat), or from the Villa Solar (Competition ground) grid. In that case, the amount of energy used throughout the competition shall be returned by pouring the energy surplus of the house at some other time.

As for energy generation, there is a limit of 10kW for the whole group of PV and not PV systems. The PV Systems used shall be available in the market at least at the beginning of the final phase of the competition and their price shall be within the limits established in the rules.

3.1.2.2 The ten contests

From the research of buildings in SDE2012 we can summarize that the process of defining the best solar residential building is very complex and is influenced by 10 contests listed below: architecture, engineering and construction, energy efficiency, electrical energy balance, comfort conditions, functioning of the house, communication and raising social awareness, industrialization and market viability, innovation, sustainability.

3.1.2.3 Architecture (jury / 120 points)

An attractive design is sought, which combines comfortable and functional spaces with bioclimatic technologies and strategies for reducing the house’s energy consumption. A jury of professional architects visited each of the houses, looking for a coherent and comprehensive project and focuses on following parameters.

Architectural concept and design approach:

- Does a clear concept guide the design process?
- Is there coherence among architectural, structural, mechanical, electrical, plumbing, and landscaping elements?
- Does the design offer a sense of inspiration and delight?

Architectural implementation and innovation

- Are the scale and proportion, indoor-outdoor connections, and composition effective?
- Is the design holistic and integrated? Will it be comfortable for occupants and compatible with the surrounding environment?
- Is the natural and electric lighting well-integrated? Are the lighted spaces rich and varied?
- Is quality demonstrated in material selection, detail, and implementation?
- Does the house reflect an innovative approach to residential architecture?

Documentation

- Do the team drawings, construction specifications, and audiovisual presentation accurately reflect the constructed house?

3.1.2.4 Engineering and Construction (jury / 80 points)

In this contest, the systems used by the teams to build their houses are evaluated. Their design and on site implementation are considered and also the advisability of their choice. A jury of professional experts reviews the teams' technical documentation and visit the house analyzing the following aspects: the structure, other constructive elements, such as the envelope (facade, roof and floor) and interior partitions (interior divisions of the spaces and their finishes), their acoustic performance will also be studied, electrical and plumbing systems, saving and water reuse systems shall be positively assessed, PV systems, solar thermal systems and the integration of the solar thermal and photovoltaic systems in the design of the building.

3.1.2.5 Energy Efficiency (jury / 100 points)

The cleanest energy is the one which is never consumed. For that reason, the competition lays emphasis on the fact that the teams meet the needs of the occupants of the houses (controlling the interior temperature, the use of appliances, etc.) by using as fewer resources as possible.

In all buildings, there are two main methods, besides the user's behavior, to reach that goal: in the first place, reducing the need to control artificially the energy input/output of the house by making a good use of the resources that the environment offers us naturally (for example, by insulating walls to keep the heat inside the house, or by renewing the air using its own motion); and in the second place, wasting the minimum amount of energy when it needs to be artificially introduced or released from the house (for example, by using low-consumption appliances or by making that the conditioning system is automatically switched on or off).

In the Energy Efficiency contest, a jury had to analyze the technical documentation created by the team and study the house assembled at the location, focusing mainly in six aspects: (1) the design of the envelope (that is, facades, in- door/outdoor roof and floor connections), (2) passive systems (those which use the energy from the environment, such as awnings, natural chimneys, etc.), (3) active systems (mainly heating, cooling, water heating, ventilation and artificial lighting systems), (4) appliances and energy saving devices, (5) control systems, which make possible that the house takes its own decisions to save energy (for example, by opening or closing shutters or windows when necessary, or by switching on the heating system before the users arrive), (6) and an analysis of the energy use in the entire house, with an estimation of its annual consumption carried out by the decathletes.

3.1.2.6 Electrical Energy Balance (Measurement / 120 points)

The ability of the houses to be electrically self-sufficient throughout the year does not depend only on having minimum consumption and the same production or a higher production than that; both things must happen simultaneously or closely in time. In order to assess those aspects, the contest is divided into three parts.

Electricity Autonomy (50 points), which is the difference between the production and the consumption of energy during the competition period is analyzed.
Temporary generation-consumption correlation (40 points), that is the immediate consumption of the energy produced and the capacity of the house to store it are positively assessed; in this way, the loss of surplus energy is prevented and there is no need to use energy from outside when the amount of energy generated is not enough.
Load consumption per measurable area (30 points), which is the aspect that is closely linked to the Energy Efficiency contest, although in this case, only electricity is considered. During some days set by the organization, an average consumption value was calculated for each house. That value was divided by their areas and the index obtained made it possible comparing the efficient use of electricity of all the participating buildings.

3.1.2.7 Comfort Conditions (Measurement-task completion / 120 points)

In this contest, the capacity of the houses to keep the appropriate conditions (temperature, humidity, acoustic performance, air quality and lighting) so that the occupants are comfortable will be assessed. All available points are earned by the teams if they keep the following average values: temperature (23-25oC: 70 points), humidity (40-55%: 10 points), acoustic performance (Dls, 2m, nT, w > 45 dB: 15 points), air quality (<800 ppm CO2: 5 points) and workstation lighting (>500 lux: 20 points). The points assigned were based on the results of the measurements obtained by the sensors installed in the house and of the acoustic test.

3.1.2.8 Functioning of the house (Measurement-task completion / 120 points)

Checks were made on the possibility of performing normal everyday tasks, such as using electrical appliances and electronic equipment, producing hot water or simply inviting students from other participating teams to dinner. A part of the score will be earned by successfully using, under certain conditions established on the competition rules, the following appliances: refrigerator, freezer, clothes washer, clothes dryer, dishwasher, home electronics, oven, hot water draws and cooking.

3.1.2.9 Communication and Raising Social Awareness (jury / 80 points)

This contest assesses teams' ability to transmit to the public the basic concepts behind the SDE competition, as well as ideas contributed by their completed house along these lines, both during the period of prior design and during public visits to the Villa Solar. A jury of experts studied the Communication Plan designed by each team over the two years of the house's development and takes the same house tour as that on offer to the public, assessing it according to its effectiveness, efficiency and creativity.

3.1.2.10 Industrialization and Market Viability (jury / 80 points)

In this contest, the possibility that the house designed for the competition by the teams can be successfully used in the housing industry is evaluated. Some of the factors considered are: the market appeal of the product, the production costs, the possibility of prefabricating some parts of the building, and the possibility of adapting the design to other house models, for example, blocks of houses. The jury considers following categories: Buildability (Do the drawings and construction specifications enable a contractor to generate an accurate construction cost estimate and then construct the house as it was intended it to be built?), Marketability (Does the house have interior and exterior appeal? Is the material, equipment, and detailing choices appealing? Do sustainability feature and strategies contribute to the house's marketability? Is the house a good value for potential homebuyers?) and Livability (Does the design offer a safe, functional, convenient, comfortable, and enjoyable place to live? Does it offer appropriate lighting, entertainment, and other controls? Does it meet the unique needs and desires of the target client?).

3.1.2.11 Innovation (jury / 80 points)

The jury has evaluated whether the teams have offered innovative solutions in any field, from architectural ideas to the development of new materials or systems. The Innovation contest is divided into five subcategories, which are likewise evaluated by a jury: Architecture, Engineering and Construction, Energy Efficiency, Communication and Social Awareness, and Innovation in the Industrialisation and Market Viability. Instead of specifically selecting a group of experts for Innovation, the juries who have evaluated the contests above mentioned have separately assessed the innovative aspects observed in those areas. The total amount of points assigned to Innovation in each contest was the score obtained by the teams for Innovation.

3.1.2.12 Sustainability (jury / 100 points)

This contest considers the environmental impact of the house in its “lifetime” – that is – from extraction and transformation of its materials, building procedures and use, to its demolition and re- cycling. Consideration is given to use of natural resources, possibilities for re-use and recycling, as well as to reduction in waste generation. Most of those impacts are linked to the use of natural resources (such as the stones used to create concrete or the fuel used for electricity generation), and with wastes production (the water polluted in the pit, the gases emitted by boilers, the parts of the building that remain in the garbage dump after being demolished, etc.). But there are also other kinds of impacts, for example, the one caused by the wrong integration of the building in the environment where it is built. It is important that the technicians taking part in the design and construction of buildings and the public using those have that global view of the problem. In the same way as for the Innovation contest, for the Sustainability contest, the reduction of those negative environmental impacts in the work of the teams related to Architecture, Engineering and Construction, Energy Efficiency, Communication and Social Awareness, and Industrialization and Market Viability are analyzed. Nevertheless, in this case it is a specific jury which will do that study based on a report included in the technical documentation submitted by the teams (especially their ‘Sustainability report’) and on the phases of assembly and operation of the house.

3.1.3 SDE2012 result analysis of participating teams

The competition took place from the 14th to 30th September, 2012. 18 teams from 11 countries (Germany, Brazil, China, Denmark, Spain, France, Hungary, Italy, Japan, Portugal and Romania), built 18 energy efficient houses (Figure 3-1) in the Villa Solar, at the Puerta del Angel site within Madrid's Casa de Campo for the SDE2012.

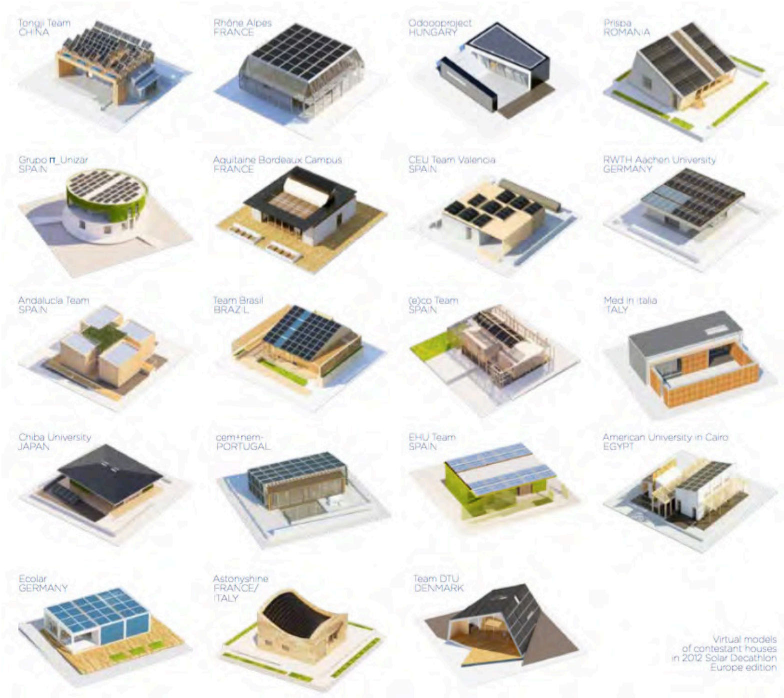


Figure 3-1: Virtual models of contestant houses in 2012 Solar Decathlon Europe edition.

To choose built objects for our case studies we decided to primarily look at the results of the jury in the category of Architecture, secondary into Engineering and Construction, Energy Efficiency, Innovation and Industrialization and Market viability. Following we compared the results with the overall results of the competition shown in Figure 3-2. According to the analyze of Slovenian property market in Chapter 2.1 those five categories should be most important for the investors. In Table 3-1 we compared points given by the jury for each house and category. First column represents points achieved in architecture competition. All houses are sorted ascending according to this column. Looking at the achieved points we decided to set following limits for chosen categories:

- For architecture, engineering and construction, energy efficiency, industrialization and market viability the limit was set to 70 points.
- For innovation category we set the limit to 50 points.
- Overall results to 800 points.
- Five internal categories to 350 points.

All results which are lover than the set limits are marked with red color in Table 3-1. All object results that are marked with green, meet the expected limits. Those projects are further analyzed to be used as case studies.

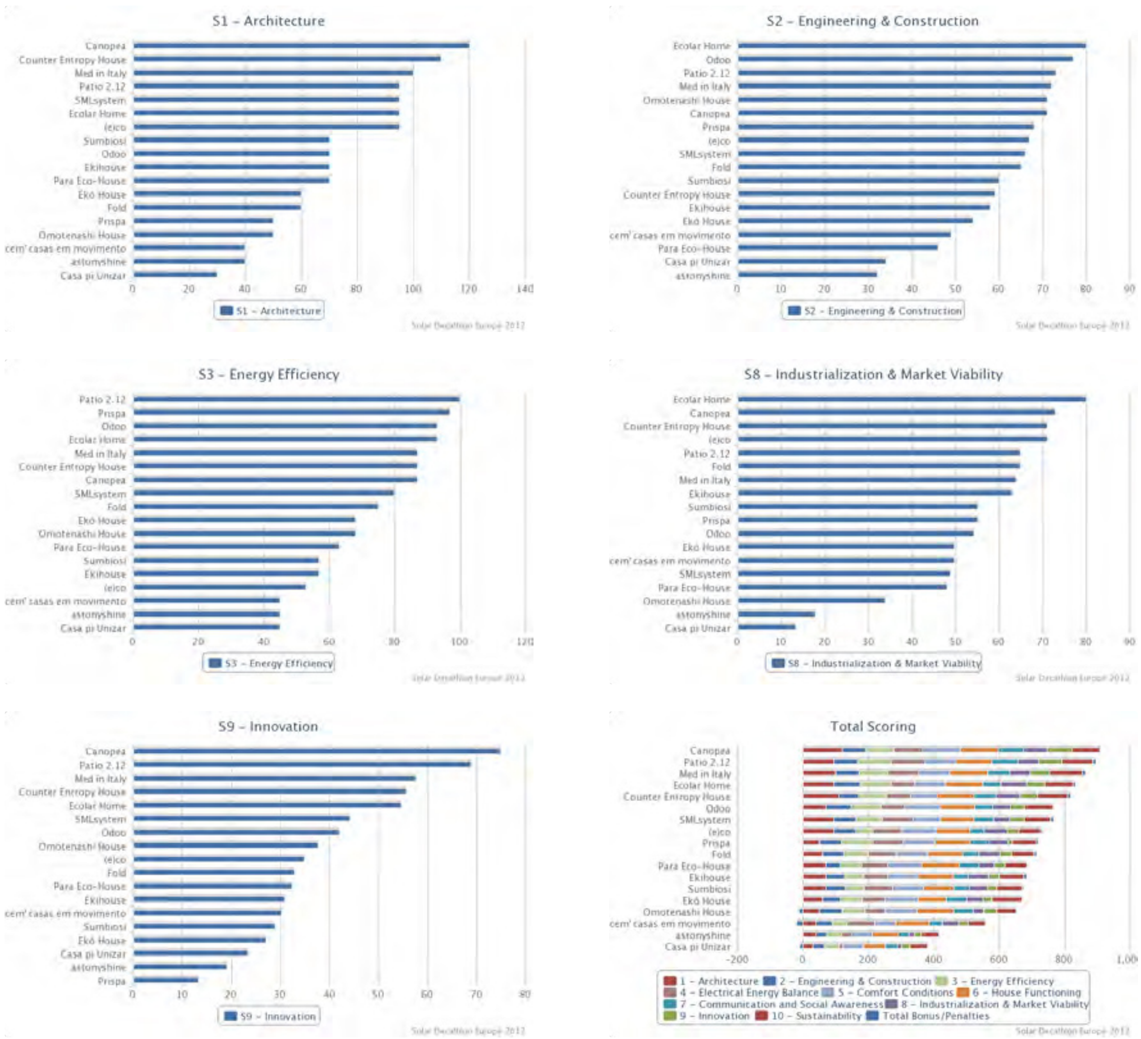


Figure 3-2: SDE2012 results in 5 categories (S1 - architecture, S2 - engineering and construction, S3 - energy efficiency, S8 - industrialization and market viability, S9 - innovation) and overall results (total scoring) taken from the final report of the jury deliberation.

	Architecture	Engineering & Construction	Energy Efficiency	Industrialization & Market viability	Innovation	Total scoring Accumulated	Internal categories (5 categories)
Canopea	120	71	87	72,9	75	908,7	426
Counter Entropy House	110	59	87	71,1	55,6	819,3	383
Med in Italy	100	72	87	64	57,6	863,5	381
Patio 2.12	95	73	100	64,9	68,9	897,4	402
SMLsystem	95	66	80	48,9	44,2	766	334
Ecolar Home	95	80	93	80	54,7	835	403
e(co)	95	67	53	71,1	35	731,5	321
Sumbiosi	70	60	57	55,1	28,9	674,8	271
Odoo	70	77	93	54,2	42,1	767	336

Table 3-1: Position by Jury in chosen categories and total scoring (accumulated and in 5 categories)

The results presented in Table 3-1 show that following 5 buildings were potential case studies: Canopea, Ecolar Home, Patio 2.12, Counter Entropy House and Med in Italy.
For the study, we wanted to evaluate a variety of different construction systems as case studies. This was an important parameter when deciding for the final three cases that where picked for further analysis and adaptation to the case study.
Since both, Patio 2.12 and Counter entropy house (Figure 3-3), have an atrium floor-plan design, consequently it is not possible to adapt their design to a compact floor-plan of the case study house. Further "atrium" is also used for their energy concept and by removing this atrium the energy evaluation results used for LCC calculation would not be objective.

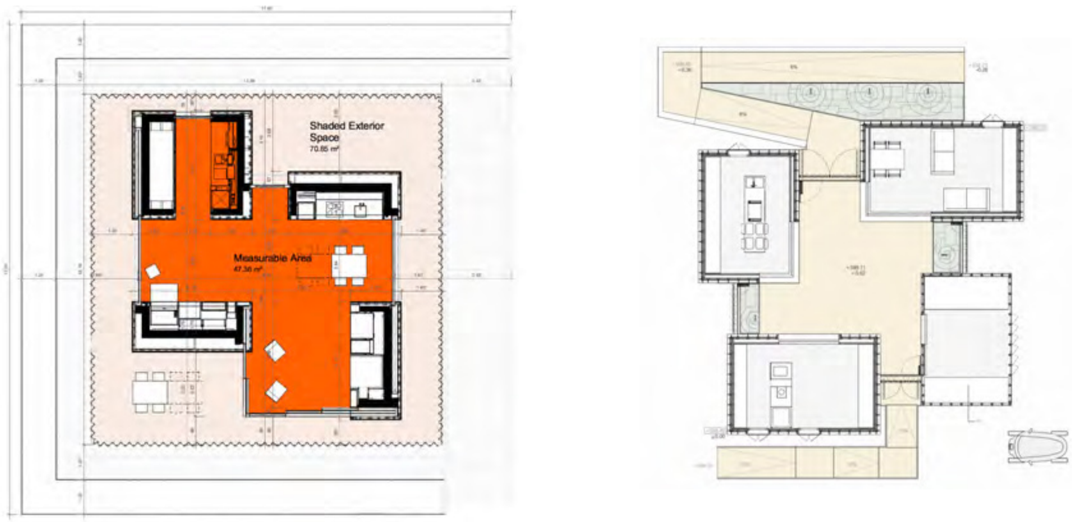


Figure 3-3: Patio 2.12 (left) and Counter entropy house (right) ground floor plans.[103]

Finally, we decided to use following three project's construction systems for the case studies: Canopea (908,7 / 426 points), Ecolar home (835 / 403 points) and Med in Italy (863,5 / 381).

Canopea uses a combined steel and timber frame system. Steel is used to make a very strong skeleton which is able to resist to the distortions due to transporting and lifting. Timber is used in form of industrialized wooden panels alloying lightness and bracing power for walls, partitions, and floors. Walls and partitions are made up of glue laminated wood panels of 27mm thick. The same composition is used for floors panels. They are multifunctional. insuring the steel structure bracing system, and secondary supporting the internal and external facing, and the equipment. They are horizontally fixed to the posts. These constructions lead to a dry process, without any need of water during the construction steps. Moreover, the dry process ensured a better quality to insulation and siding materials.

Ecolar home has a modular design of the structure. It has a timber constructional constructional grid out of columns and beams, therefore various floor, roof and wall elements can be inserted into the supporting structure. The insulated hollow box sections and the surface elements form the energy-efficient thermal envelope of the building. Weather protecting cover panels on the outside of the supporting structure and a water-bearing

[103] Solar decathlon Europe technical documentation, http://www.sdeurope.org/downloads/sde2012/, 20.10.2013

energy-roof complete the building envelope. Three types of facades (translucent, transparent and opaque) were used for the project in SDE2012. We used the special opaque facade elements that combine passive and active solar energy use in a high-energy performance element for our case study. The high tech external envelope reduces heat losses to about half a conventionally insulated external wall with the same thickness.

Med in Italy prototype was designed as a system rather than a single object. The basic building elements of the system are: 3D modules, 2D elements (walls, roofs and floors), photovoltaic surfaces. The central, three-dimensional module (3D core), hosts all the main technical and mechanical parts of the construction and is completely assembled in the factory. All the rest of the house is a timber panel system, with wood lumber frames cladded with sheets and panels. This gives to the system a great flexibility in terms of possible layouts. Adding to the typical panel walls is a cavity, that is filled with sand. Light elements are transported, and on the site, filled with humid sand in order to get the inertial mass and to optimize thermal behavior.

Using the external envelopes of selected prototypes, we got three different external skins for our case study. First is a combination of steel and wood, with a very good thermal transmittance value. Second is a high tech envelope with a dynamic u-value. Third is a low tech solution, that adds another cavity to a standardized prefabricated panel system, adding thermal mass to it with sand in filled alloy pipes.

In following subchapters, we analyze chosen SDE2012 prototypes that are used for the case study and were selected as described in the previous chapter.

3.1.4 Canopea (École Nationale Supérieure D’Architecture de Grenoble)

No.1 / 908,7 points

Contest 1: Architecture: 120,0 points.
Contest 2: Engineering and Construction: 71,0 points.
Contest 3: Energy Efficiency: 87,0 points.
Contest 4: Electrical Energy Balance: 87,1 points.
Contest 5: Comfort Conditions: 114,9 points.
Contest 6: House Functioning: 116,9 points.
Contest 7: Communication and Social Awareness: 77,3 points. Contest 8: Industrialization and Market Viability: 72,9 points. Contest 9: Innovation:75,0 points.
Contest 10:Sustainability: 86,7 points.
Bonus Points and Penalties: 0,0 points.

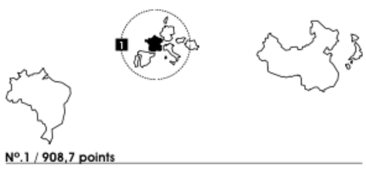


Figure 3-4: Points of the jury deliberation of the SDE2012 edition.

Team Name
- Rhone Alpes

Project Dimensions
- Built Area (two floors): 195,9 m2
- Surface area: 150,0 m2

- Net floor area: 68,8 m2
- Conditioned Volume: 202,5 m3

Figure 3-5: Canopea house by École Nationale Supérieure D’Architecture de Grenoble.[104]

List Of Singular And Innovative Materials And Systems

- Air Phase shifter (Institut Forel - University of Genève).
- Operable louvers rolling shutters (Bubbendorf)
- Vacuum insulation.
- High performance triple glazed wooden folding windows (Menuiseries André).
- Earth plastered radiant walls and ceilings (CRAterre).
- Compact P machine + air distributing system (Nilan).
- Cascading HVAC and Plumbing system at Nanotower scale.
- Radio electric fixtures and sensors (Schneider Electric).
- Photovoltaic thermal hybrid solar collectors SunEezy inverters (Schneider Electric).
- Power capping capacity. 4,7 kW storage in lithium batteries and inverter-charger (Studer).
- Silk-screened bi-glass PV panels (Tenesol). Radiative cooling PVT panels (Auversun& Solar2G).
- Energy management system and control tablet (Vesta System).
- Energy savings features: zeolite in dishwasher, PCM emulsion in DHW tank, pre-heated

[104] Team Rhone-Alpes, Project Manual #5 2012

water inlet for washing machine, clothes dryer with integrated heat pump, grey water heat recovery and night sky radiant cooling system.

Energy Balance
- Estimated energy balance: +5713 kWh/year

Cost
- Construction Cost: 700.000 €

3.1.4.1 Architecture[105]

Canopea® concept stems from the specific geophysical context of Lyon, Grenoble where land is scarce and expensive because of mountains and rivers. These are dense cities traditionally used to build six to eight story high buildings. On the other hand, 86% of French people, Rhône-alpians are dreaming of a single house in the countryside.
The urban territory was considered as an ecosystem in which space, infrastructure, land, energy and resources are mutualized in order to achieve a global sustainability. Canopea® proposes a project of collective apartment building integrated in an urban ecosystem organized around the mutualisation of infrastructures and equipment as well as the sharing of land and space.

Their architectural proposal is a NANO-TOWER (Figure 3-5), a piling up of seven single houses on a commercial basement, and topped with a common space. It shares an elevator shaft, a staircase and several connecting passageways with other nano-towers or with other traditional buildings. Each living unit occupies a complete floor. You can take full advantage of the 360° view. Garden boxes and storage boxes make the living units larger since these functions are externalized, allowing private gardens and privacy for each unit. Peripheral catwalks allow you to go around each living unit. Land cost is shared. Heavy duty mutualized equipment are installed in the basement along with commercial spaces. On the top floor, there is the common space protected by the glass PV roof panels.

The prototype, built for SDE 2012, presents the top apartment and the top common space of one of the nano-tower. The living unit floor offers a 69 m^2 apartment that presents all qualities of a single house.
Living space is organized around three "boxes" with specific functions:
- A prefabricated core containing all fluids and technical systems (kitchen, bathroom, tech-room).
- A master bedroom box offering a "cocoon-earth" ambiance to sleep in (bed, built-in cabinet, earth-plastered walls).
- An extra flexible space which dimensions can be adapted according to the displacement of a movable piece of furniture. This extra room can be used as a TV room, an office or an extra bedroom for friends, it can become a permanent bedroom for new parents or disappear to merge the kitchen and the living room in a large and fluid open space perfectly suited for parties.

[105] Team Rhone-Alpes, Project Manual #5 2012, 24-125.

Other combinations of apartments are possible:
- Two stories can be used to organize a duplex four bedroom apartment combined with a studio.
- Two studios can be layout on the same floor.

The nano-tower concept is highly adaptable to different spatial conditions in order to create social diversity. All cores are stacked vertically in order to facilitate pipes and ducts transit. Each tech-room is accessible from the exterior.

There are following innovations in architecture used for the house:
- Social mix and bearable urban density: Canopea® program is based on a variety of uses and functions that create an urban biodiversity ensuring sustainability at the city scale.
- Innovative architectural type: a nanotower is a stack of individual housing units providing spatial qualities close to those of the single house (outdoor extensions of indoor living spaces; peripheral walkways allow people to go around their home, 360° view in all directions, one apartment per floor, individual privacy in a dense urban environment) while taking advantage of city facilities (schools, health and daycare centers, public transportation systems, shops and public spaces...)
- Interior space flexibility due to movable furniture block allows people to take advantage of multiple spatial configurations (from rooms to an open space plan).
- Common space: a specific space provides a sense of community and complete the apartments' functions.
- Integration of urban agriculture in the project. Vertical farms are possible in the middle of each open block.

Engineering and construction[106]

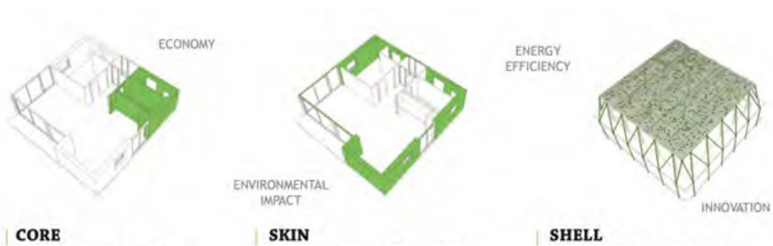


Figure 3-6: Canopea constructive system: CORE / SKIN / SHELL decomposition principle[107]

Core/skin/shell assemblage shown in Figure 3-6
- Core: Compact prefabricated block, containing all technical equipment. To limit assembly faze on the site, it can be completely industrialized.
- Skin: High performance thermal envelope which defines the tempered zones of the housing unit. The skin can be realized with local materials and prefabricated elements by local companies at controlled costs.

[106] Team Rhone-Alpes, Project Manual #5 2012, 126-263.
[107] Team Rhone-Alpes, Project Manual #5 2012, 77.

- Shell: this is the additional and innovative eco-structure, that supports photovoltaic panels and ensures solar protection. Its concept is to be produced by CNC process.

Innovative key-features of the constructive systems and structure

- a production process adapted to French building industry: industrialized CORE / locally produced SKIN / tailored prefab SHELL. They are built in dry assembly process, which reduces the assembly time on site and limits the environmental impact of the construction phase
- Mixed structure metal + timber: peripheral steel structure holding large span wood slabs, which comply with medium seismic conditions and allow a free floor plan for housing
- Use of natural materials: earth plaster on interior partition walls, heated wood sidings and exterior deck flooring

Prototype Construction

The structure of Nano-towers is designed as a simple «column and beam» system made of HEA steel profiles sitting on piles drilled in the ground. Each tower structure is separated from the other, including the vertical distribution tower, in order to prevent seismic disorders. Walkways and common slabs are equipped with sliding supports on one side. Each tower's structure can be decomposed in two parts:

- A main central load bearing structure made of columns and beams located in the SKIN part of the tower.
- A peripheral "exostructure" supporting facades and terraces of each floor. This structure is equipped with diagonal bracing in order to prevent the building to rotate under seismic accelerations.

The construction that was built for the SDE Madrid is the extraction of the two top floors of a Nano-tower, where the first floor is an apartment floor, and the top floor is a multi-purpose common space. The prototype is managed differently compared to the Nano-tower.
Due to the very short construction time it was chosen to be prefabricated at a maximum possible level. It was prefabricated according to the truck transportation possibilities. Materials with a high mechanical resistance where chosen, trying to limit the prefabricated element weight due to transporting and lifting reasons. Wood and steel where a good combination for Rhone-Alpes team:

- steel makes a very strong skeleton which is able to resist to the distortions due to transporting and lifting,
- industrialized wooden panels are light and present bracing power for walls, partitions, and floors. For the floors, they choose wooden panels' box beams. This solution presented an advantage in economy of material and its lightness. Moreover, these constructions choices lead to a dry process, i.e. without any need of water during the construction steps. This means no drying time between construction steps, which is a time-saving. The building cost is also decreasing. Moreover, the dry process ensures a better quality to insulation and siding materials.

Constructive design

The stages of the construction are: manufacture of metal belts high and low, installing and attaching floors, installing and attaching posts, installing and attaching walls and partitions walls in wood panel, the low floor joists, wood studs of walls and openings, grid wooden false ceiling.

Primary structure

Manufacture of metal belts

The belts are metal rectangular frames (Figure 3-7) which consist in four beams which receive and distribute building loads. These beams are profiles UPE 200. At the end of each UPE, a 15mm thick small plate welded to 45 ° allows the UPE to assemble together to form frames. Gussets stiffeners (15mm plates) distributed over the entire length of the UPE allow the assembly at the bottom of post to stiffen.

Figure 3-7: Metal belts

Installing and attaching floors

The floor is made of structural glued laminated wood boxes. A box is composed in two horizontal wooden boards connected by ribs (Figure 3-8). The panels are made of 3mm veneer glued together thanks to hot and very high pressure. The interior is filled with cellulose wadding that provides partial insulation of floors. The boxes are placed on the UPE belts.

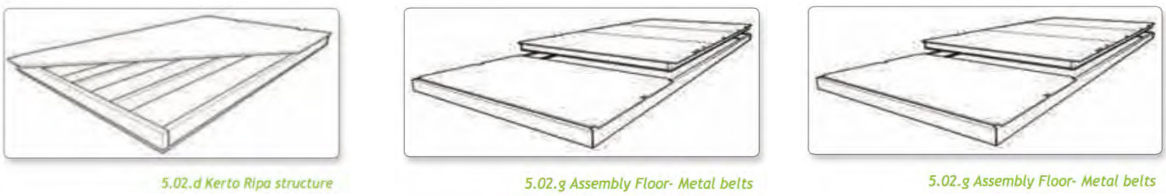


Figure 3-8: Floor assemblies

*Installing and attaching posts (*Figure 3-9*)*

The posts are specific metal profiles; there are three types :

- half IPE 200
- metallic angle bars 100
- temporary posts which are only used for transporting

The web of the post has shortened tips for better load distribution. A small metallic plate welded to 15mm post distributes the load in the bottom and top of the post. Under the posts, reinforcement metallic plates (stiffeners) can prevent the spillage of volume. The partition walls are attached horizontally to the posts with three metal plates. These metal wings are attached to poles and attached to the partition wall in glued laminated wood.

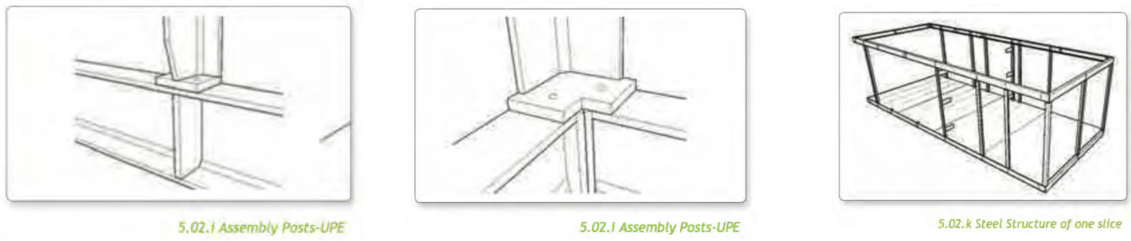


Figure 3-9: Posts assemblies

Installing and attaching walls and partitions

Walls and partitions are made up of glue laminated wood panels (Figure 3-10). It's the same composition with the floors panels. They are multifunctional: first of all, insure the steel structure bracing system, and then support the internal and external facing, and the equipment. They are horizontally fixed to the posts. With the top floor installed and attached to the slices the structure is finished.

Figure 3-10: Walls and partitions

The exostructure

The exostructure is the house shell structure; it is the support of all the protective layers of the house. It is one hundred percent steel made (Figure 3-11). The wood on it has no structural function.

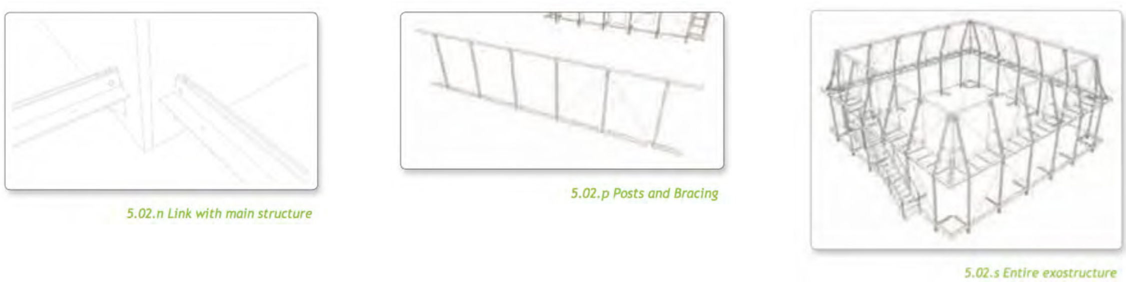


Figure 3-11: Exostructure assembly

For transportation and prefabrication reasons the four facades are independent, and each façade is divided in three parts: the base, the first floor exostructure and the second floor exostructure. The structure drawing is regular. The same elements and assembling are repeated six times on each facade. The main element composing the structure is a reformed and welded profile, that is to say a profile made especially for this structure. It has a cross drawing in the section. The base is composed of three elements: an adjustable foot, a welded pillar and a profile (a double corner iron) linking the pillar with the steel belt of the main structure. This part works like a beam, two corner irons are linked by the six pillars. Plates are welded on the corner iron, and pillars are bolt on it. Bracings make the beam stable. The four different facades are assembled together in three points. One is at the extremity of the bottom corner iron of the first floor beam, the second one is at the extremity of the top corner iron of the first floor beam, the last one is at the extremity of the top corner iron of second floor beam.

3.1.4.2 Energy efficiency[108]

The goal of the project was to reduce consumption by reducing the needs and to share production installations, and to limit network consumption peaks by shifting the internal demands. To reach these goals, the building was designed as high performance passive construction following bioclimatic principles shown in Figure 3-12.

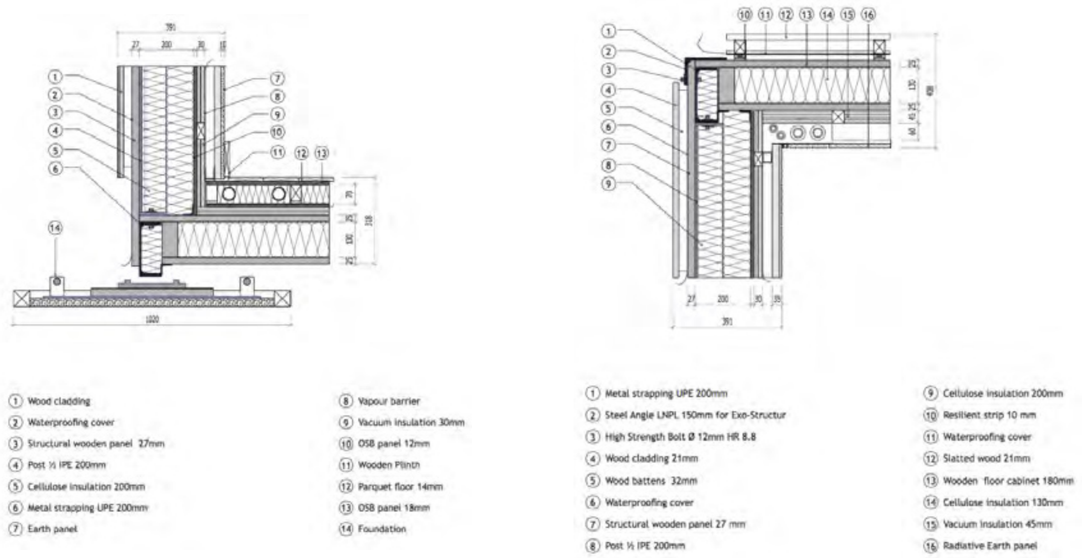


Figure 3-12: Canopea house construction details[109] (down corner section – left and upper corner section – right).

To maximize solar gains in cold season, while limiting them during the warm season, the architectural design and the high performance thermal envelope was developed (Figure 3-13), with efficient mobile and fixed solar protections as well as natural cross ventilation.

	Area	U
	m^2	$W/(m^2.K)$
Walls	66,12	0,0875
Floors	80,48	0,0872
Roof (ceiling)	80,48	0,0796

Area and thermal transmittances

Figure 3-13: Thermal transmittance of the structures

To complete this passive approach, the energetic active strategy was based on sharing of as many equipment as possible. As a key source for heating/cooling needs coverage and sanitary hot water production the building used low temperature (25°C) water thermal loop

[108] Team Rhone-Alpes, Project Manual #5 2012, 264-445.
[109] Team Rhone-Alpes, Project Manual #5 2012

accessible as a media for in/out energy exchanges. The project defines collective equipment placed in the basement and individual ones placed in each home. The PV production plant (BIPV and PV/T panels) is located on the roof and takes part in a smart electric grid.

<u>Energy strategies</u>

Environment integration: HVAC installation is integrated into its urban environment (thermal water loop, resources...)

Seasonal strategy:

- Limited heating needs due to low thermal loses through high performance thermal envelope (Figure 3-13)
- Efficient cooling strategy thanks to efficient equipment and solar protection
- PV plant optimized for summer production

Phase-shifting strategy (limits instantaneous consumptions on urban network during consumption peaks):

- Thermal storage thank
- Thermal air-phase shifter (ventilation system)
- Electricity storage: PV production stored in batteries for consumption peaks power-capping

Energy loses valorization: energy is also considered through its quality. The objective was to use any source of energy until its exergy is not null, losses of a system can be a resource for another.

Cascading systems: HVAC installations are designed on different levels of production for a global efficiency. Repartition of systems between individual and collective scale takes into account efficiency and footprint to ensure inhabitants comfort.

Metabolism systems: innovating connections between efficient equipment lead to a better global efficiency

Regulation system: flow and temperature sensors permit to know instantaneous systems' status. A smart regulation system collects these data to make the best combination choice for energy efficiency, sobriety and occupants awareness.

Building Management System: each home is equipped with a BMS allowing to pilot interior comfort conditions through a tactile tablet.

<u>Passive strategies - Architecture and systems</u>

Bioclimatic design: thermal envelope provides high insulation performances with the thermal performance of other shell of U = 0.20 W/(m^2K) as shown in Figure 3-13

- The envelope: net floor are/ gross floor area – an efficient ratio;
- Bioclimatic openings repartition: natural lighting from the four directions, various solar protections, four side orientation for natural ventilation, multiple buffer spaces
low intro for a quick thermal answer;

Passive equipment: lower energy consumptions while improving global efficiency (thermal air phase-shifter, power pipe)

<u>HVAC systems</u>

Ventilation (and part of heating/cooling):

- Thermal air-phase shifter + Compact P: air/air heat pump combined with counter current air exchanger
- Distribution: air blown in floor distribution ducts, extracted in ceiling

Heating/cooling:

- Collective storage tank connected to the collective water/water JVP heat pump + mixing bottles
- Terminal unit: radiant ceiling panels

Domestic hot water (DHW) production (3 levels of heating):

- Power pipe on grey water (passive system)
- Collective storage tank connected to the collective water/water heat pump
- Individual storage tank connected to the individual air/air heat pump

3.1.4.3 Industrialization and market viability [110]

Canopea® project implies important evolutions in management as well as the use of new constructive systems favoring prefabrication and dry assembly in order to improve quality control level and to lower construction costs. Building's innovative constructive system follows a CORE/SKIN/SHELL decomposition principle (Figure 3-14). These three pieces put together and made in very different ways, according to very different techniques, with various knowhow and tools, make it possible to build very quickly. The biggest part of the final cost is related to labor cost, that is why for this project it was essential the quicker the assembly of the three pieces, the cheaper the house. These different parts are assembled on site mechanically. The idea is to mix high-tech and low-tech so that high performances standards can be reached and local jobs are preserved.

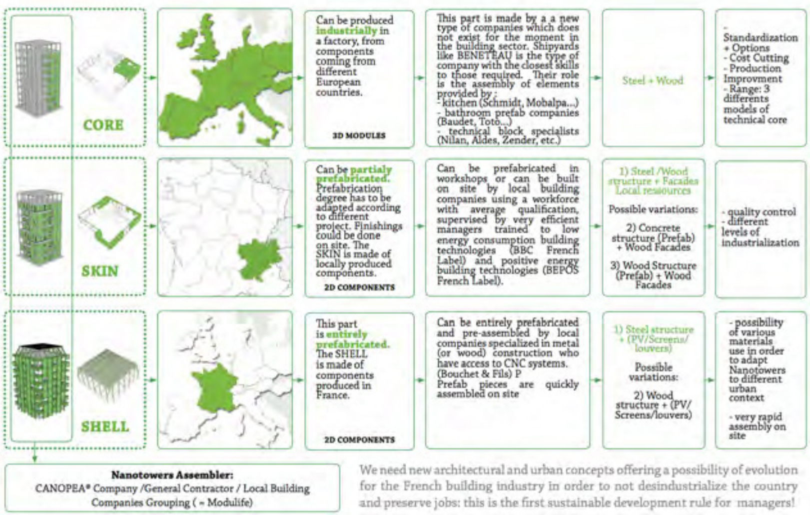


Figure 3-14: : Nano tower industrialization concept[111]

The real nanotower programs that were planned in Lyon and Grenoble show that it would be possible to position Canopea® on the actual market in the 1800€/m^2 SHON (Surface hors oeuvre nette - net surface) to 2000 €/m^2 SHON VAT free construction costs range.

[110] Team Rhone-Alpes, Project Manual #5 2012, 558-664.
[111] Team Rhône-Alpes, Industrialization & Market Viability Brief Report 2012, 5.

The idea is to sell the project to real estate companies and to control its construction costs thanks to the core-skin-shell principles. It can also position itself in the niche market of cooperative housing. Canopea® project innovation is finally as social and spatial as technological. Materials and technologies used in the project already exist. But it is the specific way they combine them and articulate them in a real ecosystem that makes the difference (Figure 3-14).

3.1.5 Ecolar Home (University of Applied Sciences Konstanz)

No.4 / 835,0 points

Contest 1: Architecture: 95,0 points.
Contest 2: Engineering and Construction: 80,0 points.
Contest 3: Energy Efficiency: 93,0 points.
Contest 4: Electrical Energy Balance: 72,8 points.
Contest 5: Comfort Conditions: 95,4 points.
Contest 6: House Functioning: 113,9 points.
Contest 7: Communication and Social Awareness: 56,0 points.
Contest 8: Industrialization and Market Viability: 80,0 points.
Contest 9: Innovation: 54,7 points.
Contest 10:Sustainability: 86,7 points.
Bonus Points and Penalties: 7,5 points.

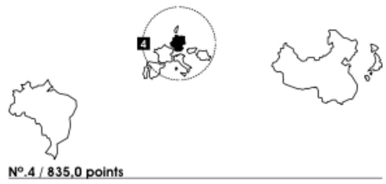


Figure 3-15: Points of the jury deliberation of the SDE2012 edition.

Team Name
- Ecolar

Project Dimensions
- Gross area: 78,40 m2
- Net floor area: 67,60 m2 Conditioned Volume: 175,76 m3

Energy Balance
- Estimated energy balance: + 8891 kWh/year

List of Singular and Innovative Materials and Systems
- Building Integration Photovoltaic (BIPV).
- Lucido facade system: Innovative glass façade panels with a PV cells layer in front of an air cavity with wooden fins that reflect most of the sun`s rays during summer months and absorb solar energy in the winter time, insulated with wood- wool.
- Latent Thermal energy storage (LTES): PCM enriched clay plates in the radiant cooling ceiling. - - Humidity regulation: Clay plates at ceiling help to regulate the humidity level.
- Daylight system with the use of optical fibre technology.
- Photovoltaic thermal hybrid solar collectors for passive heating/cooling.
- Night sky radiant cooling system.
- Grey water heat recovery.

Cost
- Construction Cost: 360,000 €
- Industrialized Estimate Cost: 200,000 €

Figure 3-16: Ecolar house concept by University of Applied Sciences Konstanz.[112]

3.1.5.1 Architecture[113]

The ECOLAR Home consists of six modules. Four of them serve as interior spaces; two of them are designed as patios. The modular concept of the building is clear from the outside (Figure 3-16). The inserted wall panels can easily be distinguished from the columns and beams. The facades of the patios are glazed, so natural light can reach the interior. In order to increase protection from the sun and privacy, the patios can be screened with curtains.
The architecture of ECOLAR prototype is based on a modular system with a 16 m^2 cube as basis. The rooms have a square floor plan that offers the maximum flexibility in terms of utilization. The geometry allows both, the typical residential usage as living room, bedroom, dining, kitchen, guest rooms, sanitary facilities and so on, as well as alternative uses such as office workstations, recreation room etc. This ensures a high level of sustainability with regard to the use of resources. Another essential approach of this prototype is the possible extensibility (or reduction ability) of the concept in all three dimensions (Figure 3-17): length, width and height. The statics of this developed prototype allows a three- to four-story house. It can function as a pavilion, atrium, row-house or multi-story-building with the same architectural concept.
The prototype is an exemplary solution of the ECOLAR concept. It has 6 room units, of which 2 are formed as two-sides-open patios. The rooms are in principle open to every use and can be defined by using the specially designed, also modular so called “super cabinets”.

[112] Team Ecolar, Project manual 2012
[113] Team Ecolar, Project manual 2012, 12-15.

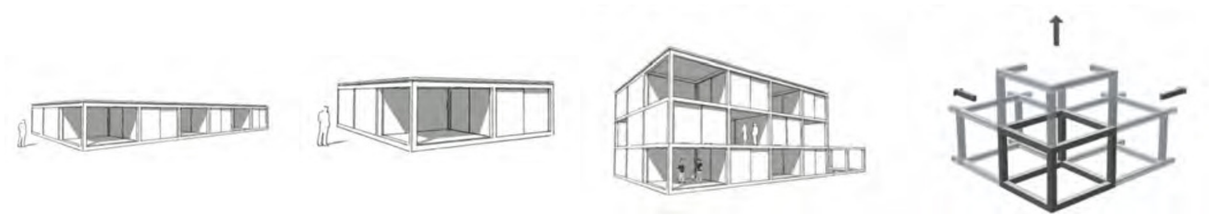


Figure 3-17: Extensibility of the concept in all three dimensions[114]

Another important aspect of the prototype is the integration of innovative high-performance technology, without compromising the residential character of the building itself. All surfaces, apart from the glazing, are made from local wood. The entire building technology is fully integrated and invisible.

3.1.5.2 Engineering and construction[115]

The structure of the prototype is based on the potential expandability in all three dimensions as shown in Figure 3-17. It is following modular principles. Primary structure is the constructional grid out of columns and beams. Infill elements, such as various floor, roof and wall elements, are then inserted into the structure. These elements form the energy-efficient thermal envelope of the building. With weather protecting cover panels and a water-bearing energy-roof they complete the building envelope. Three types out of many possible were built for SDE 2012 (translucent, transparent and opaque):

- Type 1: fully glazed transparent elements provide a very good daylighting and relate the interior to the exterior. Due to a special sliding technique the facades open wide and the outer space can be connected to the interior.
- Type 2: newly developed translucent elements form an attractive room structure with diffuse daylighting. Filled with a special fleece and wooden slats the facades are optimized for south or north sides with a focus on daylight transmittance or solar control.
- Type 3: Special opaque facade elements combine passive and active solar energy use in a high-energy performance element. The translucent photovoltaic coating on the outside produces electrical power, the inner layers of special wooden slats and hemp insulation work in combination with solar radiation highly insulating and reduce heat losses to about half a conventionally insulated external wall with the same thickness.

The structural elements are made entirely from renewable resources. The columns and beams are hollow box girder made of wood. They reach a much higher static efficiency compared to a solid wood construction with the same usage of material. Special glued wooden boards, made from split wood veneers without losses in the cutting process, are used for the construction. The cavities of the elements are filled with fast growing hemp fibers. Thus, construction and facades can be constructed in a common plane, which allows maximum flexibility. The elements are connected by simple single supports made of steel and bolted joints. The entire construction of the structure and building envelope can be fitted and removed very quickly, with only three types of screws. The horizontal bracing in the

[114] Team Ecolar, Jury reports 2012, 1.
[115] Team Ecolar, Project manual 2012, 16-64.

longitudinal direction is set by the opaque facade modules, which are statically connected to the columns and beams. The transverse bracing were provided by a newly developed system made from static effective glass-wood composite (Figure 3-18).

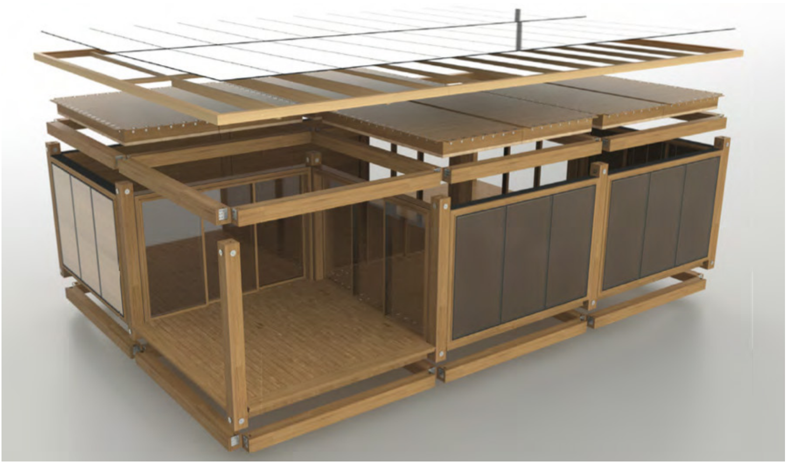


Figure 3-18: Construction design of Ecolar prototype[116]

In this prototype water plays an important role since all thermal energy flows are realized through the medium of water. All pipes within the building are integrated into the wall, ceiling and floor panels. Tall downpipes for rain-water are integrated into the inner columns of the structure. Integrated into the outer layer of the opaque walls are built-in semitransparent photovoltaic elements that characterize the building with its homogeneous, translucent appearance of the view. The modules serve also as a weather protection of the facade and through the translucency allow passive solar gains.

3.1.5.3 Energy efficiency[117]

The ECOLAR prototype's envelope is base on the fact that a good building envelope is the basis for every energy-efficient building.
This prototype concept ensues the following conditions:
- Only local wood from sustainable forests are used for structural parts.
- Only local, fast growing and purely biologically treated hemp (cannabis plant) fibers are used as insulation material.
- Only triple-glazing is used (with the future goal: vacuum glazing)

The building envelope uses solar gains in the heating period and offers an effective external and individually adjustable sun protection in cooling periods. All unshaded surfaces are used for active solar energy, which is creatively integrated into the overall concept and always meets multiple uses.
Based on these conditions, a building envelope was created that provides an appropriate use of materials with maximum energy efficiency. The floor and roof elements, have a very good U-values of less than 0,15 W/m2K in a total thickness of just 30cm. The window elements with a Low-E-Coating and inert gas filling achieve U-values of 0,6 W/m2K. The newly developed translucent glass elements (Figure 3-20) in the south and north facades are filled

[116] Team Ecolar, Jury reports 2012, 5.
[117] Team Ecolar, Project manual 2012, 65-87.

with horizontal wooden slats in the outer layer and with a special fleece in the inner layer (Figure 3-19).

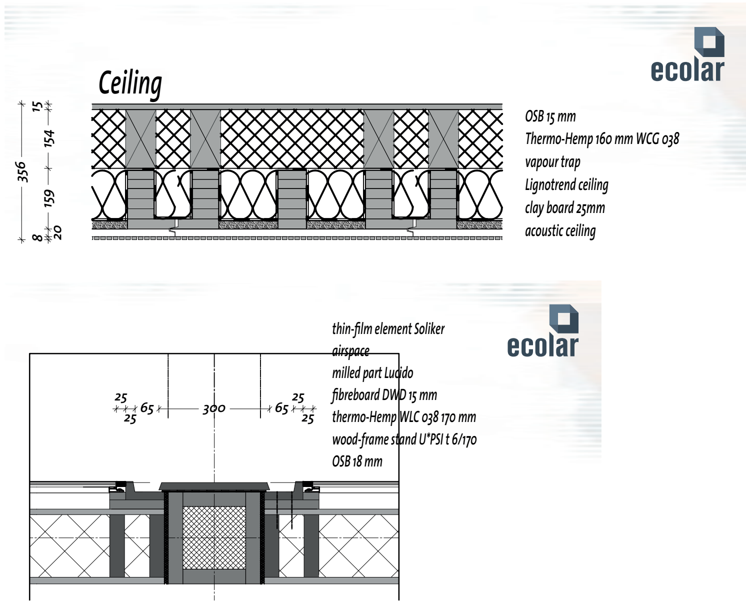


Figure 3-19: Ecolar house construction details[118] (ceiling detail – up and Lucido wall system – down).

The wooden slats adopt the horizontal structure of the longitudinal walls. In the version for the south side they are slightly tilted to form an effective sunscreen. The fleece forms the sight protection and provides for a homogeneous and diffuse light. Both fillings act as a convection barrier and generate without noble gas also a Ug-value of 0,6 W/m2K.

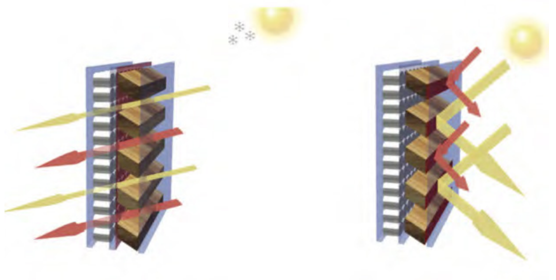


Figure 3-20: Translucent multifunctional façade element[119]

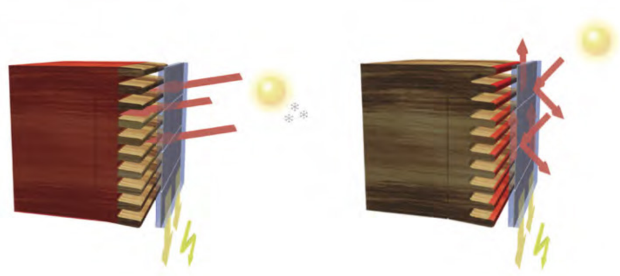


Figure 3-21: Opaque multifunctional façade element[119]

On the longitudinal sides the envelope is formed by 4 different layers, which together provide a combination of passive and active solar energy use. The inner layer consists of hemp insulation, followed by a specially milled layer with horizontal wooden slats, which are slightly inclined downwards and after that an air gap. The conclusion and weather protection is a laminated glazing that is coated with a translucent photovoltaic layer (Figure 3-21). Additional solar beams can pass through the 30-percent translucence, and they warm the wooden slats and the spaces in between them. This leads to higher temperatures than outside, which greatly reduces the heat losses by transmission. Calculated openings at the top and bottom

[118] Team Ecolar, Project manual 2012
[119] Team Ecolar, Project manual 2012, 284-285.

effect that during the heating season, an unmoved layer of air forms at a low temperature level in between the glass. At high temperatures however these openings prevent overheating of the facade element via convection. This creates a dynamic U-value, with a value of less than 0,01 W/m2K during heating season. The system is as efficient as a conventionally insulated exterior wall of double thickness.
Energy efficiency of the prototype is targeted at efficient minimization of consumption and a widest possible use of solar radiation. Building envelope's surfaces are using passive or active solar radiation to generate heat, daylighting, power generation or cooling. All solar power generated by the photovoltaic cells is used directly in the building if it is needed. Most ventilation is provided by an effective cross-ventilation through location of individually adjustable sliding doors.

3.1.5.4 Industrialization and market viability[120]

The prototype uses prefabricated, standardized elements, thus the modules can be simply reproduced. The modules can be combined in horizontally and/or vertically, designing individual living space. In need of change, the building adapts easily. The idea behind this prototype is to revolutionize the residential market with this design concept. This could be done with its high flexibility, the very short assembly time and the low price that can be achieved by prefabrication of all the components.
ECOLAR brand of the prototype is linked with environmentally friendly buildings and living space. The ECOLAR house should provide sustainable, energy efficient living space for everybody and shorten long construction times for clients. Long-term goal is to make such building financially accessible to the mass market. According to people behind this prototype, with the modularity and flexibility of the ECOLAR Home, it is possible to realize a cheap and basic self-sufficient house. There are also important innovative principles used for the house. One of them is the possibility to individually design an inexpensive prefabricated house, that holds the highest degree of flexibility and the cutting edge of technology, focusing aesthetically and comfortably on to the highest level. The advantage of this system is that the basic concept can always be used. The structural elements never change and individual components can be erected and rearranged as needed.

	Low production level 1-2 houses/year	*Medium production level 100 houses/year*	*High production level 1000 houses/year*
Production costs per house	*€ 500,000*	*€ 350,000*	*€ 200,000*
*Recovery time**	*4 – 5 years*	*1 year*	*2 months*
Benefits per house	*€200,000*	*€150,000*	*€100,000*

**It is assumed that the initial investment amounts €1.5 million.*

Figure 3-22: Economical evaluation of Ecolar prototype[121]

The ECOLAR Home is by Team Ecolar considered as a high-price house at the beginning of the product life cycle. However, according to them the modular design significantly reduces

[120] Team Ecolar, Project manual 2012, 229-269.
[121] Team Ecolar, Project manual 2012, 252.

the costs and the focus should shift from the capital cost to the Life Cycle Costs (Figure 3-22).

3.1.5.5 Innovation[122]

The biggest innovative advantages of the ECOLAR home are:
- short assembly time because of a high degree of prefabrication and a simple unit construction system
- individual combination of interior and exterior equipment
- extension or reduction of the ECOLAR Home at every time
- low costs as a result of leasing models and lowest running costs by being self-sufficient
- the house can adapt to the inhabitants needs, and can even move with them

The following integrative and multifunctional approaches have been realized in design:
- The energy-roof is drained into an internal gutter; the downpipes are integrated into the inner columns of the structure.
- The interior floor elements have a built-in floor heating made from new graphite-coated wooden slats.
- The roof elements include a clay layer behind acoustically effective wood slats, which balances the humidity through little gaps. Moreover, the clay layer is mixed with PCM material, thus achieving a high degree of thermal buffering of heat loads in the interior. Finally, the clay layer is additionally permeated with water carrying pipes, so that the ceiling can be used as an active cooling-element, if needed.
- Two ventilation appliances with heat recovery are integrated into the storage units and are easily accessible for maintenance.
- The air supply works via the light gap between the cabinet modules and the ceiling.
- For the air intake and the exhaust air, the gaps between the opaque facades and the construction are activated. Between the “active” glazing and the construction elements, a corresponding grill is integrated.
- The gaps between the cabinet and the ceiling are activated by built-in LEDs for interior lighting.
- The service connections, water storage and building automation systems are included in the super-cabinet behind the kitchen, which can be opened towards the room.
- In the bathroom, the illuminated ceiling is fitted both with LEDs and daylight extraction elements. These are connected by wall-integrated fiber optic with the light receptor in the pool outdoors.
- Integrated in the outermost layer of the opaque walls are semi-transparent thin film photovoltaics, which characterize the elevation of the house with its homogeneous translucent appearance.
- The water bearing roof forms the completion of the cubic structure via a gap. It includes opaque and transparent photovoltaic cells on the whole surface. Additionally, the rear

[122] Team Ecolar, Project manual 2012, 270-299.

side is equipped with solar-thermal absorber and serves, next to the water bearing, as an electricity and solar heat generator and night-cooling radiation device.

3.1.6 Med in Italy (Università degli Studi di Roma TRE + Sapienza Università di Roma + Free University of Bozen + Fraunhofer Italy)

No.3 / 863,5 points

Contest 1: Architecture: 100,0 points.
Contest 2: Engineering and Construction: 72,0 points.
Contest 3: Energy Efficiency: 87,0 points.
Contest 4: Electrical Energy Balance: 93,9 points.
Contest 5: Comfort Conditions: 96,5 points.
Contest 6: House Functioning: 115,9 points.
Contest 7: Communication and Social Awareness: 66,7 points.
Contest 8: Industrialization and Market Viability: 64,0 points.
Contest 9: Innovation: 57,6 points.
Contest 10:Sustainability: 100,0 points.
Bonus Points and Penalties: 10,0 points.

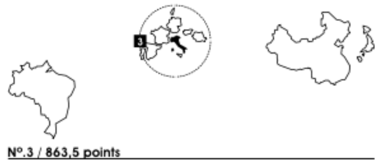


Figure 3-23: Points of the jury deliberation of the SDE2012 edition.

Team name
- Med in Italy

Project Dimensions
- Gross area: 68,04 m2
- Net floor area: 55,49 m2
- Conditioned Volume: 143,89 m3

Energy Balance
- Estimated energy balance: +8501,97 kWh/year

List of Singular and Innovative Materials and Systems
- Thermal mass, walls with interior layer of aluminium tubes filled with sand
- Windows frame design avoiding thermal bridges Selective glazing
- Advanced Building Automation and Control System (BACS)
- Active solar systems combined with thermal mass Low embodied energy materials
- Recyclable and reusable outdoor flooring made of recycled plastic panels filled by vegetables (exhausted olive pomace)
- Ventilated walls with canvas cladding
- Bitumen free waterproofing membrane based on vegetal components
- High concentration of plants in the “3D core” Mechanised ventilation windows controlled by the house automation and control system
- Climate control system powered by a small power air to water heat pump with controlled mechanical ventilation and active heat recovery
- Radiant ceiling
- 3 water buffer tanks: for space heating, for space cooling and for DHW.
- PV architectural design

- High efficiently polycrystalline silicon cells Efficient appliances with remote control features for energy savings
- Optimised natural lighting on work areas Photo-luminescent products for safety indoor use Mechanical filtering of grey water and UV disinfection device

Cost
- Construction Cost: 160.000 €
- Industrialised Estimate Cost: 124.000 €

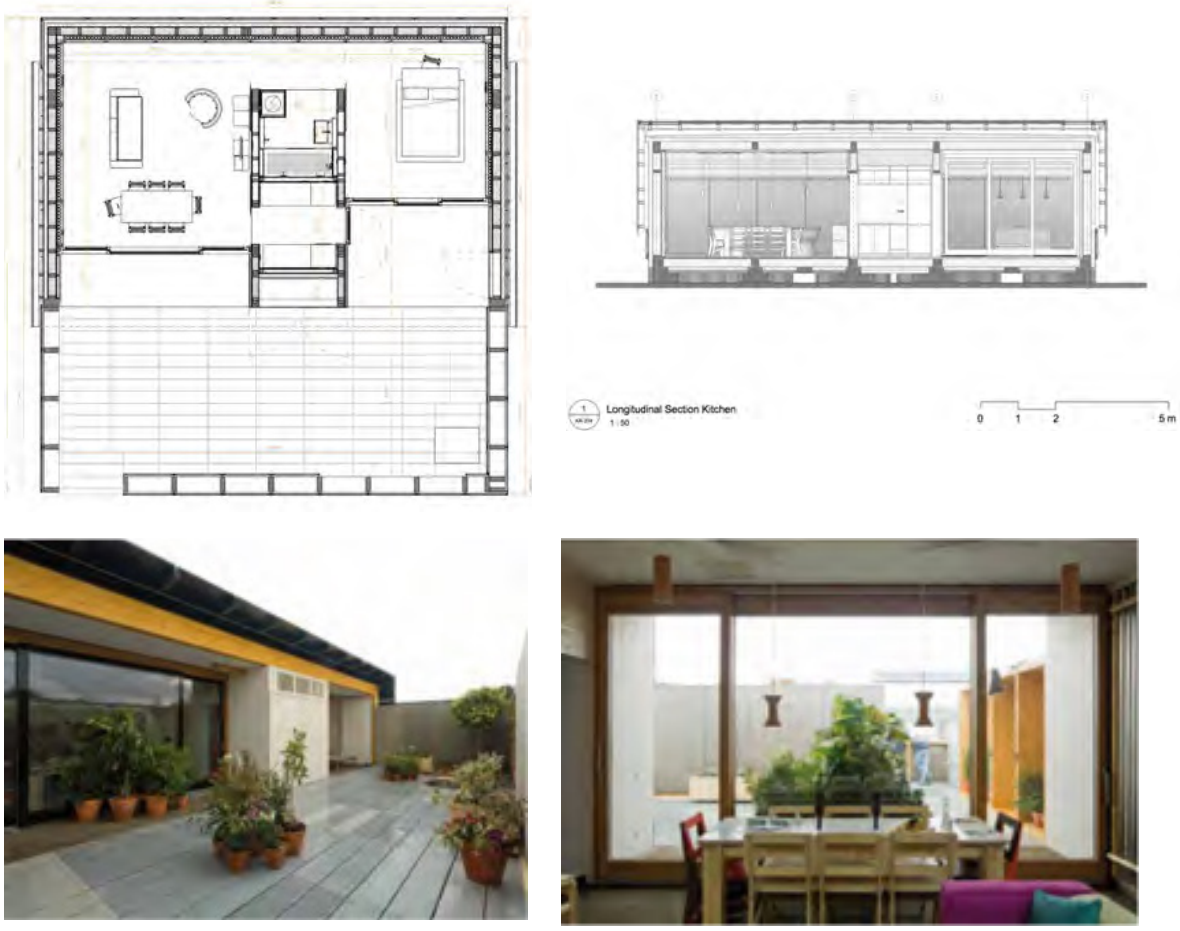


Figure 3-24: Med in Italy house concept by Università degli Studi di Roma TRE, Sapienza Università di Roma, Free University of Bozen and Fraunhofer Italy.[123]

3.1.6.1 Architecture[124]

In this design, the outdoor space is an integral part of the residential area and accomplishes specific bioclimatic functions to moderate the temperature difference between the inside and the outside, strongly reducing psychometric problems in the building envelope (Figure 3-24). Outdoor plant sensors reveal the presence of pollutants and indicate potential biological damage to living organisms in actual situations of air pollution. Internal comfort control derives from traditional Mediterranean typological and morphological solutions to "passively"

[123] MED Team, Deliverable #7 2012
[124] MED Team, Deliverable #7 2012, 6-51

manage inside temperature and “buffer zone” areas, frequently designed as loggias, courtyards or patios.
Architectural design of Med in Italy prototypes is a mixture of innovation and tradition. Bioclimatic concept is derived from tradition and innovation in adapting traditional model to the contemporary needs. The house was conceptually designed for Mediterranean climate, where more effort is needed for cooling than for heating. For team MED it was essential to avoid heat, therefore the design provides: protection from solar radiation, heat inertial storage and thermal dissipation by using temperature alternation between day and night. The interior is connected to living in the outdoor spaces according to the Mediterranean context.

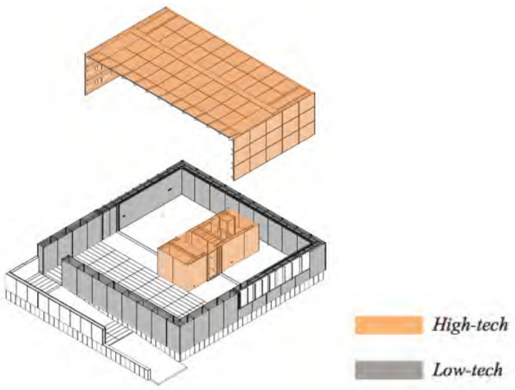


Figure 3-25: High tech internal core and PV envelope and Low tech external walls.[125]

Figure 3-26: Internal alloy tubes in-filled with wet sand in the cavity of the wall.[125]

The outdoor space is an integral part of the residential area in this prototype and accomplishes bioclimatic functions to mediate the temperature between inside and outside, highly reducing the psychometric problems of the building envelope. The design’s essential principle is the contrast between hi-tech and low-tech construction (Figure 3-25). The low-tech part has an external textile layer out of hemp canvas that shapes the building and is also used for shading. The assumption of the prototype is that textile, if properly exposed, could give high performances, right for building envelopes in temperate to hot climate.

Primary wooden structure holds this textile formwork, and is filled with loose inert from the building area, such as sand or soil. This heavier wall with thermal inertia is in sharp contrast to the lighter North European systems (framed). They act as thermal fly-wheels in winter and in summer. The massive material in the prototype is wet sand, contained in aluminum tubes, for easy dis/assembly (Figure 3-26).
The high tech is divided into external and internal. The roof and east and west walls are protected and shaded with PV envelope, which becomes a building element. The internal high-tech core of the house hosts kitchen and bathroom as well as the HVAC technical room. It concentrates all the technical appliances avoiding electrical dispersion, reducing water distribution length and facilitating assembling phases.
In the interior there is the same contrast between tradition and innovation and low tech and high tech of the architectural design. At the spatial level the house is conceived as a

[125] MED team, Architectural brief report 2012, 3-9.

traditional one, in which the living room, kitchen and the bedroom are strongly separated. However, the continuity and fluidity of the space is assured by an “art gallery” on the corridor wall that also has a thermal gain function.

3.1.6.2 Engineering and construction[126]

The main principle of this design is to have a prefabricated house, where as much as possible is manufactured at the factory, but to still have a great variety of outputs to maintain appeal to architecture. To achieve this strategy, a system was designed, rather than a single object. This system has following building components: 3D modules, 2D elements (walls, roofs and floors) and photovoltaic surfaces. All designed with transportation vehicles as parameter. One of the strategies was to keep the construction elements simple and therefore easily adjustable, enabling greater flexibility horizontally and vertically. The construction parts can be used as (Figure 3-27): extensions, partial demolitions, retrofitting etc.

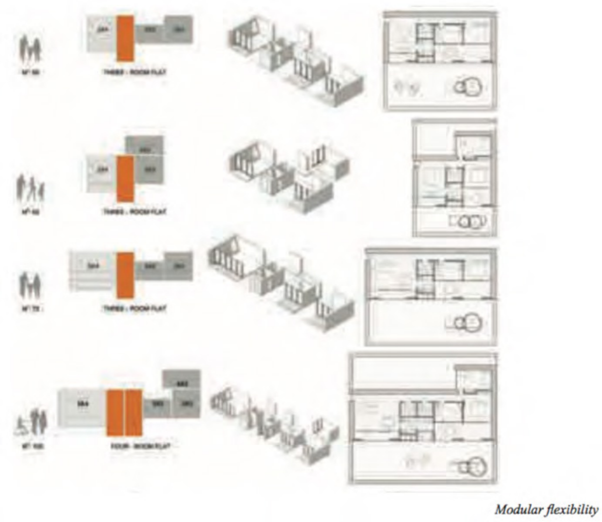


Figure 3-27: Modular flexibility of the prototype.[127]

All prototype’s hi-tech components are assembled in a “3D core”, which is totally prefabricated. The three dimensional module contains the bathroom, with accessories, finishes and plumbing, the fully equipped kitchen and the mechanical room with all technical supplies. This all is fitted into a transporter width of 2,4 m.
Besides the “3D core”, the flexibility of layouts is granted due to wooden construction made of clapped wood lumber frames. The innovation of the prototype is brought by the cavity. Light aluminum tubes are transported and put in the inner cavity and in filled with humid sand locally. The construction behaves as heavy masonry due to optimized thermal mass of the lightweight construction. Sand can also be substituted with similar local materials.
PV envelope is integrated into architectural design of the prototype. They are used for electricity production and also as a shading device. They are multi-oriented and detached from the external skin, to produce electricity during different periods of the day.
Even though it was not required by the competition rules the prototype’s structure is able to sustain seismic forces since it’s design is for Mediterranean. This is the main reason for the

[126] MED Team, Deliverable #7 2012, 52-133.
[127] MED team, Architectural brief report 2012, 8.

introduction of steel plates and brackets all along the house and in particular in special nodes.

3.1.6.3 Energy efficiency[128]

Through the combination of the higher mass solution, shading strategy, daylighting and natural ventilation the prototype reaches 90 kWh/m^2 of primary energy consumption which is below the passive standard limit.

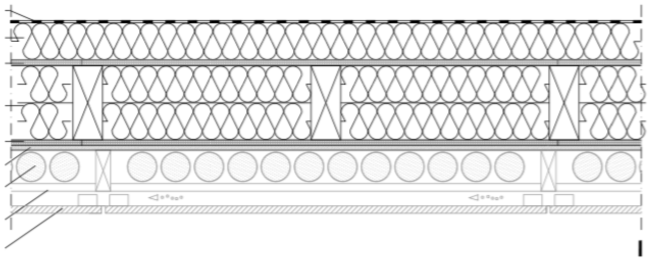


Figure 3-28: Detail of the wall prototype with aluminum pipes.[129]

The aim of the prototype was to develop an efficient strategy for hot climates, with a timber frame structure. To achieve this goal, thermal mass of the wooden frame structure was increased with sand filled aluminum pipes (Figure 3-28 and Figure 3-29) as described in previous chapters. The reduction of the total weight of the structures is up to 30% less, compared to a homogenous layer of dry sand and the whole thermal capacity was increased at least up to 20% thanks to increased surface exchanging the heat, due to a ventilation of the mass itself. It makes this wooden structure comparable with a traditional insulated brick wall.

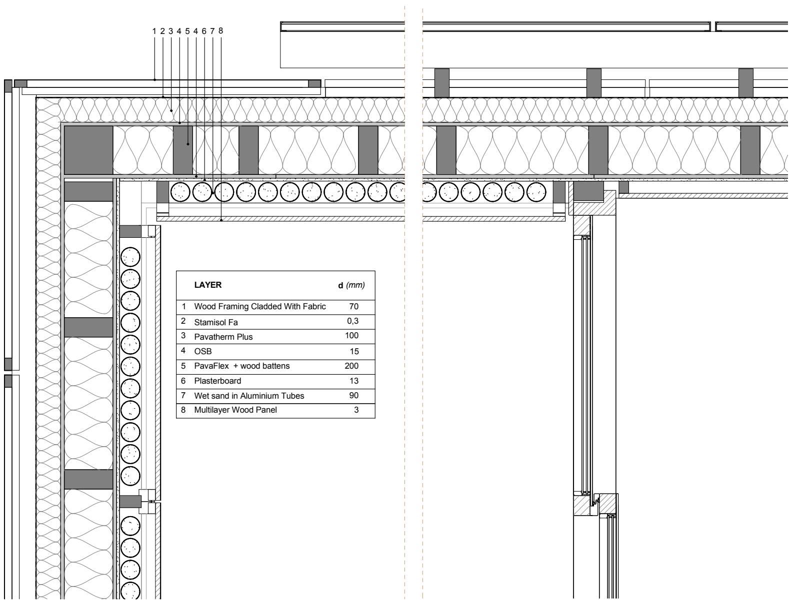


Figure 3-29: Med in Italy house construction details (wall – horizontal section).[130]

[128] MED Team, Deliverable #7 2012, 134-190.
[129] MED Team, Deliverable #7 2012, 346.
[130] MED Team, Deliverable #7 2012

The two main active circuits of the HVAC system are a heat pump air-to-water and an upgraded air-exchange system to satisfy the humidity and CO2 in peak times. To reduce the electrical power demand and to improve the contemporaneity of energy production and energy requests, thermal storage systems have been adopted in form of three different tanks:
- 200 l of 55 °C hot water for sanitary, shower and kitchen uses;
- 100 l of 35 °C hot water for heating purposes;
- 100 l of 15 °C cold water for cooling purposes.

3.1.6.4 Industrialization and market viability[131]

According to Team MED two factors could make the Med in Italy value offering unique in the Italian and international competitive arena. This factors are high levels of considered functional (fit for warm climates) and emotional (Italian design) features. It is appealing for end users, moreover also for constructors willing to widen their product lines, entering a new market.
The principle of the house is at the same time efficient and highly customizable to the needs and desires of possible householders. The structure is mostly prefabricated but there are no standard components. A series of standard material sources is given and then all the rest of the process is customization of those base components through CNC machining. The idea behind it is to develop a "mass customization", that does not require standardization of building components, and aesthetic of repetition. Crucial to this process is therefore an integrated design system, able to link dynamically the generation of construction and performance information with the development of a possible layout for the houses.
They designed a digital structure for the generation of design, engineering and construction information, where different specialists and sources could converge in a centralized "intelligent" 3D model of the house. This allowed them to manage a network of contributions, since know-hows and products coming from many partners of theirs, needed translation and combination to be constantly managed in their implications on a house that works as an integrated system, no matter how simple or complex.

3.1.6.5 Innovation[132]

According to MED Team the industrialization of the Med in Italy prototype is linked to a strategy of advanced prefabrication. All the components of the house would be produced in the factory, directly from digital les. It generates a totally new concept of prefabrication, that does not require standardization of building components, and therefore an aesthetic of repetition. The most interesting aspect of this process lies in the industrial aspect of it.
As described by Team MED the innovation of product happens only with an innovation of process. Therefore a new structure had to be developed, in order to manage a new kind of outcome.

[131] MED Team, Deliverable #7 2012, 246-339.
[132] MED Team, Deliverable #7 2012, 240-241.

The result is the possibility to offer the market a house product, where all the quality and the emotional impact of a Mediterranean and Italian architecture is fed by its technological generation.

3.2 Reference prefabricated lightweight construction house in Slovenia

In this chapter we will present the prefabricated lightweight construction house system that is used as a reference model to the researched case studies. For this study we choose a Lumar house because in an independent research "Best Buy Award" 2015/2016 they received for the second time in a row the “Best Buy Award – Nr. 1” for best price performance in the category of prefabricated houses. They are a company with the highest credit rating in Slovenia and were 2015 selected into 50 best rated Slovenian companies. [133] The international research for Best Buy Award was done by the Swiss company ICERTIAS (International Certification Association). The research is based on a survey of 1200 samples done in Slovenia. The survey participants were limited to persons involved in building sector (architects, civil engineers and technicians, construction workers, building managers, private investors etc.)[133].

3.2.1 House Primus by Lumar

For this research we used their house model Primus, which is according to Lumar[134] their best sold house model.

3.2.1.1 Architecture

House model Primus, shown in Figure 3-30, has a compact floor-plan with open living spaces, joining living, dinning and cooking.

Figure 3-30: Lumar house Primus-R120 (Sample house and floor-plans)[135]

It has two floors and steep or a flat roof to be chosen by the client. It has a flexible design, which is one of the parameters of it being appealing to the property market. The house is designed with energy efficiency parameter highly regarded. The house model has a compact

[133] Best buy award - Drugič zapored z najboljšim razmerjem med ceno in kakovostjo, http://www.lumar.si/novica.asp?ID=152, 18.11.2015

[134] Predstavili bodo najbolje prodajano hišo Primus (15.3.2015), http://www.finance.si/8818940/Predstavili-bodo-najbolje-prodajano-hišo-Primus, 15.5.2015

[135] Primus F-120, http://www.lumar-haus.at/haus.asp?ID=109, 15.5.2015

form, to decrease the thermal transmittance. Passive solar energy is collected through big opening oriented towards the south and has smaller openings on the northern side.

3.2.1.2 Engineering and construction

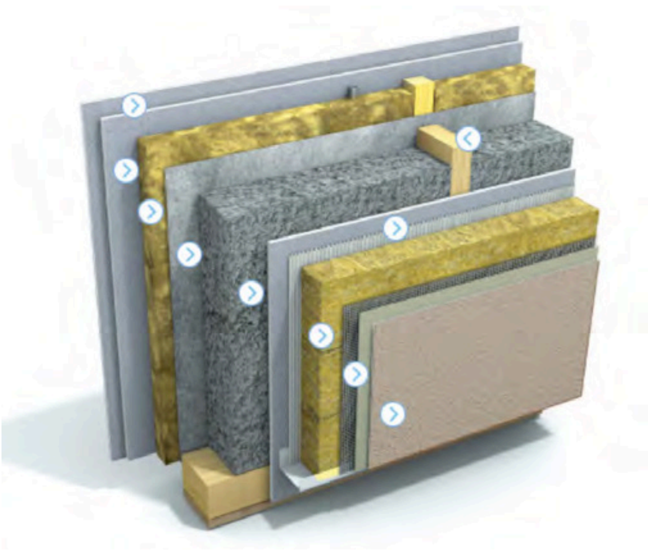
Overall design is accompanied by Lumar's trademark energy efficient building construction technology, with optimized details. With its design simplicity and energy efficiency, this house model presents an optimal entry level house into very good energy efficient one-family prefabricated houses. The use of standardized building materials is one of the main advantages of this timber panel system.

Prefabricated walls have main vertical bearing elements in form of linear timber elements. The most common cross section in use is 60x160 m. This is because of the thickness of insulation. Typical distances between vertical linear elements is a=1250 mm. Standardized height of this elements are h=2500 to 2600 mm. Vertical timber elements are enclosed with sheets of board-material fixed by mechanical fasteners to both sides of the timber frame. There are many types of panel sheet products used, which may have some structural capacity such as wood-based materials: plywood, oriented strand board, hardboard, particleboard, etc., or fibre-plaster boards. Between the timber studs and girders, a thermo-insulation material is inserted. By default, the thermal insulation used is air-injected cellulose. The thickness of thermal insulation depends on the type of external wall. The sheathing boards on both sides of the wall can be covered with a 12.5 mm gypsum- cardboard.

3.2.1.3 Energy efficiency

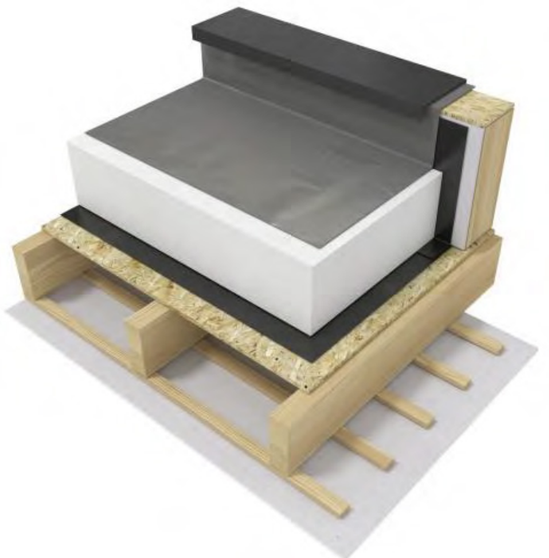
Lumar offers a variety of construction composite elements of different types, relating to energy efficiency. In this study we use their widely used system Lumar Prestige. This system features a very good thermal and sound protection. The main geometrical and material properties of the LP1 wall element are presented graphically in Figure 3-31 and Figure 3-32. House model Primus with Lumar Prestige system is categorized as a very good low energy house by default. The energy demand for such house is according to Slovenian legislation between 15 kWh/m^{2}a and 25 kWh/m^{2}a. To achieve this standard, the house model has a sufficient external thermal layer including the efficiency of the exterior furnishing. Also important is a sufficient air tightness of external envelope, which is smaller than n50 > 1,0h-1. The system is open to vapor diffusion.

The technical installations are placed into insulated installation layer maintaining the air tightness. Cellulose thermal insulation for cavities between construction studs and mineral thermal insulation for installation layer and exterior insulation layer is used. With this system, it is possible to achieve an overall energy demand between 20 to 25 kWh/m^{2}a. Because of low energy demands the heating is done with floor-heating (or wall, or ceiling) and a thermal pump, which is by default air to water. Such houses are entitled for subsidies by the “Eco” funding of Slovenia (2015).



01	Final layer	2 mm
02	Reinforced plaster	3 mm
03	Thermal insulation (mineral)	100 mm
04	Plaster-fiberboard	15 mm
05	Timber bearing construction	160 mm
	Thermal insulation (cellulose)	160 mm
06	Vapor barrier	0,2 mm
07	Timber substructure	60 mm
08	Thermal and sound protection	60 mm
09	Plaster-fiberboard	15 mm
10	Plaster-fiberboard	10 mm
	Wall thickness	**365 mm**
	Thermal insulation thickness	**320 mm**
	Thermal conductivity (W/m2K)	**0,119**

Figure 3-31: Lumar Prestige construction system - wall[136]



01	Polyethylene waterproofing	2 mm
02	Mineral inclined thermal	300 mm
03	bitumen vapor barrier and	
04	OSB panel	18 mm
05	Laminated spruce beams 60/240	240 mm
	timber under construction 70/22	22 mm
06	Plasterboard (fire proof)	12,5 mm
	Roof thickness	**367 mm**
	Thermal insulation thickness	**30 mm**
	Thermal conductivity (W/m2K)	**0,11**

Figure 3-32: Lumar standard flat-roof system[136]

3.2.1.4 Industrialization and market viability

The degree of prefabrication has been gradually increased since the introduction of timber panel systems, and it has already reached the limits imposed by the system itself[137]. Thanks to its great flexibility and high degree of prefabrication, it has been widely accepted as the standard by the building industry of prefab houses[137]. The further development of platform frame system is the panel construction and further timber framework construction. The wall elements with a total length of up to 12.5m, containing openings for doors and windows are now completely produced in a factory[138]. The construction systematically creates a floor-by-

[136] Tip konstrukcije, Lumar Prestige & Lumar Energy, http://www.lumar.si/konstrukcijski-sistemi_prestige-energy.html?phpMyAdmin=25d4dda21d1770ec1efe0cc63d777e6b, 15.5.2015
[137] Deplazes 2009, 99.
[138] Kozem Šilih/Premrov 2010, 1656.

floor building. After the walls are constructed the floor platform for the next level is built, therefore, this system is very useful and popular for multi-story buildings and interest in this system is growing around the world[139].

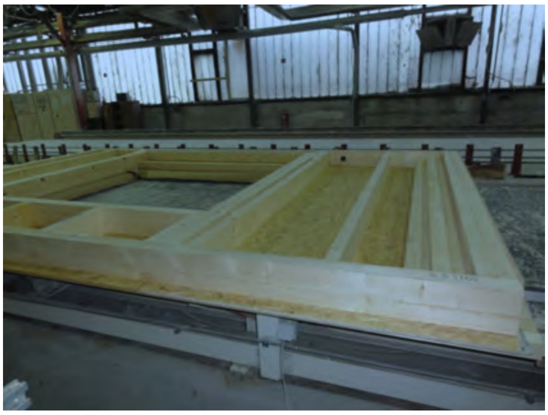


Figure 3-33: Factory manufacturing of prefabricated timber-frame walls.

Figure 3-34: Panel construction assembly on site.

Such systems are used so, that whole wall assemblies, including windows and doors, are prefabricated in a factory on a horizontal plane (Figure 3-33), from where they are transported to the building-site (Figure 3-34). Consequently, there is practically no need for horizontal connections between wall elements, therefore the houses are built in a substantially shorter period of time, compared with platform frame construction.

[139] Žegarac Leskovar 2012, 12.

4 METHODOLOGY

In the following subchapters research methodology and software used for this case study is presented. Methodology is used according to the BIM use purposes consistent with Kreider and as presented in Figure 4-7. Two kinds of software are used for the research. To gather and generate information we used BIM Software Archicad[140]. Case study analysis where done with the integrated life cycle analysis software Legep[141].

4.1 Value for money in construction

Nowadays, not only Slovenia, but the whole world is facing very tough economic challenges. It is more important now than ever before to work wisely with the resources you have at disposal and therefore optimize the **value for money**.

While traditional economic evaluations for real estate focus on the market value of the asset, investors generally evaluate an investment's opportunity by understanding the relationship between the investment cost and value. This issue can impact other values, such as physical, social, environmental and economic factors that might act as elements of the decision-making process for an investor[142].

A building offers better value for money when the benefits derived from it significantly exceed its lifetime cost. But benefits are derived from the functions that a building performs, rather than from building itself. This means that a project that is built cost-effectively but that falls short of the client's objectives does not provide good value, despite being built within budget. The same goes if the project includes features at additional cost, that were not stated by client's objectives. This means, that to improve **value for money**, the project team must define clearly the needs of the client, eliminate unnecessary expenditure and obtain optimum balance between cost, time and quality[143].

Value analysis is an organized effort directed at analyzing the functions of systems, equipment, facilities, services and supplies for the purpose of achieving essential functions at the lowest life-cycle cost consistent with the required performance, reliability, quality and safety[144].

It is a team based, process-driven methodology that uses function analysis to analyze and deliver a product, service or project at optimum whole life performance and cost without detriment to quality[145].

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[140] Graphisoft Inc.
[141] Weka Bausoftware Gmbh.
[142] RICS 2014
[143] Cost model: Value for money, http://www.building.co.uk/cost-model-value-for-money/1348.article, 18.11.2015
[144] Kurita 2007, 3.
[145] Male et.al. 2006, 3.

For more than 40 years VA/VM has been applied to construction projects in different concepts. Initially it was developed an applied by North Americans[146] Dell' Isola 1988, Fallon 1980, Kaufmann 1990, Miles 1972, Mudge 1990, O'Brein 1976, Parker 1985, Zimmerman and Hart 1982. It diversified during the late 60s and into the 70s primary through the manufacturing sector in Japan, the UK, Italy, Australia and Canada. During the 1980s and 1990s different perspectives began to emerge with the international use of VM in construction.

Developments in VM thinking and practice have resulted in a diversity of definitions, procedures and official standards internationally. Three principal definitions were discussed in the paper Managing Value as Management Style Projects published in 2006. The SAVE International standard, which uses the term value methodology (VM) and includes following known processes: value analysis, value engineering, value management, value control, value improvement and value assurance (SAVE1998). Second is the European Standard for Value Management (BS EN 12973:2000) which defines Value management as a style of management. Its goal is to reconcile differences in views between stakeholders, and, internal and external costumers as to what constitutes value. The Australian Standard (DR 04443, Standards Australia 2004) defines VM as a structured and analytical group process which seeks to establish and improve value and where appropriate, value for money, in products, processes, services, organizations and systems. According to it is Value for money closely associated with more traditional applications of value analysis and value engineering in activities such as design, procurement, operation and disposal of entities. This was derived from a modified definition (AS / NZS 418:1994) for value management which defined the VM as a process to achieve value for money by providing all necessary functions at the lowest total cost, with required levels of quality and performance.[147]

According to Male et.al. in order for appropriate value-for-money decisions, a value system or systems that interact, need to be made explicit and aligned or re-aligned[148]. This is seen as primary core element of VM.

Michael D. Dell'Isola[149] stated that Value analysis is moving in two directions. First relies on mandated requirements from government and corporate entities. The second direction of Value analysis is going into direction, where VA becomes a value-added service which is incorporated in the overall design and construction process. According to Dell'Isola VA practitioners believe that VA can be better integrated into the design process to build a value-enhanced design concept. Value analysis should be applied during the design and construction, this to owner's benefit, design-builder's benefit, or both. Figure 4-1 shows the cost relationship between time and change, with the best opportunity in the time period, to improve a project in the design phase.

[146] Dell'Isola 1988
[147] Male et.al. 2006, 2.
[148] Male et.al. 2006, 3.
[149] Dell'Isola 2003, 9.

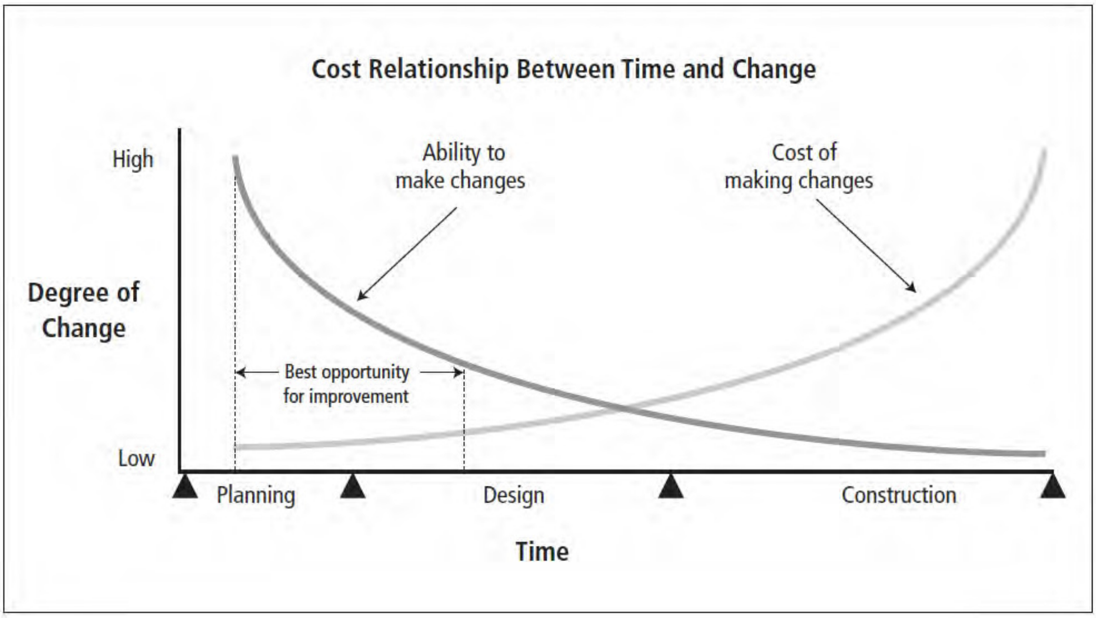

Figure 4-1: Cost relationship between time and change.[150]

According to Dallas[151], value is often quite difficult to measure or quantify. It is one of those things that everybody understands but does this differently. What is most important, that it is one of most powerful concepts in the market. Value is subjective, perceptive and can have pre-conceived notions. For VM it is essential that value is measured and quantified.

According to Kelly et. al.[152] early pioneers of VM in construction (Parker, Crum, Mudge, Thiry, Zimmerman and Hart) identified three parameters influencing value:

- **Utility** is concerned with deriving maximum benefits for the end-user (*Will it work effectively and do what it is expected to do*?). Buildings are constructed to accommodate and support different specific activities and will be a failure if they do not do that effectively. In many buildings maximizing the productivity of what is done is a key component of the utility value.
- **Exchange** value objectives underpin most commercial development in the market (*Can it be sold for a profit?).* Property and real estate market is driven by the concept of exchange value. Exchange value relies on the fact that parties involved in the exchange have different values. The concept of value drivers enables project teams to optimize value for their projects. Normally this will involve exchange between different stakeholders to obtain the optimum balance between their differing values.
- **Esteem** value is primarily related to the impact a building's image and reputation on its stakeholders (*Will it convey status or provide a "feel good" factor?*) For buildings that need to bear an image or otherwise contribute to their environment, esteem is a primary value.

As an example, Designing Buildings Wiki, explains[153]: A corporate headquarters must convey to the public and clients what the corporation is about - that it is successful, it cares about

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[150] Dell'Isola 2003, 9.
[151] Dallas 2006
[152] Kelly/Male/Graham 2015, 379-381.
[153] Value management techniques for building design and construction, http://www.designingbuildings.co.uk/wiki/Value_in_building_design_and_construction, 24.11.2015

details and it cares that its costumers and things that its costumers care about. In addition, the building must work as a building (utility value) and it must be salable as an exit strategy (exchange value), but the overriding importance is the esteem in which the outside will hold the building and, by extension, its occupiers.

If we transfer this example to a residential house, a family house must foremost function as a shelter for the family (utility value), it must be salable, if for example it is built for the property market (exchange), and it should be visually appealing for the possible buyers (esteem). The importance of these three core values will vary, depending on an individual's perception of values.

4.1.1 Value for Money (VfM) as method

Value for money (VfM) as a concept, relates to the optimum balance between the benefits expected of a project and the resources expended in its delivery.

As stated in Value Management in Construction[154] there are different terms used or associated with value for money. These are Value Management (VM), Value Engineering (VE) and Value Analysis (VA). They are all key elements of VfM concept but they differ in function and have systematic differences:

- Value Management (VA) which is *about getting the right project*
- Value Engineering (VE) is done *to get the project right*
- Value Analysis (VA) relates to the *improvement of a construction, manufacturing or management process* and also to a *post project review* to establish value achievement

According to Michael F. Dallas, value in context of construction, is generally taken to mean the balance between how well the building satisfies the owner's expectations and the sacrifices, in terms of resources used, he must make in order to get it. The ratio shown in Figure 4-2, between benefits delivered and resources used is called the Value ratio.

$$\text{Value} \propto \frac{\text{Benefits Delivered}}{\text{Resources Used}}$$

Figure 4-2: The value ratio.[155]

Because in construction the use of resources often translates in use of money, this ratio is often referred to as Value for money – VfM[156].

The resources used in construction projects are land costs, material costs, time and labor. All of these can be measured. Benefits however are more complex to measure. The techniques

[154] Mukherjee et. Al. 2011
[155] Dallas 2006, 14.
[156] Dallas 2006, 14.

of function analysis (describing what things do, rather than what they are) provide a powerful way of measuring benefits.

A key principle of VfM is to analyze each of the functions and to assess what it actually costs to preform a function[157]. It is vital, that in considering the basic function of a component, other functions to which it contributes are taken into account to assess its true "worth".

There are generally a number of components of value, each of which contributes to the overall value of the item in question. Since many of the functions in construction projects are not physical in nature, the concept of "value driver", instead of primary function, is often used[158]. Functions explain what things must do, what they contribute to the whole, in terms of contributing to the utility, esteem or exchange values, rather than what things are. Value drivers are those things, that taken together, include all benefits that contribute to the value of the completed project to the business. Achieving the value drivers is vital for success. Use of generic value drivers (Figure 4-3) creates the advantage of comparability, where components/projects with similar objectives can be benchmarked against one another.

	Value driver	Addresses the question
1	Enhance/achieve desired financial performance (of the building)	Is the building affordable?
2	Manage the procurement process effectively (maximise project delivery efficiency, minimise waste)	Are the project management processes efficient? Are the right people engaged? Is the supply chain effectively managed? Are materials and labour used efficiently?
3	Maximise operational efficiency, minimise operational costs	Does the building work well for the end users?
4	Attract and retain employees/occupants	Is it a nice place to work?
5	Project the appropriate image	Does the building convey the appropriate image?
6	Minimise maintenance costs	Is the building easy to maintain and clean?
7	Enhance the environment	Is the building environmentally friendly? Is it built using the principles of environmental sustainability?
8	Comply with third-party constraints	Does the building conform to legal and other external stakeholder requirements?
9	Ensure health and safety during project implementation and in operation	Is the building safe to build and use?

Figure 4-3: Generic value drivers according to Dallas.[159]

Using weighted value drivers as evaluation criteria provides an objective way of making decisions. When doing the benchmarking the best option is the one scoring best in option selection method and this is the one that best satisfies the requirements of the project objectives. A value score for each option is obtained by multiplying the weighting of each value driver by the degree to which the option satisfies it.

[157] Value management techniques for building design and construction, http://www.designingbuildings.co.uk/wiki/Value_in_building_design_and_construction, 24.11.2015
[158] Dallas 2006, 125.
[159] Dallas 2006, 127.

Value for money is a further sophistication of option selection technique. It is calculated (Figure 4-4) by dividing the value score by the total cost of the option. This helps to differentiate between two options, each of which has a sufficient value score, but where one costs significantly more than the other.

$$\begin{array}{c}\text{Value in}\\ \text{construction}\\ \textbf{Value for money}\end{array} = \frac{\begin{array}{c}\text{Benefits delivered}\\ \textbf{Function (value}\\ \textbf{drivers)}\end{array}}{\begin{array}{c}\text{Resources used}\\ \textbf{Total costs (Life}\\ \textbf{Cycle Costs)}\end{array}}$$

Figure 4-4: Value for Money formula (VfM in construction)

Out of the VfM formula it is evident, that its main function is not to reduce cost but to improve value. Greater value can also be seen as the benefits the clients or the occupants of a such building enjoy[160].

There are three major ways to improve Value for money[161]:

- to provide the required project function but at a lower life cycle cost
- to provide improved/additional function without increasing life cycle cost
- to provide improved function at a lower life cycle cost

Value for money is trying to achieve a balance between quality (function) and life cycle costs.

4.1.2 Life cycle costing (LCC)

It is estimated that initial costs of a building represent less than 30% of the total life-cycle cost of a building[162]. This is significantly important for the investors in perspective of total cost and the value of investment.

Cabeza reasserted most of the available literature on LCCA, and could conclude that the operational phase contributes more than 80 to 85% share in the total life cycle energy of buildings[163]. Therefore, it is suggested that future efforts should be focused on reducing the operational phase, even at some cost to other less significant phases.

According to Rangelova and Traykova, in Value for Money method, life cycle costing is used as a tool for evaluation[164], assessing different design alternatives, different constructions and skins, considering costs of ownership over the economic life of each alternative and doing all this in present value. They state that “Life cycle costing is a method for economic evaluation which considers the costs applicable to the total life of the asset.”[164]

[160] Rangelova/Traykova 2014, 430.
[161] Norton 1995, 14.
[162] Far/Pastrana/Duarte 2015, 1.
[163] Cabeza 2014, 402.
[164] Rangelova/Traykova 2014, 431.

Life Cycle Cost (LCC) analysis of buildings is included in Life Cycle Assessment (LCA). It takes into account all costs of acquiring, owning, and disposing of a building or building system[165]. LCA methods have been used for a long time for environmental evaluation of product development processes. However, in the building sector, LCA as state of the art analysis has been applied over last 10 years[166]. There is big interest in incorporating LCA methods into evaluation and optimization of the buildings performance, design and construction practices.[167]

Further LCC is defined in The National Institute of Standards and Technology (NIST) Handbook 135 (1995 edition) as the total discounted dollar cost of owning, operating, maintaining, and disposing of a building or a building system over a period of time[168].

Leckner and Zmeureanu explain that the lifecycle costs analysis looks at the economics over the life of the product.[169]

In the Architectural Handbook for Professional Practice, Life Cycle Costing is used to assess the economic consequences of various facility design decisions and is used for three types of analysis.[170] First two are typically completed during early planning and programming, where energy and maintenance related analyses are preformed during design development of the project. The tree types are:

- decide whether to renovate, build new, expand, lease, or continue the current situation
- to establish the annual facility budget to cover the life cycle costs of the project
- to compare the life cycle costs of various building systems alternatives for the purpose of selecting the best alternative for the design

We use the comparative analysis for VfM method in this research.
Consistent with Rangelova and Traykova, following costs are taken into account when calculating LCC: initial investment cost, energy costs, operation and maintenance costs, replacement of components costs, occupancy costs, alterations costs, taxation costs and salvage revenue and disposal costs.[164]

Mohsen Shojaee Far et.al. studied the Computer Integrated Construction research program at the University of Pennsylvania (2011), which identified 25 BIM uses during the life cycle of a facility, and suggests three of them to integrate into economic evaluation of LCC. The 3 selected uses are (1) cost estimation with quantity take-off methods, (2) energy consumption analysis, and (3) building maintenance scheduling (preventive). The integration and combination of these 3 provide an instrumental integrated approach to run more accurate LCCA.[171]

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[165] Cabeza 2014, 395.
[166] Buyle/Braet/Audenaert 2013, 381.
[167] Asdrubali/Baldassarri/Fthenakis 2013, 73-89.
[168] Fuller/Petersen 1996, 1-1.
[169] Leckner/Zmeureanu 2011, 234.
[170] AIA California Council et.al. 2009, 356.
[171] Far/Pastrana/Duarte 2015, 4.

The periods for LCC calculations in construction are not standardized and have to be selected. Service life of components has to be taken into account. Case studies reviewed by Cabaeza et.al. show that for residential buildings lifetime of the analysis is between 20 and 50 years.[172]

Blengini performed LCA of building which was demolished in the year 2004 by controlled blasting. The results demonstrated that building waste recycling is not only economically feasible and profitable but also sustainable from the energetic and environmental point of view.[173]

Jutta Schade studied life cycle cost calculation models for buildings (2007) and consistent with her review of literature, the data requirements for carrying out LCC analysis are categorized and graphically presented in Figure 4-5. These different data influence the LCC in different stages of the life cycle.

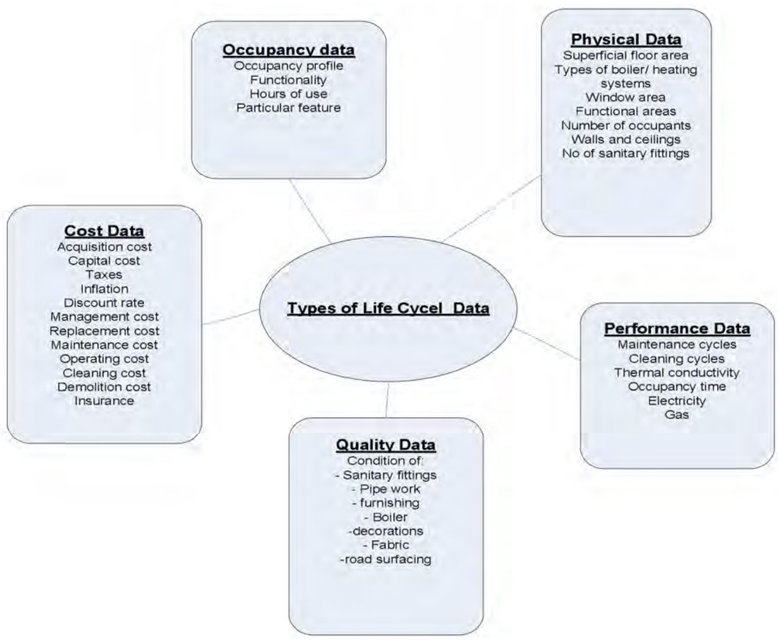


Figure 4-5: The required data categories for a life cycle cost analysis.[174]

To calculate initial investment cost for the materials and systems used in a house is a challenging task. Prices can be significantly different from year to year and will depend on location, manufacturers, vendors, market fluctuations, etc.[175] In order to get most accurate prices for our case models, up-to date prices of sirAdos database used in Legep software were taken into account and compared to Slovenian construction prices to estimate the correction factors, which is further explained in Chapter 4.7.2.

[172] Cabeza 2014, 408-412.
[173] Blengini 2009, 319.
[174] Schade 2007, 3.
[175] Leckner/Zmeureanu 2011, 234.

Life Cycle costs are according to Hofer defined as the total cost of a building or of a specific building component throughout its lifetime, including the costs for planning, design, acquisition, operation, maintenance, demolition and disposal less any residual life. The life-cycle costs include both, the investment costs and operational costs throughout the whole functional lifetime, including demolition. LCC is included as a specific criterion in German Sustainable Building Council's certification (Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB) 2009) and in the Austrian certification for a Total quality building.[176] Hofer also claims that LCC is the main indicator for the economic sustainability. Since different design options in constructing a building may have consequences on the investment, energy, maintenance, cleaning and operation costs, LCC takes all of them into account. In this concept the "lowest life cycle cost" option is the most economic one. [177]

European project IMMOVALUE (2010) showed the impact of LCC in the value of the real estate. Findings showed that sustainable buildings have a higher marketability. It was also shown that there is a clear correlation between lower operating costs and higher net rent revenues.[178]

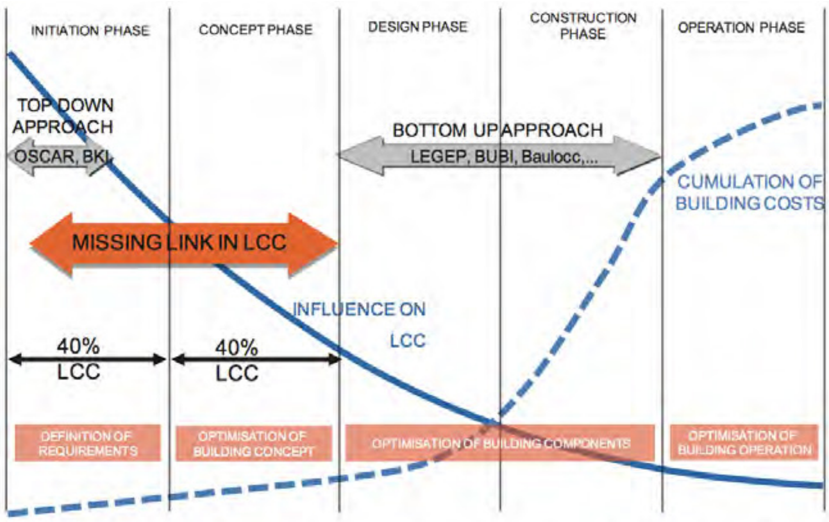


Figure 4-6: Missing link in models for calculating life cycle costs during the design phase.[179]

According to Hofer existing software tools for calculating LCC are base on the bottom-up approach, which means that itemized data has to be entered (for example type of paint coating/finish of paint). This means that a lot of data has to be collected when calculating LCC, which is a problem in the early design stages of construction projects.[179] Namely approximately 80% of all investment and operating costs are determined in the initial design phase[180] as shown in Figure 4-6. According to Statsbyggs Building finance section management, operation and maintenance (MOM) costs comprise 35-50% of the total annual costs of their buildings and they have a significant impact on rents. As a result, calculating

[176] Hofer et.al. 2011, 1073.
[177] Hofer et.al. 2011, 1074.
[178] Bienert 2009
[179] Hofer et.al. 2011, 1074.
[180] Hofer et.al. 2011, 1075.

correct MOM costs is as important as calculating correct investment costs. They use real interest rates in its calculations.[181]

That is why in order to calculate LCC quickly but accurately, it is essential to use Software which has a cost database for investment and running costs. This is the reason we use Legep software for this study.

4.2 Research methodology

To simplify the workflow of the case studies, we limited ourselves to a small residential house BIM model with simple functionality. BIM software enables us to model and simulate the real construction process and its cost in a virtual environment. Essential part of the BIM model is information and performance of each building element, which provide an estimation possibility of accurate initial cost of a building, as well as the renovation and maintenance cost. Energy evaluation can be performed either in external applications (Legep) or directly inside a BIM program (Archicad), in which it analyses the parametric model in terms of environmental behavior and energy consumption. Based on the total cost per year based calculations, resources used for the building can be presented. This provides the total utility of all costs, including maintenance and operation cost for the LCC calculation. It is important to present an accurate planning system, connected with time and cost and with scheduling and tracking of service and maintenance events associated with their cost. This method provides an integrated approach to estimate the whole cost of maintenance and service.[182]

Figure 4-7: The BIM Use Purposes[183]

Building Information Modelling (BIM) has been defined 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.”[184] A BIM Use can be defined as “a method of applying Building Information Modelling during a facility’s lifecycle to achieve one or more specific objectives.”[185] According to Kreider and Messner, BIM Uses can be classified primarily based on the purpose for implementing BIM throughout the life of a facility.[186] For the methodological approach of this study, four primary categories (Figure 4-7) of BIM purposes and objectives are used: gather, generate, analyze and communicate.

[181] Statsbygg LCC Tool 2011
[182] Far/Pastrana/Duarte 2015, 4-7.
[183] Kreider/Messner 2013, 6.
[184] National institute of Building Sciences 2007 ,150.
[185] Kreider/Messner 2013, 6.
[186] Kreider/Messner 2013, 2.

In the following chapters our developed method for Value for money evaluation is presented. The layout of the method is presented in Figure 4-8.

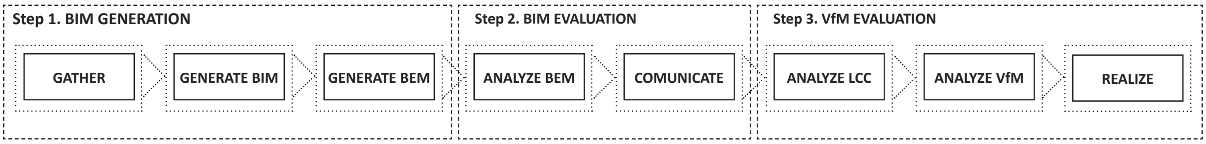


Figure 4-8: Value for money evaluation method with used primary BIM use purposes.

4.2.1 BIM Generation

First step of our method is the BIM Generation for which we used following two primary BIM Use purposes: gather and generate.

4.2.1.1 Gather[187]

BIM can greatly assist in the effort to gather information about a building during various phases of its lifecycle. There are two resources of data to collect and organize information about the building. One is the initial investment/construction cost. To calculate this, different costs addressed to each building element, have to be collected. Second one refers to the information needed to simulate the Life Cycle Cost of the facility to obtain its utility cost.
In this primary purpose of BIM uses, we collect, gather and organize information about the building. In this phase the building information is collected, gathered and organized, therefore the meaning of collected information is not yet being determined.

First the geometric and attribute data about the building is being **captured**, to represent the current or wanted status of the building and building elements. Next the amount of specific building elements is being **quantified** to express or measure the amount of a building elements for future cost breakdown and LCC calculations. This purpose is often used as part of the estimating and cost forecasting process.[187]

To be able to calculate LCC and VfM we need the quantities and costs for each building element for the cost breakdown. For the LCC evaluation, energy evaluation (Archicad) and utility cost (Legep) of the project have to be simulated. Four necessary sources have been identified and gathered in this step:
a) Physical properties of construction elements:
- Characteristics of each material: thickness, volume, heat capacity, thermal conductivity, collected from Archicad database;
- Environmental data: location, surroundings, climate data, sun protection, wind protection, collected from Archicad/Strusoft Climate Server;
b) Function:
- Buildings function has to be set. For the case studies we set the function as a residential building.

[187] Kreider/Messner 2013, 9-10.

c) Building systems :
- What kind of systems are used in the building for heating and cooling. Prices for energy purchase have to be gathered.

4.2.1.2 Generate[188]

All disciplines that interact with the lifecycle of a building will generate information about the building. This means that the Use purpose of BIM includes prescribing, arranging, and sizing building elements to various levels of development. The design team within the design phase, adds the primary generators of information, while the subcontractors in the construction phase, generate most of the information. Those that maintain the facility in the operations phase, generate that information, when they update or change that facility. "Anytime new information is authored, modelled, or created, it is generated."[188]

When all needed information was identified, the virtual building in Archicad has to be constructed with all the attributes of building materials. In Archicad the virtual materials are a simulation of real materials and not just a graphic presentation and have all the physical properties assigned (thickness, volume, heat capacity, thermal conductivity). Building elements are a combination of different materials in composites, which represent walls, slabs, roof, etc.

First step of generation purpose was **BIM generation** to create information about the building. For this we use secondary BIM use purposes to **prescribe** room functions, **arrange** rooms and **size** spaces in the building. We first modelled the case study model, which is a standalone house with a net floor are size of 98,77 m2 (net floor area). Each case model has reinforced concrete foundation plate wit a U-value of 0.2 W/m^{2}K. Reinforced concrete plates are most common type of foundation used for prefabricated houses in Slovenia. The internal walls have a U value of 0.2 W/m^{2}K. For each BIM model case then a different external wall construction is applied, according to chosen type of SDE2012 house and the base model with the chosen Lumar construction external shell as a reference.

When the basic building structure is modelled (floor, walls, roof) the rest of the building elements are introduced into the BIM model, such as doors and windows. For more accurate results, all of the case models have same type of windows and doors. Each of these elements also contains information related to orientation, glazed area and frame parameter, glazed and opaque area data (u-value, total solar transmittance and direct solar transmittance).

Second step in the **BEM generation**. To be able to run energy consumption simulation, it is necessary to define the thermal blocks of the project, which are each a collection of one or more rooms or spaces in the building that have a similar orientation, operation profile and internal temperature requirements (also called thermostat control requirements). Because

[188] Kreider/Messner 2013, 10-11.

our building is a residential house, we only have one thermal block. All specific data for energy evaluation is gathered in previous primary step (gather): the environmental data, functional/operational profile and building systems. When this information is **prescribed** to the BIM model, it is transformed into a BEM model (Building Energy Modeling) by the automatic model geometry and material property analysis functionality of Archicad.

4.2.2 BIM Evaluation

Second step of our method is BIM Evaluation, where we analyze the BIM and communicate the results between Archicad and Legep.

4.2.2.1 Analyze

Next step is the BIM (and BEM) analysis for the Value for Money evaluation, where Life Cycle Cost is most important parameter. To be able to analyze the construction cost and operation cost and further estimate the LCC, the future performance of the building and the building elements has to be **forecast**. For all these evaluations it is very important to have a good database. Though Legep software is an integral planning Software solution, energy evaluation in Legep is calculated according to German EnEV. Therefore, all energy related calculations are done with German environmental data. Consequently, to evaluate energy specifically for Slovenian environmental data, we use Archicad with its integrated energy evaluation tool to forecast energy needs of the buildings. This offers an accessible workflow for performing dynamic building energy calculations and has direct access to Strusoft Climate Server and its climate database. The result of this calculations is information, such as the project's energy related to structural performance, yearly energy consumption, energy balance, and carbon footprint.

To forecast the LCC, a construction cost database has to be used or manual input would have to be done. Since such a database does not exist for the Slovenian construction market, Legep with its database is used together with a correction factor described in Chapter 4.7.2.

4.2.2.2 Comunicate

According to Kreider and Messner[189] the communication stage's objective is to present information about a facility in a method in which it can be shared or exchanged. Therefore, the quantity information of each element with all of its parameters is exported out of Archicad and imported into Legep to do the LCC analysis and get the final results for value for money calculations. The final results are then based on the quantity take-off list of each element from the virtual construction model (BIM) done in Archicad. The export is done in form of schedules and tables and imported into Legep LLC Module manually. The energy amounts are differentiated by energy medium (e.g. power demand for auxiliary power units, power requirements for lighting, electricity consumption for heating etc.).

[189] Kreider/Messner 2013, 13.

4.2.3 VfM Evaluation

Final step of the method is the Value for money evaluation where we analyze the LCC and VfM and then realize the results in form of suggestions for future stakeholders.

4.2.3.1 Analyze LCC

To be able to run the **forecast** for LCC in Legep, thermal blocks for the case studies have to be defined. Each of them is a collection of one or more spaces in the building, that have a same orientation, operational function and internal climate requirements (thermostat control requirements). After this information is set the LCC evaluation can be preformed. The outcome of this evaluation is a calculation, evaluation and forecast of LCC costs for operation, cleaning, maintenance, repair, dismantling and disposal.

4.2.3.2 Analyze VfM

After we gather the LCC forecast we can import the results into Excel for the final value for money evaluation of each case study according to the VfM formula (VfM=F/LCC). All the results are compared to the reference case.

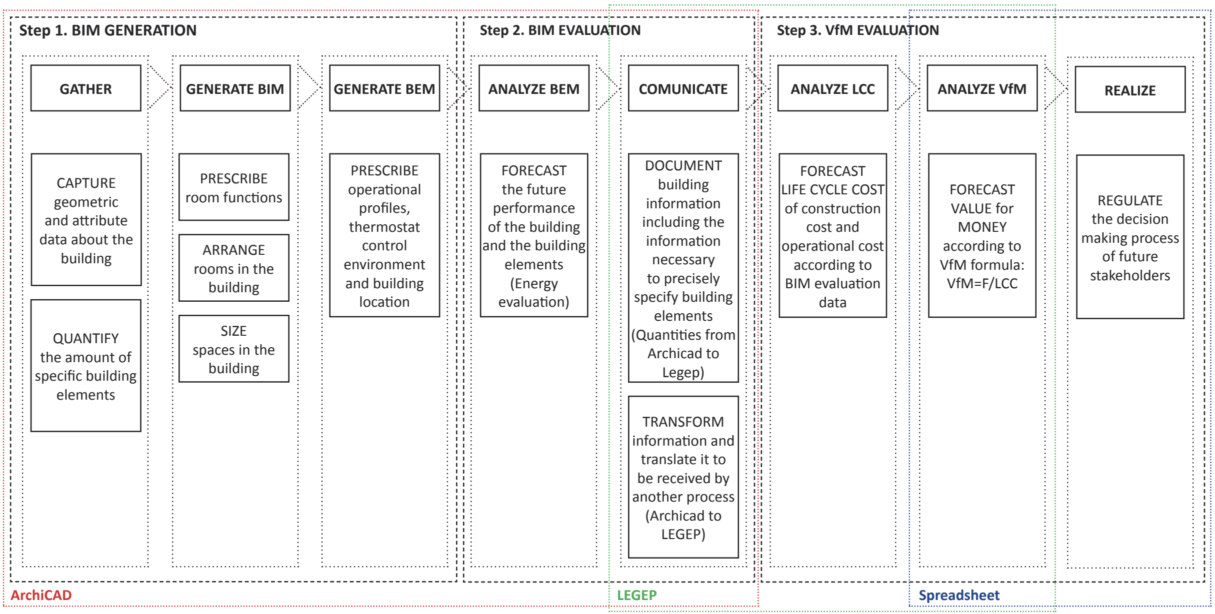


Figure 4-9: Extended Value for money evaluation method with used primary and secondary BIM use purposes.

4.2.3.3 Realize VfM

The objective of this BIM use purpose (**realize**) is to make or control a physical element using using facility information. BIM is beginning to allow the industry to fabricate or assemble specific elements or parts of a building, without the direct input of human interaction. We cannot fabricate physical elements with generated information, but we can regulate the decision making process of future stakeholders with our findings. Therefore, information generated through our Value for Money evaluation method (Figure 4-9), can be for instance used by designers and investors in the decision making process for a particular prefabricated wall construction. The final stage, where all calculations are realized through accurate simulations and analysis, represents the choice of different construction decisions, which impact directly the value for money, that represents an important economic evaluation for investors.

4.3 Description of the case-study model

In this chapter the case study sample house (Figure 4-10) that is used for the value for money evaluation is presented.

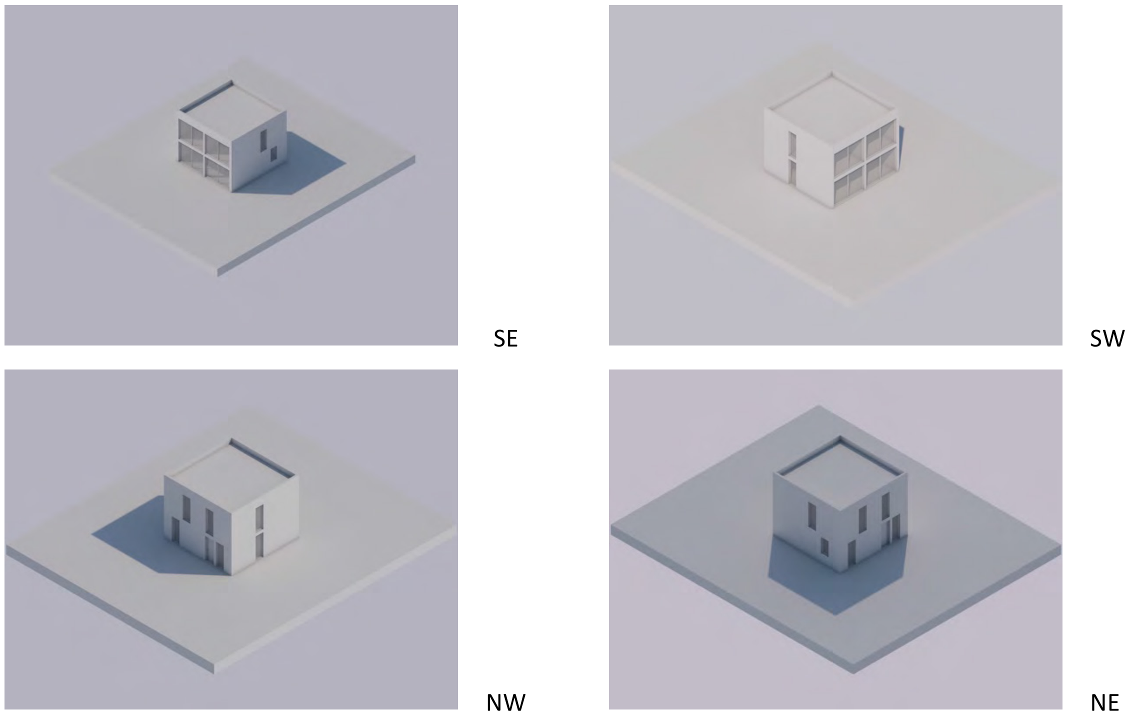


Figure 4-10: Case study 3D model

4.3.1 Plans

A prototype done by architectural office Arhisol of a two-story single-family house was selected and modified for the case study model as presented in Figure 4-11. The selected prototype was modified to fit the needs for a most typical Slovenian family as researched in Chapter 2 of this study. It is a house for a family with two children. The case model has a ground floor, upper floor and a flat roof. The fix internal horizontal dimensions are 7.2 m x 7.2 m for both floors. The total heated floor area of the model is 98,77 m^2 and the total heated volume is 249,90 m^2. The shape factor (Fi=A/V) of the building is 0.78 m^{-1}.

4.3.2 Construction

All applied exterior shells for the case study models are lightweight constructions. It is important to underline that the presented research is limited to lightweight construction only.

The influence of different thermal capacities of the different case study envelopes are taken into consideration. External wall skins and the roof are changing parameters according to the case models selected in Chapter 4. Foundation slab, first floor slab and internal walls are fixed parameters for all models. The U-value of the foundation slab is U=0,15 W/m^{2}K. All shells are described in detail in Chapter 5.

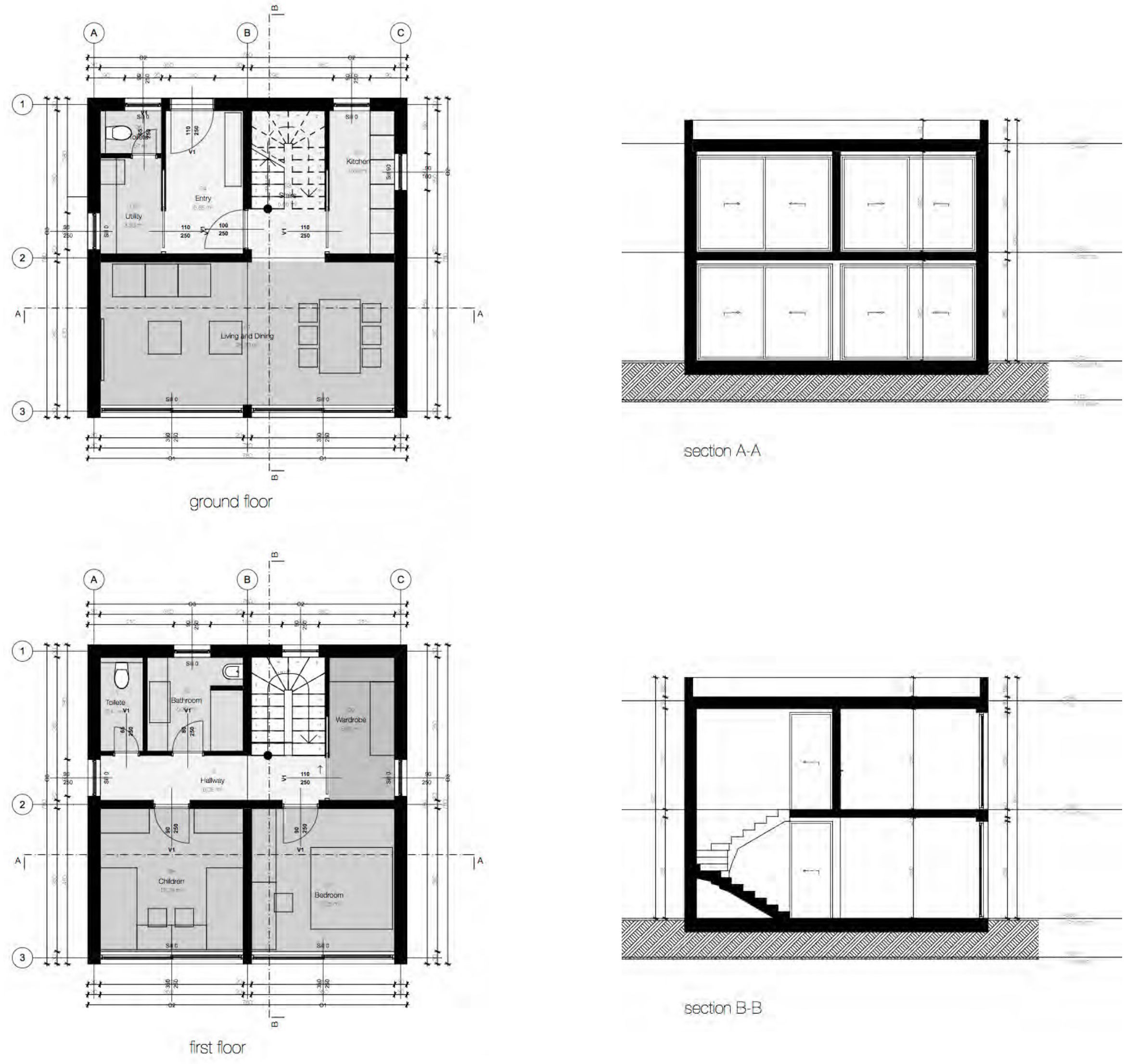


Figure 4-11: Case study model plans

4.3.3 Windows

All external windows (and the external entrance door) are considered fixed parameters in the size and their energy specifications for all models. The glazing is considered with three layers of glass. The glazing configuration has U-value (U_g) of 0.47 W/m^{2}K and a g-value of 52%. That assures a high level of heat insulation and light transmission. The frame type is a wooden window frame with a U-value (U_f) of 0.73 W/m^{2}K. The overall window U-value for energy calculation is 0,87 W/m^{2}K.

4.3.4 Shading

All external openings are shaded with an external shading device in form of external louvers.

4.3.5 Location, orientation and climate data

The house is located in the surroundings of Maribor in Vinarje, at the following geographical location (Figure 4-12) of 46° 34' 53" N latitude and 15° 38' 22" E longitude and an altitude of 297m. The building is oriented with the open glazed facade facing the south side. The south, east, north and west elevations are presented in Figure 4-10.

City of Maribor has an average altitude of 275 m. The climate data for the case study is retrieved by the Strusoft climatic data server used by Archicad energy evaluation software. The Strusoft climate data are created from NCEP Reanalysis data provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA, from their website at http://www.cdc.noaa.gov/. According to the data, Maribor has a Climate Type A (Moist), identified as a 5A zone, with the average annual temperature of 10.55 °C, minimum temperatures in January -9.67 °C and warmest temperatures in July 38.17 °C. It has the average annual humidity of 78.82%. The average solar radiation is 163.80 Wh/m^2. Winds at the location achieve an average speed of 2.38 m/s.

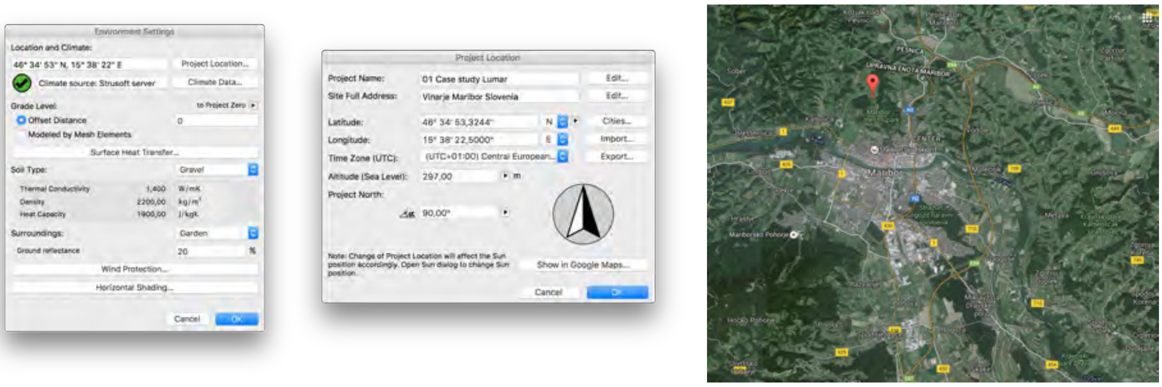


Figure 4-12: Geographical location

4.3.6 Building operation profiles

Operation profiles presented in Figure 4-13 are used for energy evaluation. The house is considered as a residential house of a family of two working parents with two children therefore a residential operation profile is used. The profile is parted in workdays from Monday to Friday and the weekend (Saturday and Sunday). Maximum temperature is limited to 26 °C and minimum to 20 °C and at night to 18 °C. Total usage hours for the building are considered for 8760 hours, which is a data range for all year.
The lighting for internal heat gains and electricity demands is considered to be LED lighting. Occupancy count is 25 m2 per capita (4 persons). The equipment for internal heat gains and electricity demands is considered to use 1 W/m^2 during operational hours.

The occupancy data for residential type is considered to produce 70 W per capita of human heat gain, 40 l of water per day per capita and a humidity load of 2g per day and m^2.

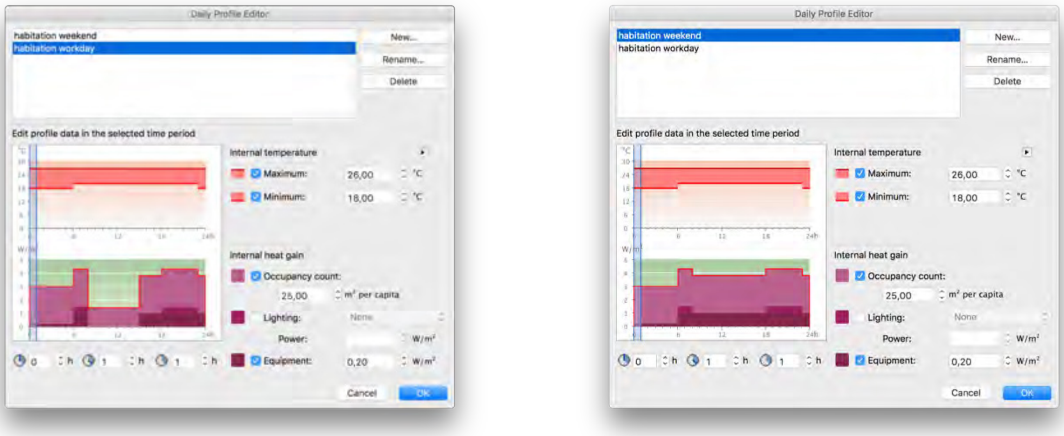


Figure 4-13: Operation profiles used in Archicad for all case study models.

4.3.7 Active technical systems

The calculated HVAC Design data predicts that the used heating period is 3639 hours and cooling period is 575 hours a year.

For each case study two energy evaluations are done. One energy evaluation is done with no specified heating, cooling and ventilation equipment. That way the energy demand for heating and cooling is calculated.

Second energy evaluation is done with domestic hot water generation and requirement for space heating and cooling covered by air/water heat pump. Such heating source is used as a standard offer for prefabricated residential houses in Slovenia (example: Lumar)[190]. The interior temperatures were designed to a min of 20°C (and 18°C during night) and max of 26°C. Domestic hot water generation is evaluated for cold water temperature of 10°C and hot water for 60°C. No solar collectors are installed. A manual window ventilation is planned.

Space heating requirements and hot water generation by a heat pump with an air to water heat exchanger is evaluated for a heat pump with 11800 W of heating output, with a 250 l accumulator tank and a COP of 4,55. The minimum operation time was seat to Energy star default of 10 min.

4.3.8 Parameters varied

The value for money evaluation is studied for different external envelopes used in the selected projects for the Solar Decathlon Europe edition in 2012 that are applied to the case study model. Skin modifications where made separately for each case study for the external walls and the roof. For each external skin a separate BIM model is modelled. Each house model is created in a way that all of them have the same internal areas and heated volumes.

[190] Zelo dobre nizkoenergijske hiše - optimirane za pridobitev subvencije eko sklada, http://www.lumar.si/energetski-koncepti.asp?m3=21, 12.10.2015

Different external envelope composites are applied in the form, that they get thicker from inside polyline of the wall to the exterior. Such approach is chosen to get same parameters for energy calculations of each case study and also for property value calculations, which are done per m^2 of net floor are.
The different modified envelopes are presented in following chapter. Basic data for all case studies with two different evaluations of each is also presented. The thermal transmittance of the foundation and floor slab, windows, doors and internal walls remain constant in all of the studied cases.

4.4 Object of the research

The object of this research is to answer two research questions. If future construction systems and envelopes that connect research, praxis and PR effect in form of SDE2012 competition are suitable for Slovenian prefabricated house property market. Further we want to answer if stakeholders can already in the design phase, use an effective economic evaluation method when deciding for a construction system.

4.5 Limitation of the study

The study offers an evaluative perspective on value of different prefabricated construction systems to be used for residential houses, using a VfM methodology that is developed through the research. As a direct consequence of this, the study encountered a number of limitations, which need to be considered.

- It is important to underline that the presented research is limited to lightweight construction only. Therefore, all applied exterior shells for the case study models are lightweight constructions.

- The most common period for major renovations in the residential sector in practice is according to Zavrl et.al.[191] is 30-40 years and 60 years is defined as lifetime in national regulation for maintenance of buildings. Therefore, 50 years are taken as calculation period for this study.

- To simplify the workflow of the case studies, we limited ourselves to a small residential house with simple functionality.

- The case study house is estimated at approximately 100 m^2 heated net floor area for a family with two children.

- The considered budget for the houses is based on current economic situation in Slovenia.

[191] Zavrl/Tomšič/Gjerkeš 2012, 163.

- It is assumed that all envelope cases provide a residential building standard that creates healthy and comfortable lives for their occupants without negative impact on the climate.
- All envelopes are applied on to the case models in a way that ensures same internal volume and floor area for all of them.

- All external walls except 03 Ecolar have their final external layer adapted to plaster to simplify the workflow and comparability of results.

- Because the Legep software uses the sirAdos database which is only available for the German construction cost prices, a cost adjustment factor was calculated to be used for construction cost calculation for the Slovenian construction cost prices. There is no existing database with construction elements prices on the Slovenian market.

- It is important to stress that this research considers only the mid-European climate conditions for the specific location at an altitude of 298 meters above sea level, latitude of 46.03° and longitude of 14.3° east.

- Single sided optimization usually does not provide the best results. In further research whole building envelope including internal slabs and walls of each prototype should be evaluated.

4.6 Description of the software

In following subchapters software that is used for this study is described. Additionally, a preliminary study that derived Legep as the software to be used for LCC analysis, is presented.

4.6.1 Archicad

Archicad is an architectural BIM CAD software for Mac and Windows computers developed by the company Graphisoft. It offers CAD solutions for all common aspects of aesthetics and engineering during the whole design process of the built environment (buildings, interiors, urban areas, etc.). It is being developed since 1982. Archicad has been recognized as the first CAD product on a personal computer able to create both 2D and 3D geometry, as well as the first commercial BIM product for personal computers.[192]
EcoDesigner STAR is an Archicad extension providing a full BIM to BEM workflow that enables designers to fully utilize and further extend Archicad's built-in building energy modelling capabilities. It can be used to evaluate building energy performance under any kind of circumstances and locations around the world and it utilizes a custom dynamic building simulation method that is valid worldwide. This allows users to precisely evaluate building energy performance in any climate or location. It’s analysis engine complies with ANSI/ASHRAE Standard 140- 2007 Standard Method of Test for the Evaluation of Building

[192] Archicad, http://www.graphisoft.com/archicad/, 6.1.2016

Energy Analysis Computer Programs. This test method represents the industry standard for the quality assurance of simulation accuracy. It is referenced by most major sustainable building design regulations worldwide, including LEED, Green Star, BREEAM, DGNB and CASBEE, as well as most national standards that endorse dynamic simulation (e.g. ASNRAE 90.1, NatHERS, BCA Section J).[193]

4.6.2 Legep

For accurate and objective LCC calculations right software has to be used. Since there is no available integral software for LCC calculations on the Slovenian market and Slovenian standards in building sector have been mostly developed or are based on German DIN standards, we decided to use German LCC software. A research on available LCC software on German speaking market was done.
Hofer et. Al. Suggest Legep as the bottom up approach software for LCC calculation in the design and construction phase (Figure 4-14).[194]

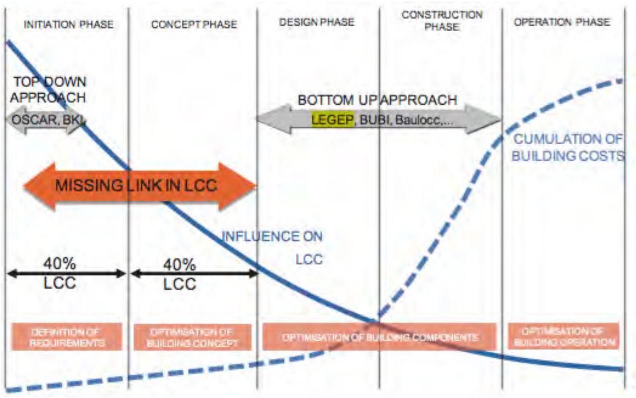


Figure 4-14: Missing link in models for calculating life cycle costs during the design phase (use of Legep in design phase).

Kohler et. al.[195] used Legep for life cycle assessment of passive buildings for their research done in 2016. They describe Legep as an assessment tool of integrated lifecycle performance of buildings (Figure 4-15): »LEGEP is a tool for integrated life-cycle analysis resulting from basic research in Germany, Switzerland and France. It supports the planning teams in the design, construction, quantity surveying and evaluation of new or existing buildings and building products. The LEGEP database contains the description of all elements of a building (based on the German DIN 276 standard which can be mapped to other similar standards); their life cycle costs (LCC/WLC based on German DIN 18960) and the final report EU-TG4 LCC in Construction. All information is structured along the five life cycle phases (construction, maintenance, operation, refurbishment and demolition.) LEGEP establishes simultaneously and for the whole life cycle: the energy needs for heating, hot-water, electricity (following German standard EnEV 2002 and EN 832); the construction, operation (energy, cleaning etc.), maintenance, refurbishment, and demolition costs; the

[193] Graphisoft, EcoDesigner STAR User Manual 2014, 28.
[194] Hofer et.al. 2011, 1074.
[195] Kohler et.al. 2016

environmental impact (effect-oriented evaluation based on ISO 14040–43) and resource consumption (detailed material input and waste)."[196]

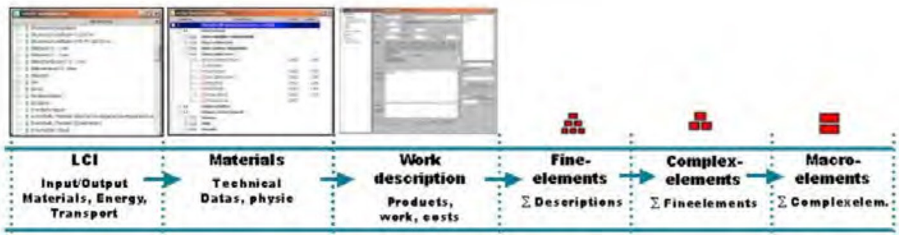


Figure 4-15: Hierarchical organization of data "staircase" in Legep.[196]

Xie describes Legep in his book Modeling and Computation in Engineering II in chapter 3 Methodology of an integrated BIM-LCA. According to Xie Legep software is an effective tool of integrated LCA and LCC, which not only calculates the environmental impacts of a building, but also considers the economic factors in the same physical framework.[197]

Armines et.al.[198] asses Legep as Building specific tool in their existing list of building LCA tools done for the EU research Energy Saving through Promotion of Life Cycle Assessment in Buildings between 2007 and 2010.

Edvardsen[199] lists Legep tool in the study Overview report on LCC approaches, tools and indicators done for Immovalue project supported by Intelligent energy Europe. In chapter "LCC tools" it is described as an integrated software tool for calculation and estimation of buildings of any use, that includes the building costs, life cycle costs, energy consumption and ecological impact. According to Edvardsen output of LEGEP at each phase is a complete, interrelated set of cost, energy, mass-flow and environmental indicators. It is possible to show separately specific indicators or all indicators, for each life cycle phase (new construction, operation, cleaning, maintenance, refurbishment, demolition) of the building and it can be used for new or existing buildings.
Daberkow[200] compares LCC and LCA software from the perspective of clients. He compares LQG, LC Profit and Legep. Consistent with him, Legep can be used when LCC or LCA calculations are to be made over the entire period of development of a construction project, because Legep is always customizable to the project status. He also states that even if developers and project managers need detailed information, Legep also fulfils their requirements.

Therefore, for this study Legep is used for construction cost and life cycle cost evaluation, with its sirAdos database. SirAdos is a product from WEKA MEDIA GmbH und Co. KG, which in last 25 years developed to one of the market leaders in construction cost documentation.[201] For the cost estimation in Legep, the same breakdown of elements has to

[196] Kohler et.al. 2016, 1-2.
[197] Xie 2013, 84.
[198] Armines et.al. 2010, 19.
[199] Edvardsen 2010, 19-20.
[200] Dabrekow 2010, 2.
[201] sirAdos, http://legep.de/uber-uns/sirados/, 12.1.2016

be set as in BIM model in Archicad. Due to the lack of resource database in Slovenia for maintenance and replacement costs, sirAdos database is used again for these costs. This is another limitation of this study, but the workflow is the same for all case study models.
According to König[202] of Legep software, Legep is a tool for integrated life-cycle analysis. It supports the planning teams in the design, construction, quantity surveying and evaluation of new or existing buildings. The LEGEP database contains the description of all elements of a building (based on DIN 276); their life cycle costs (LCC) based on DIN 18960 and on the calculation rules of the German DGNB and BNB Sustainability Certification. All information is structured along life cycle phases (construction, maintenance, operation, cleaning, refurbishment and demolition).
LEGEP is organized along several software tools, each with its own database. The method is based on cost planning by “elements”. The database is hierarchically organized (Figure 4-15), starting with the LCI-data at the bottom, building material data, work-process description, simple elements for material layers, composed elements like windows, and ends with macro-elements like building objects. The data are fully scalable.
Elements at each level contain all necessary data for cost, energy, and mass-flow and impact evaluation. A building can be described using either preassembled elements or defining elements from scratch. The user can also define a specific composition by exchanging layers or descriptions of the element. The costs of the elements are established by the SIRADOS database, which is published each year. The LC Inventories are based on the German Ökobau.dat, used for the German DGNB and the BNB Sustainability Certification.[202]

4.7 Appendix – Economy

When doing economic evaluation, it is not important to evaluate Construction cost for a specific year or determining the Energy consumption of a building for a single year. An economic evaluation wit LCC analysis considers the long-term economy of a building. Therefore, some information regarding the project of a building is needed, which was not inquired so far.
It is important to understand that the taken life cycle period of a building is actually not the expected life expectancy of it. Rather, it is an artificial segment in overall lifetime of a building.
The economic evaluation of an object over a longer period is a subject of specific rules of economic calculations. Consequently, individual factors of future economic development, are being determined with numbers. For example: inflation rates are taken into account.
In following subchapters these economic numbers that were considered for our calculation with Legep software are further described.

[202] Legep, http://legep.de/?lang=en, 11.10.2016

4.7.1 Cost planning

The cost planning in Legep, is according to WEKA MEDIA GmbH & Co. KG, with sirAdos - program module, done precisely, quickly and is data consistent. For the costing for this research following data types are used (from the five available, shown in Figure 4-16).

Grobelemente – "Macro-elements"
Planning with such elements is particularly suitable when amounts have been extracted from CAD, where they have been identified and associated with building structures. They are suitable especially for a detailed cost estimation or for cost calculations. A "Macro-element" is a compilation of "Micro-elements" to describe a building construction for a given structure (Roof-structure, Wall-Structure etc.). The cost is calculated from Micro-elements.

Feinelemente – "Micro-elements"
Micro-element is a composition of service positions in a structure (bricks and substructure, interior ceiling sheeting ect.). Price is automatically calculated from the position prices.

Leistungspositionen – "Service positions"
Such position describes a precise individual specification together with all required materials, labor and time. These are real prices with an adjustable market margin (from-middle-to-prices).

Elementtyp	Kostenermittlung	Beschreibung
Gebäudeelement (optional erhältlich)	Kostenrahmen	Beschreibt die gesamte Konstruktion (KG300) oder die technischen Ausrüstung (KG400) eines Gebäudes.
Makroelement	Kostenschätzung	Beschreibt ein Bauteil eines Gebäudes (Deckenbauteil einschl. Belägen, Treppen etc.; Außenwandbauteil einschl. Anteile der Öffnungen, usw.). Der Preis errechnet sich aus den zugrunde liegenden Feinelementen
Grobelement	Kostenberechnung	Ein Grobelement ist eine Zusammenstellung von Feinelementen, um eine Baukonstruktion für einen vorgegebenen Aufbau zu beschreiben (Dachkonstruktion, Außenwandkonstruktion o. ä.). Der Preis errechnet sich aus den Feinelementen
Feinelement	Kostenberechnung/ Kostenanschlag	Zusammenstellung von Leistungspositionen zu Rohbau- oder Ausbaukonstruktionen (Dachbelag mit Ziegel und Unterkonstruktion, Innendeckenbekleidung o.ä.). Preis wird automatisch aus den Positionspreisen errechnet
Leistungsposition	Kostenanschlag	Beschreibt eine konkrete Einzelleistung mit dem erforderlichen Material-, Lohn und Zeitaufwand. Konkrete Preise mit einem marktüblichen Spielraum (Von-Mittel-Bis-Preise).

Figure 4-16: Element types for cost calculation in Legep. [203]

The pricing with sirAdos database does not contain calculated building costs, instead determined prices form invoiced bills, that are used in Legep (Example: the purchase price for a carpet flooring may already differ depending on the amount of the flooring. For instance,

[203] © 2014 WEKA MEDIA GmbH & Co. KG

between 35 EURO for 10 m2 and 17 EUR for 1,000 m2. The same goes for placing the flooring etc.).

4.7.2 Cost correction factor

As described in previous Chapters construction cost is done with Legep software and its extended and continuously updating sirAdos construction price database. Since the construction prices for labor and material in sirAdos database are for German market, a price correction factor is used for all Legep calculations to adapt the prices to the Slovenian market.

The costs determined by the elements described in previous chapter are not identical to the settled costs of construction. Therefore, Legep uses “Price adjustment factor” to adapt the construction cost related inputs to a project specific cost. This price adjustment factor is then added to all construction cost related calculations.
The sirAdos construction price documentation always consists of three costs which reflect the usual market level (von-mittel-bis). The desired price level is selected in the menu as shown in Figure 4-17. The three costs settings already allow a variation of costs up or down to 20%. It is suggested by Legep documentation to use “von” (lower) costs, since this estimate is closer to the "purchasing price".

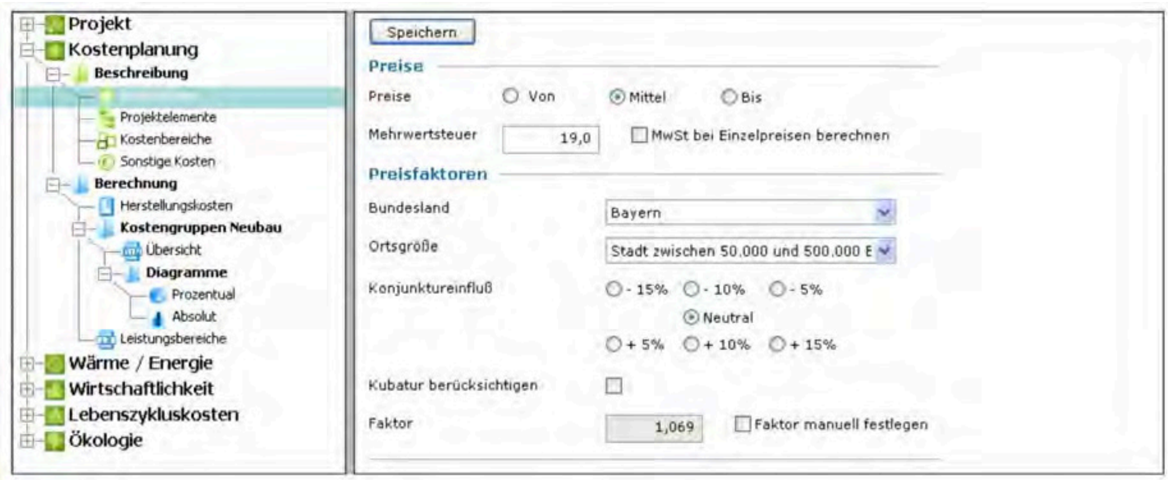


Figure 4-17: Cost correction factors for adjusting the construction prices to the project prices in Legep.[204]

To adjust the construction cost prices to the Slovenian market, the Legep manual adjustment factor is used (Figure 4-17). This correction factor makes the total construction cost less or more expensive. This input factor is then directly calculated into all costs.
This factor-related changes in the construction costs of all components will not affect the cost of cleaning, maintenance and repair. These preserve the preset costs.

[204] © 2014 WEKA MEDIA GmbH & Co. KG

To set the cost correction factor in Legep, the international building cost comparison report, done by EC Harris in their 2013 research (Figure 4-18), is used. The middle price value for Germany according to their research is 103,5. The Slovenian value for construction cost (high price, which is use for biggest cities Ljubljana, Maribor) is 81. With these values, (81/103,5) the price correction factor of 0,78 is calculated and used in Legep calculations (Factor position shown in Figure 4-17).

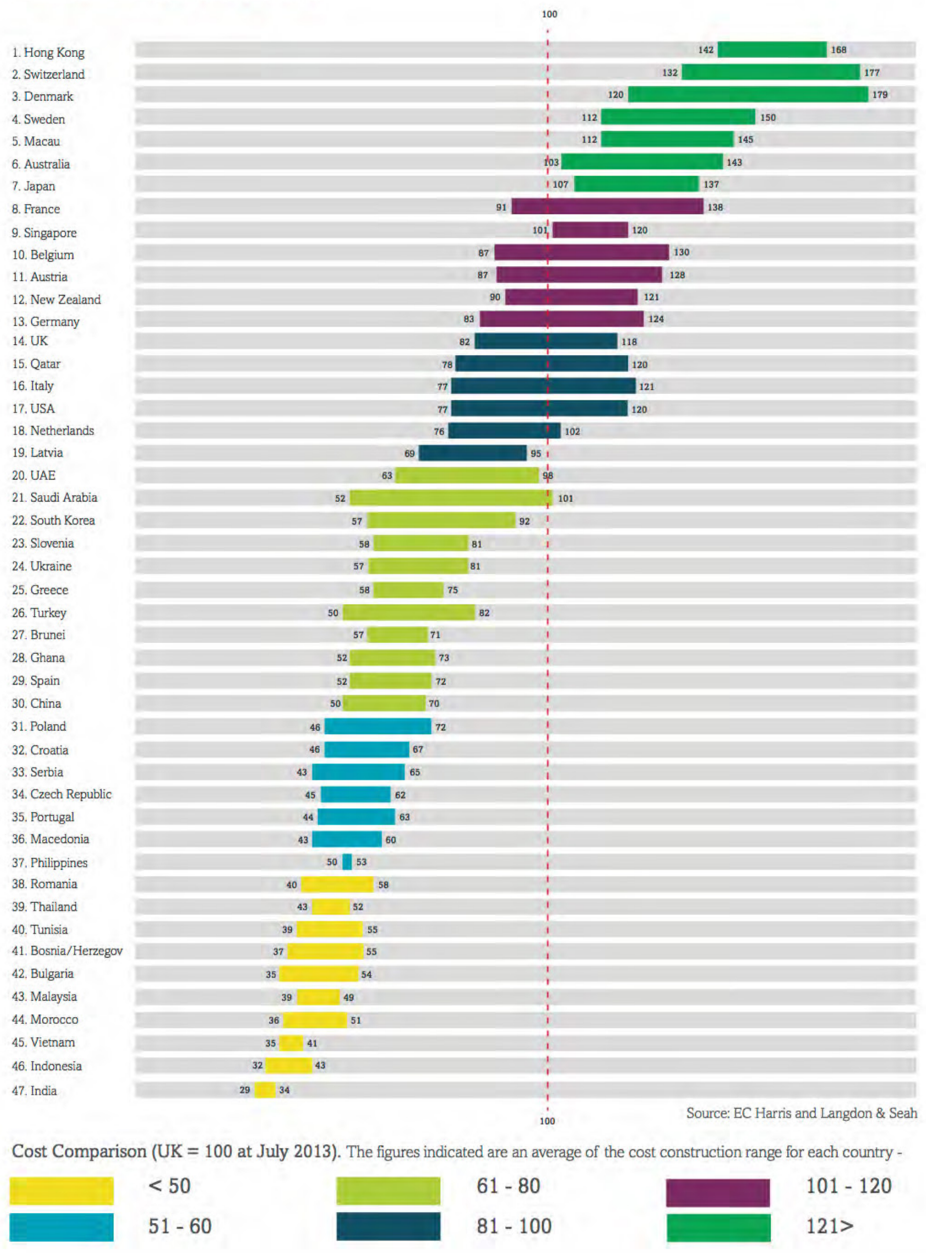


Figure 4-18: International building cost comparison in international construction cost report done by EC Harris in their 2013 research.[205]

[205] Rawlinson 2013, 15.

4.7.3 Financial settings – construction costs and energy prices inflation

For the dynamic Life cycle cost calculations, we used following financial specifications (Figure 4-19). Building cost inflation is set to 2% and energy price to 4%, according to data obtained from Statistical office RS[206]. The energy prices inflation is set to 4% independent from common price increases. The inflation for the contraction prices could be set individually, but long-term inflation is according to Legep expected to be between 2-3% yearly.

The tax was changed to Slovenian tax for building sector, which is 9,5% for all gross calculations.

4.7.4 Net present value

The present value in economics is also known as present discounted value. This is the value of an expected income stream determined as of the date of valuation. The present value is always less than or equal to the future value because money has interest-earning potential, a characteristic referred to as the time value of money, except during times of negative interest rates, when the present value will be less than the future value.[207] Time value can be described with the simplified phrase, “A dollar today is worth more than a dollar tomorrow”. Here, 'worth more' means that its value is greater. A dollar today is worth more than a dollar tomorrow because the dollar can be invested and earn a day's worth of interest, making the total accumulate to a value more than a dollar by tomorrow. Interest can be compared to rent.[208]

In the net present value method, all deposits and withdrawals are based on the time of investment at the present value. Therefore, net present value is the basis for various applications in the real estate business.

In calculating with the net present value method, all payments, that incur at a later time, are not considered with their nominal value, they are rather considered with the financial expanse, that would have to be invested, considering the preset calculated interest at the initial starting point of the investment, in order to generate the subsequent amounts. In this way, all payments are discounted to the start time of the investment and so their present value is calculated.

The net present value of a payment is getting smaller, the more the payment is set in the future or with the height of the chosen real interest rate. If the real interest rate is set to 0%, then each payment in the considered period has the same value.

[206] Cene in inflacija, http://www.stat.si/statweb, 12.12.2015
[207] Moyer/Kretlow/McGuigan 2011, 147-498.
[208] Broverman 2010, 4–229.

The dynamic LCC calculation with Legep is done according to Net present value NaWoh[209] 4.1.1 and for a period of 50 years. For the net present value calculation following default interest rates are set (Figure 4-19): a yearly inflation of 2%, a capital interest of 5,5% and the real interest rate of 3,5%.

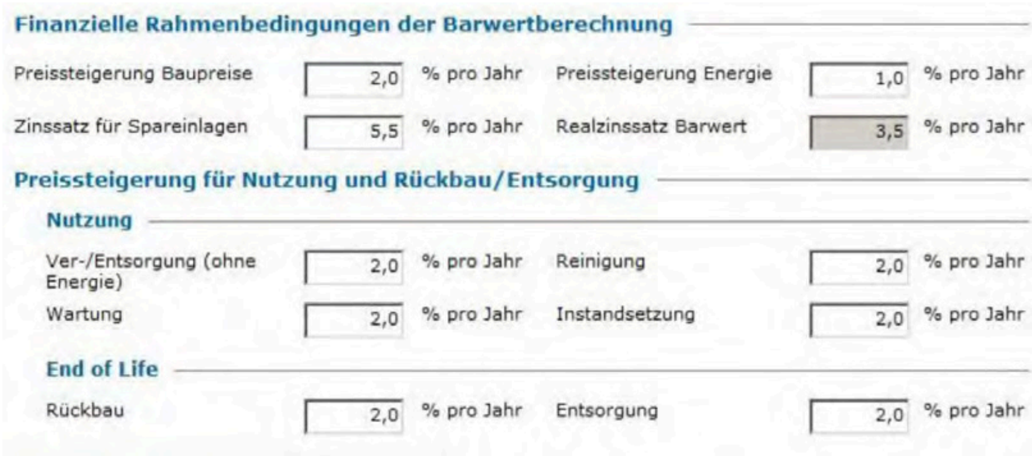


Figure 4-19: Financial settings for Net present value calculations in Legep software (with default values).[210]

[209] Verein zur Förderung der Nachhaltigkeit im Wohnungsbau (NaWoh), http://www.nawoh.de
[210] Legep software Help, Finanzielle Rahmenbediengungen der Barwertberechnung

5 VALUE FOR MONEY EVALUATION

Value for money analysis of each case study is presented in this chapter. Results gathered through method described in previous chapters are evaluated and compared to determine the value for money of each system.

5.1 Case study analysis

The analysis is presented separately for each case study model. The values for the Annual heating energy demand in further text (Q_h), the cooling demand (Q_k) and the Electricity demand (Ql+e) are presented graphically and in tables. For comparison purposes some of the results are presented in figures at the end of each sub chapter. All used external skins are presented graphically in plans and in tables with basic data for each case study. As presented in Chapter 4.3.2, the foundation slab, first floor slab (Figure 5-1) and internal walls (Figure 5-2) are all fixed parameters for all models. The U-value of the foundation slab is U=0,15 W/m^{2}K.

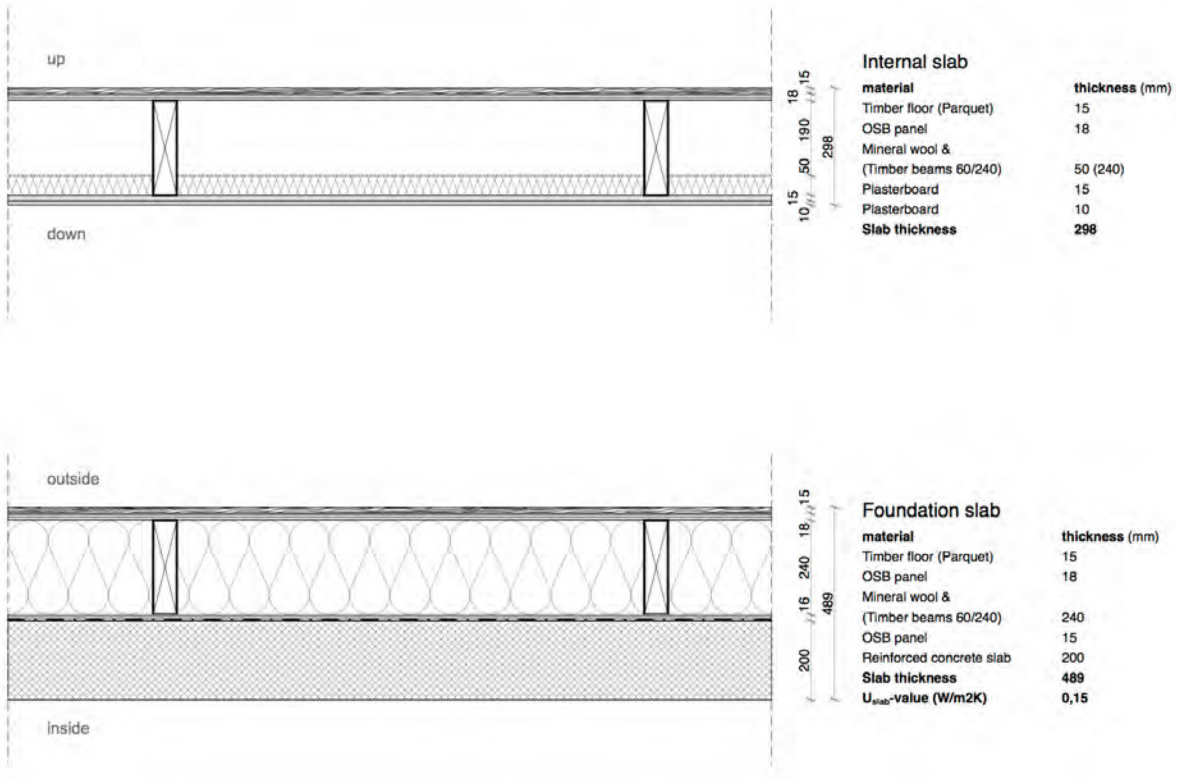
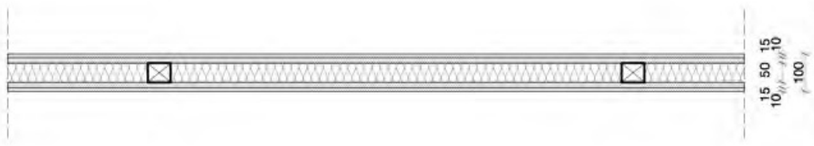
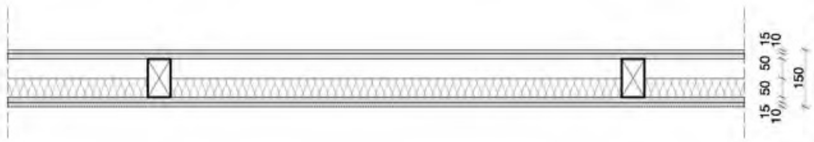


Figure 5-1: Composition of foundation slab (lower figure) and internal slab (upper figure) which are fixed parameter for all case models.



Internal separating wall

material	thickness (mm)
Plasterboard	10
Plasterboard	15
Mineral wool &	
(Timber studs 60/50)	50
Plasterboard	15
Plasterboard	10
Wall thickness	**100**



Internal bearing wall

material	thickness (mm)
Plasterboard	10
Plasterboard	15
Mineral wool &	
(Timber studs 60/100)	50 (100)
Plasterboard	15
Plasterboard	10
Wall thickness	**150**

Figure 5-2: Composition of the internal separating wall (upper figure) and internal bearing wall (lower figure) which are fixed parameter for all case models.

5.1.1 Reference house - Lumar Primus

For the reference construction we used Lumar's house Primus which is their most sold house model in last years.[211]

5.1.1.1 Envelope system

As described in Chapter 3.2 we used their energy system Lumar Prestige. The building is according to Steib et.al.[212] a timber panel system built in timber framework construction principle as presented in Chapter 2.5.2. House model Primus with Lumar Prestige system is categorized as a very good low energy house. They use cellulose thermal insulation for cavities between construction studs and mineral thermal insulation for installation layer and exterior insulation layer. According to Lumar it is possible to achieve an overall energy demand between 20 to 25 kWh/m^{2}a with this system. Because of low energy demands the heating is done with floor-heating. Lumar Prestige envelope has a very good thermal and soundproofing properties and it is a system open to vapor diffusion. According to Lumar it is a system best used for very good low energy buildings and in some cases also for passive houses. The envelope composition of the system is classified as the highest rank for house Eco-funding in Slovenia.

In Table 5-1 the construction and energy system with basic data is presented. It is a prefabricated timber panel construction (Figure 5-3) that consists of a wall that has a thickness of 365 mm and a U-value of 0,119 W/m2K. The flat roof (Figure 5-3), has a thickness of 593 mm and a U-value of 0.11 W/m2K. All other parameters are fixed and have a value as presented in Chapter 4.2.

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[211] Primus se predstavi, http://www.lumar.si/novica.asp?ID=106, 5.5.2014
[212] Staib/Dörrhöfer/Rosenthal 2008, 114.

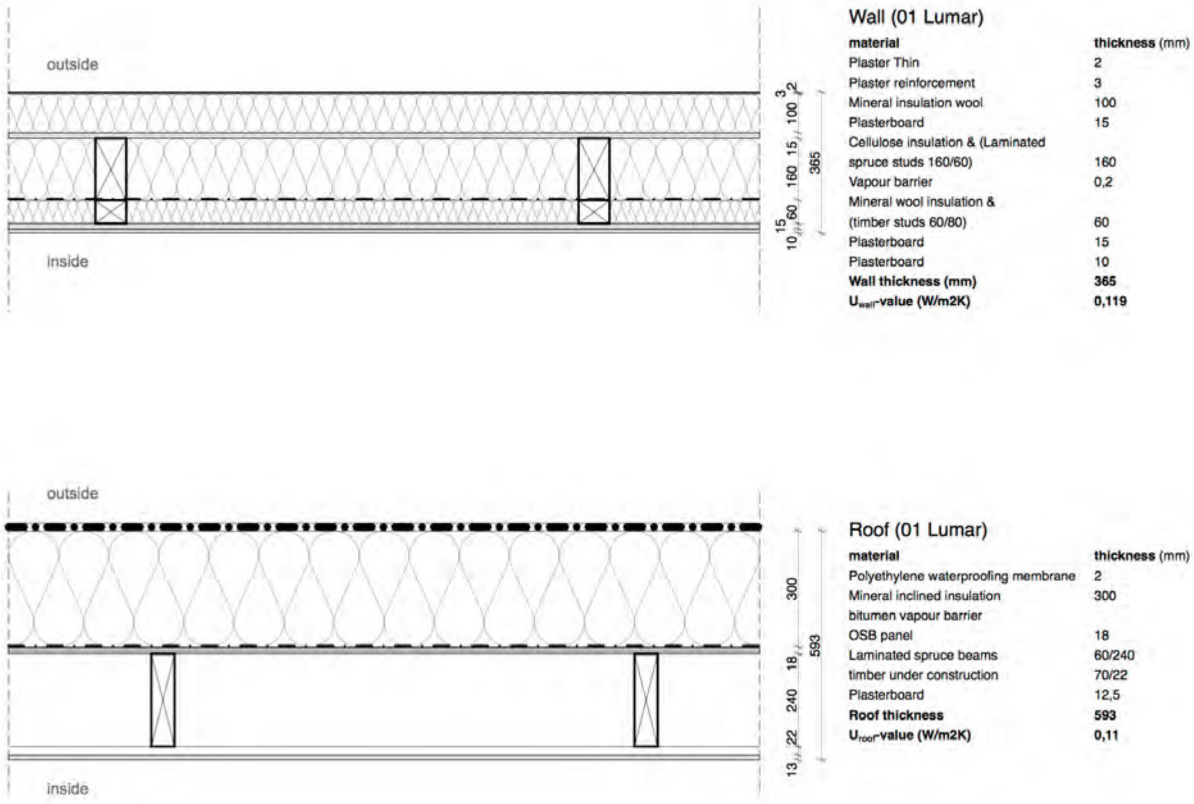


Figure 5-3: Composition of 01 Lumar wall (upper figure) and 01 Lumar roof (lower figure) external layer.

Table 5-1: Composition of Lumar case envelope (wall, roof).

wall		roof	
material	**thickness** (mm)	**material**	**thickness** (mm)
- Plaster Thin	2	- Polyethylene waterproofing membrane	2
- Plaster reinforcement	3	- Mineral inclined insulation	300
- Mineral insulation wool	100	- bitumen vapour barrier	
- Plasterboard	15	- OSB panel	18
- Laminated spruce studs	160	- Laminated spruce beams	60x240
- Cellulose insulation (between)	160	- timber under construction	70x22
- Vapour barrier	0,2	- Plasterboard	12,5
- Timber under construction	60		
- Mineral wool insulation (between)	60		
- Plasterboard	15		
- Plasterboard	10		
Wall thickness	**365**	**Roof thickness**	**593**
Uwall-value (W/m2K)	**0,119**	**Uroof-value (W/m2K)**	**0,11**
Wall area external (m2)	**137,61**		
Wall insulation area (m2)	**127,65**		
Wall area internal (m2)	**90,99**	**Roof area (m2)**	**55,36**

5.1.1.2 Energy evaluation numbers

The evaluated model has an interior heated volume of 249,90 m^3, treated net floor area of 94,44 m^2, gross floor area is 118,36 m^2 and a glazing ratio of 23%. It has an average U-value rating (building shell and openings) of 0,31 W/m^2K.
According to the energy evaluation in Archicad that is presented in Figure 5-4, the case model house with the Lumar envelope presents a good low energy building with a net heating energy value of 36,33 kWh/m^2a. The annual energy demand for heating is 3431,1 kWh/a. The service hot-water heating energy demand is evaluated to be 2868,0 kWh/a. The sum total electricity need for lighting and equipment is 609,9 kWh/a.

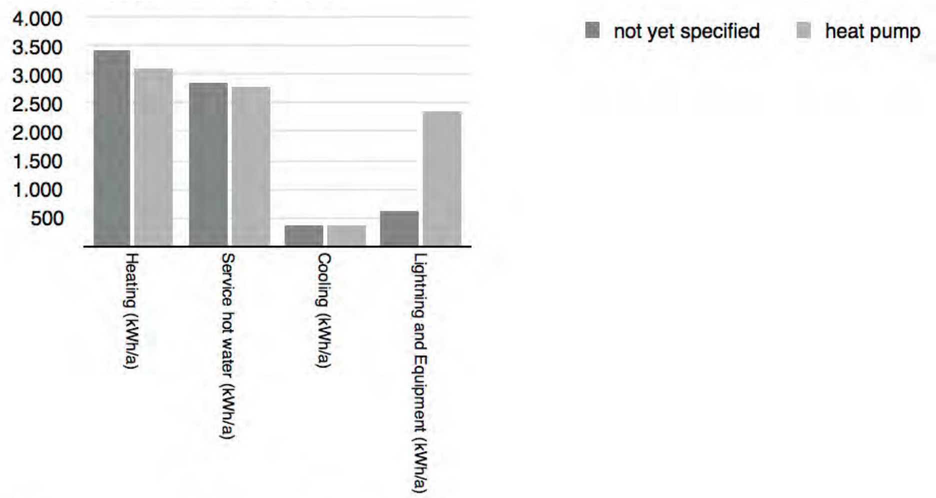


Figure 5-4: Energy evaluation results for house Lumar.

According to the evaluation of the case study (Figure 5-4) using the energy air to water heat pump, the net heating energy drops to 32,86 kWh/m^2a. Secondary electricity energy consumption for heat-pump operation is calculated to be 1757 kWh/a, with annual heating demand dropping to 3103,6 kWh/a and the service hot water demand to 2765,3 kWh/a.

5.1.1.3 Construction cost evaluation

As described in Chapter 4.6 construction cost estimation was done with Legep software and its extended and continuously updating sirAdos construction price database. For the Lumar case study the estimation was done with Legep. According to prices comparison between German and Slovenian construction market, as described in Chapter 4.7.2, a cost correction factor was added to accordingly adjust the German construction prices to the Slovenian construction market (Neupreisfaktor: 0.78). The tax was changed to Slovenian tax for building sector, which is 9,5% for all gross calculations. Following values were set for dynamic LCC calculations. Building cost inflation is set to 2% and energy price inflation to 4%, according to data obtained from Statistical office RS[213]. Real interest rate and capital interest rate are left as Legep defaults at 3,5% and 5,5%.
The estimated construction cost data is presented in Table 5-2. For each case study we decided to make an evaluation for three different variations. One with a wood pellet stove (01

[213] Cene in inflacija, http://www.stat.si/statweb, 12.12.2015

Lumar 01) which has been widely used for residential houses in recent years because of the low prices for pellets (EUR/MWh) in Slovenia[214]. Second (01 Lumar 02) variation suggests the use of air to water heat pump, which is included in the offers for very good low energy prefabricated houses by Lumar[215]. The third one is a conventional gas heater with a water tank (01 Lumar 03).

Table 5-2: Construction cost evaluation for Lumar case.

	04 MED 01 with pellet stove	04 MED 02 with heat pump air to water	04 MED 03 with gas stove
building construction	**115.963,85**	**115.963,85**	**115.963,85**
- exterior wall with windows and shading	74.856,15	74.856,15	74.856,15
- roof	12.849,40	12.849,40	12.849,40
01 technical equipment (MEP)	**25.811,09**	**28.523,47**	**20.213,54**
- heating	15.151,36	17.863,74	9.553,81
outdoor facility	**16.269,38**	**16.269,38**	**16.269,38**
Tax (9,5%)	**15.014,21**	**15.271,89**	**14.482,44**
Building cost (gross)	**€142.662,96**	**€145.633,02**	**€136.533,64**
delta	**€6.129,32**	**€9.099,38**	**€0**
Cost key value (€/m2)	**1.035,33**	**1.056,88**	**990,85**

The results in the evaluation show that lowest initial building construction cost for the house and outdoor facilities for the investor is as predicted the variation with the gas stove. The 127.812,16 EUR net cost is comparable and acceptable for a 120 m^2 (gross) prefabricated house as shown in the Chapter 2.1. The highest investment presents the variant with the heat pump (Air to Water HP, 12-20kW, with a storage, for heating and service hot water), which sums at 136.911,53 EUR. For 2970,06 EUR less it is estimated to build the same house with a wood pellet stove (Wood pellet stove, 5-25 kW, 200l storage) for 133.941,47 EUR.

5.1.1.4 LCC costs (50 years)

For the value for money evaluation the most important parameter to be evaluated is the LCC (Life Cycle Costs), which was also done with Legep software and for a period of 50 years. This is also the default value suggested by the software. The LCC results are presented according to DIN 276 + DIN 18960 + VDI 2067 which is a part of the "certification Steckbrief 4.1.1 (NaWoh)" report done by Legep LCC evaluation as the present value (net). The construction cost for presented LCC certification is calculated for cat. 300 (Building construction) and 400 (Technical facilities) according to DIN.
The LCC evaluation results are also presented for all three MEP variations as presented in chapter 5.1.1.3.

[214] Sistem zagotavljanja kakovosti lesenih pellet, http://www.s4q.si/info, 15.1.2016
[215] Lumar super-niedrigenergiehäuser, http://www.lumar-haus.at/energiekonzepte.asp?m3=21, 13.1.2016

Table 5-3: Life cycle costs for Lumar case (50 years).

	01 Lumar 01 Pellet			01 Lumar 02 HP			01 Lumar 03 Gas		
Overall cost	Net in EUR	% of construction cost	Present value in EUR	Net in EUR	% of construction cost	Present value in EUR	Net in EUR	% of construction cost	Present value in EUR
Construction cost (Cat. 300 and 400 acc. to DIN) (net value)	€106.052,29		**106.052,29**	€108.764,67		**108.764,67**	€100.454,74		**100.454,74**
Cleaning	€237,26	0,22%	**5.792,52**	€237,26	0,22%	**5.792,52**	€237,26	0,24%	**5.792,52**
Maintance	€278,73	0,26%	**14.758,34**	€305,86	0,28%	**16.757,35**	€222,75	0,22%	**10.633,61**
Regular service and repair (VDI2067)	**€322,09**	0,30%		**€376,34**	0,35%		**€210,15**	0,21%	
Service and repair (KGR300/ 400)	€2.306,80	2,18%	**42.534,48**	€2.374,33	2,18%	**43.792,02**	€1.940,87	1,93%	**35.679,57**
Supply and disposal	€879,73	0,83%	**18.775,88**	€764,55	0,70%	**16.718,39**	€978,29	0,97%	**20.536,77**
	Present value in EUR		Present value/m² GFA	Present value in EUR		Present value/m² GFA	Present value in EUR		Present value/m² GFA
Construction cost and LCC	**€187.913,51**		**1.493,27**	**€191.824,95**		**1.499,58**	**€173.097,21**		**1.375,53**
Net difference	€14.816,3			€18.727,74					

Comparing the 3 variations in the evaluation presented in Table 5-3, the results show, that the gas stove heating presents the highest supply and disposal costs with a present value of 20.536,77 EUR for a period of 50 years. This present value is 1.760,89 EUR higher than for pellets stove variant and 3.818,38 EUR higher when compared to the heat pump variant. Results are different when looking at the maintenance costs. Most expensive maintenance is for the 02 variant with a net value of 16.757,35 EUR in 50 years. The maintenance for the 03 Gas is 1.999,01 EUR lower and the lowest maintenance net value is for the 03 Gas variant, which is 6.123,74 EUR less.

But when we compare the service and repair costs according to KGR 300/400 evaluation, then the 03 Gas is the most economical solution, with a present value of 35.679,57 EUR in 50 years. Followed by 01 Pellet, which has 6.854,91 EUR higher net value and the most expensive variation's present value for service and repair, for the 02 HP evaluated to be 8.112,45 EUR higher.

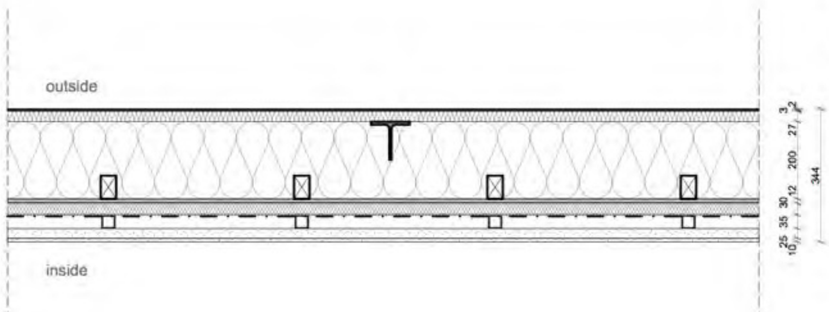
The result comparison of LCC evaluation shows that the most economical variation is the 01 Lumar 03 Gas. Its construction cost and LCC present value is evaluated to be 173.097,21 EUR. Second to it would be 01 Lumar 01 Pellet with LCC of 187.913,51 EUR which makes a difference of 14.816,30 EUR. The most expensive solution would be the 01 Lumar 02 TC with 191.824,95 EUR and a difference of 18.727,74 EUR in LCC costs compared to the 03 variation.

5.1.2 Canopea case study model construction system

Canopea case study was chosen as the first case model to be evaluated because it was the winner od SDE2012 competition as described in chapter 0.

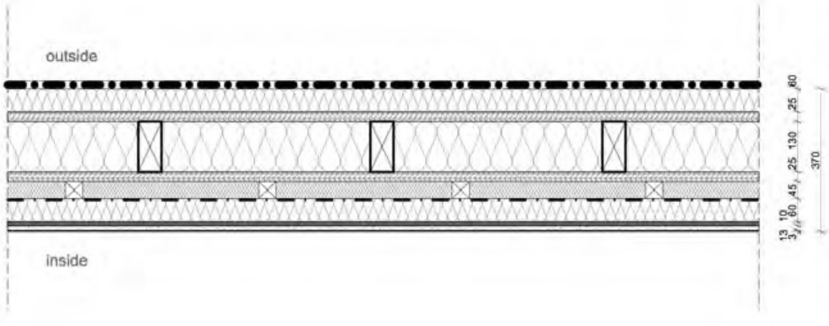
5.1.2.1 Envelope system

For Canopea prototype in SDE2012 a high performance thermal envelope, which defines the tempered zones of the housing unit, was used. This primary envelope is built in steel panel system according to Steib et.al.[216] in platform construction principle. Its exostructure, which was not used for our case model, is a steel frame system built with frames with continuous columns. According to Canopea team their external skin can be realized with local materials and prefabricated elements by local companies at controlled costs. It has a prefabricated steel frame construction, filled with cellulose insulation and combined with contemporary insulation materials, with vacuum insulation panels in the interior and Kerto-Q LVL panels on the outside (Figure 5-5). Final interior skin is earth coating. The system can be used for passive houses comparing to case study company Lumar and their Lumar Passive Eco energy system that has a U-value of 0,1 W/m^{2}K.



Wall (02 Canopea)

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**



Roof (02 Canopea)

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 5-5: Composition of 02 Canopea wall (upper figure) and 02 Canopea roof (lower figure) external layer.

In the table bellow (Table 5-4) the construction and energy system with basic data is presented. The walls have a thickness of 344 mm and a very good U_{wall} value of 0,08 W/m^{2}K.

[216] Staib/Dörrhöfer/Rosenthal 2008, 111.

The flat roof, has a thickness of 370 mm and a U-value of 0.07 W/m^{2}K. All other parameters are fixed and have a value as presented in chapter 4.2.

Table 5-4: Composition of Canopea case envelope (wall, roof).

wall		roof	
material	**thickness** (mm)	**material**	**thickness** (mm)
Plaster Thin	2	Polyethylene waterproofing membrane	
Plaster reinforcement	3	Wood joist + cellulose insulation	60
Kerto-Q LVL panel	27	Kerto-Q LVL panel	25
Cellulose insulation	200	cellulose insulation	130
OSB panel	12	Kerto-Q LVL panel	25
Vakuum insulation	30	Vakuum insulation (timber)	45
Vapour barrier	0.2	Vapour barrier	0.2
Proliferated steel rails	35x84	Cellulose insulation (timber)	60
Fibralith panel	25	Reflective insulating screen	10
Earth coating	10	Plasterboard	12.5
		Earth paintwork (Akterre)	3
Wall thickness	**344**	**Roof thickness**	**370**
Uwall-value (W/m2K)	**0,08**	**Uroof-value (W/m2K)**	**0,07**
Wall area external (m2)	**136,78**		
Wall insulation area (m2)	**122,30**		
Wall area internal (m2)	**90,81**	**Roof area (m2)**	**55,2**

5.1.2.2 Energy evaluation numbers

The interior heated volume is 249,90 m^3 and is the same as with the base case study Lumar. It also has same values for treated net floor area with 94,44 m^2. The gross floor area is 117,26 m^2 and the glazing ratio is 23%. It has an average U-value rating (building shell and openings) of 0,28 W/m^{2}K.

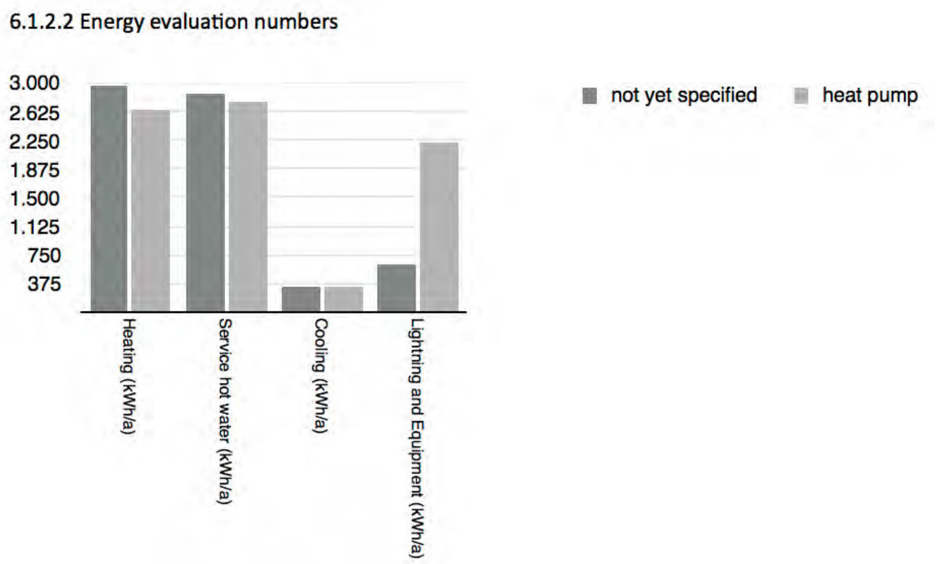


Figure 5-6: Energy evaluation results for Canopea case.

According to the energy evaluation in Archicad (Figure 5-6) the case model has a net heating energy value of 31,53 kWh/m^{2}a, with 2977,3 kWh/a annual energy demand for heating. The annual energy demand for service hot water and electricity are the same for all case studies, due to exact same parameters for scheduled residential use of the building.
The results of the evaluation of the 02 Canope case study using the energy air to water heat pump, show that the net heating energy is lowered to 28,10 kWh/m^{2}a. Secondary electricity energy consumption for heat-pump operation is projected to be 1540 kWh/a, with annual heating demand dropping to 2653,6 kWh/a. In both case variations such building would be clarified as B2 energy class in Slovenia. According “Dena-Gutesiegel Effizienzhaus” described in Chapter 2.4 the house variation without thermal pump would be considered a KfW Efficiency House 55 and the one with thermal pump as KfW Efficiency House 40.

5.1.2.3 Construction cost evaluation

In Legep evaluated construction cost data is presented in Table 5-5. The evaluation was done with the same parameters as for case study Lumar and these parameters were also used for all case models.

Table 5-5: Construction cost evaluation for Canopea case.

	02 Canopea 01 with pellet stove	02 Canopea 02 with heat pump air to water	02 Canopea 03 with gas stove
building construction	**€90.937,44**		
- exterior wall with windows and shading	€48.123,12		
- roof	€14.589,82		
01 technical equipment (MEP)	**€25.811,09**	**€28.523,47**	**€20.213,54**
- heating	€15.151,36	€17.863,74	€9.553,81
outdoor facility	**€16.269,13**		
Tax (9,5%)	**€12.636,70**	**€12.894,38**	**€12.104,93**
Building cost (gross)	**€145.654,61**	**€148.624,67**	**€139.525,29**
delta	**€6.129,32**	**€9.099,38**	**€0**
Cost key value (€/m2)	**972,04 €/m²**	**993,59 €/m²**	**927,55 €/m²**

Table 5-5 shows the results of the cost assessment for Canopea case study by different MEP. The results for Canopea match the results done for Lumar and show that lowest initial building construction cost for the house and outdoor facilities for the investor is variation with the gas stove. The gross building cost for case 01 pellet is 145.654,61 EUR, for case 02 HP with the heat pump it is 148.624,67 EUR and the lowest investment for the 03 gas with 139.525,29 EUR.

5.1.2.4 LCC costs (50 years)

The LCC values for the 02 Canopea case study for all 3 variations are presented in Table 5-6 according to DIN 276 + DIN 18960 + VDI 2067 which is a part of the certification (Steckbrief 4.1.1 (NaWoh)) report done by Legep LCC evaluation.

Table 5-6: Life cycle costs for Canopea case (50 years).

	02 Canopea 01 Pellet			02 Canopea 02 HP			02 Canopea 03 Gas		
Overall cost	Net in EUR	% of construction cost	Present value in EUR	Net in EUR	% of construction cost	Present value in EUR	Net in EUR	% of construction cost	Present value in EUR
Construction cost (Cat. 300 and 400 acc. to DIN) (net value)	€116.747,15		**116.747,15**	€119.459,53		**119.459,53**	€111.149,60		**111.149,60**
Cleaning	€237,26	0,20%	**5.792,52**	€237,26	0,20%	**5.792,52**	€237,26	0,21%	**5.792,52**
Maintance	€289,30	0,25%	**15.012,09**	€316,43	0,26%	**17.011,07**	€233,32	0,21%	**10.887,39**
Regular service and repair (VDI2067)	**€321,85**	0,28%		**€376,10**	0,31%		**€209,91**	0,19%	
Service and repair (KGR300/ 400)	€2.404,73	2,06%	**44.626,02**	€2.472,26	2,07%	**45.883,56**	€2.038,80	1,83%	**37.771,11**
Supply and disposal	€854,98	0,73%	**18.333,67**	€736,34	0,62%	**16.214,44**	€946,43	0,85%	**19.967,33**
	Present value in EUR		Present value/m² GFA	Present value in EUR		Present value/m² GFA	Present value in EUR		Present value/m² GFA
Construction cost and LCC	**200.511,45**		**1.593,38**	**204.361,12**		**1.623,98**	**185.567,95**		**1.474,63**
Net difference	**14.943,5**			**18.793,17**					

The assessment of LCC costs by MEP variation shows again that the gas stove heating needs are the highest and therefore present the highest supply and disposal net value that sums up to 19.967,33 EUR. That is 1.633,66 EUR more in 50 years then for 01 pellets stove and 3.752,89 EUR more than for heat pump variant. Most expensive maintenance is for the 02 variant with heat pump which is evaluated to be as high as 17.011,07 EUR. The maintenance for the 01 Pellet would have a net value of 15.012,09 EUR and the cheapest maintenance would be for 01 Pellet and with 10.887,39 EUR.

The KGR 300/400 service and repair cost asses that the 03 gas stove case is the most economic one with the present value of 37.771,11 EUR, comparing to 44.626,02 EUR and 45.883,56 EUR for the 01 Pellet and 02 HP cases. That is a difference of 6.854,91 EUR and 8112,45 EUR in the 50 years' period.

The assessment of LCC evaluation shows that the most economical variation is the 02 Canopea 03 Gas, its construction cost and LCC cost is evaluated to have a net value of 185.567,95 EUR. Second to it would be 02 Canopea 01 Pellet with 200.511,45 EUR. The most expensive solution would be the 02 Canopea 02 HP with 204.361,12 EUR.

5.1.3 Ecolar case study model construction system

For Ecolar case study we used the special opaque facade elements that combine passive and active solar energy use in a high-energy performance element. We applied this high tech external envelope that reduces heat losses significantly, as described in chapter 3.1.5.

5.1.3.1 Envelope system

The walls envelope for this case study is a high-energy performance wall element. It is a combination of the primary structure which is a timber frame system built in post and beam construction principle (according to Steib et.al.[217]). The high tech infill panels are a timber panel system built with timber framework construction principle. This inner layers of special wooden slats and hemp insulation work in combination with solar radiation highly insulating and reduce heat losses to about half a conventionally insulated external wall with the same thickness. The photovoltaic external layer was excluded from our case study.

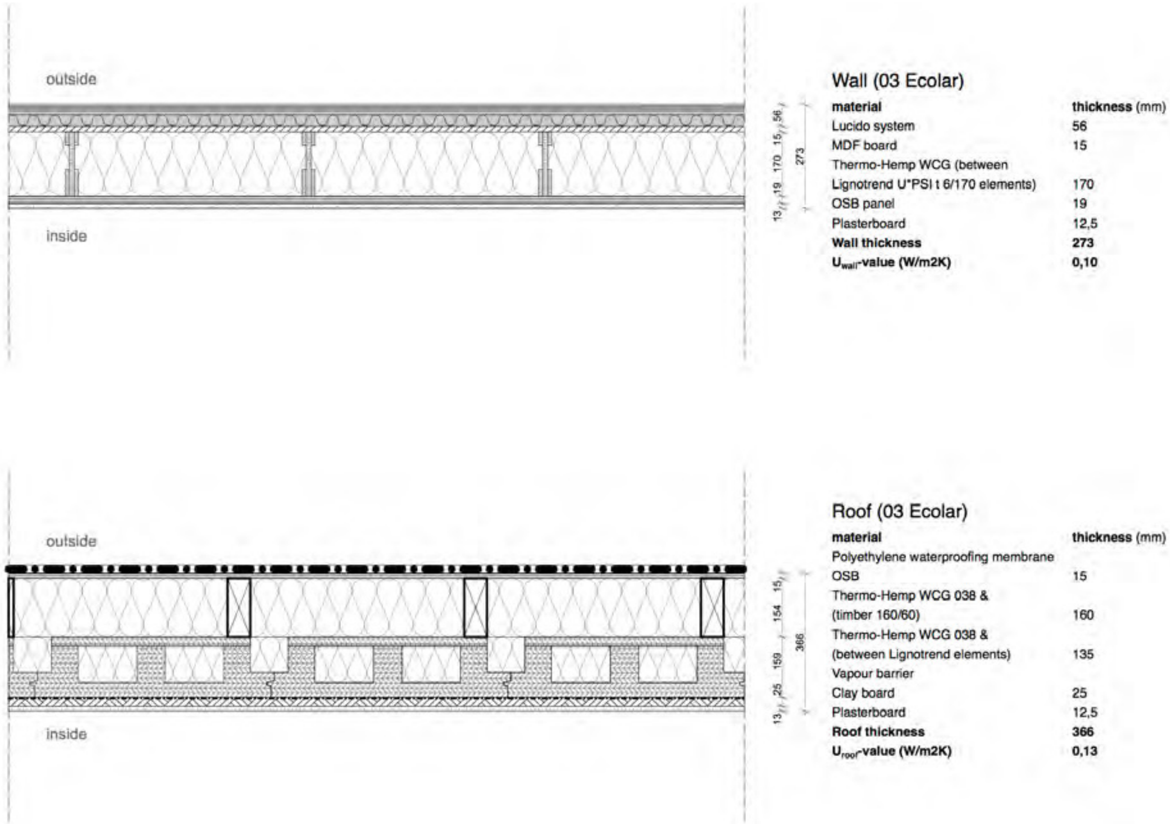


Figure 5-7: Composition of 03 Ecolar wall (upper figure) and 03 Ecolar roof (lower figure) external layer.

The inner layer of external walls (Figure 5-7) consists of hemp insulation, followed by a specially milled layer with horizontal wooden slats, which are slightly inclined downwards and after that an air gap. The final and weather protective layer is a laminated glazing. Additional solar beams can pass through the 30-percent translucence, and they warm the wooden slats and the spaces in between them. This leads to higher temperatures than outside, which

[217] Staib/Dörrhöfer/Rosenthal 2008, 114.

greatly reduces the heat losses by transmission. Calculated openings at the top and bottom effect that during the heating season, an unmoved layer of air forms at a low temperature level in between the glass. At high temperatures however these openings prevent overheating of the facade element via convection. This creates a dynamic U-value, with a measured value (by team Ecolar) of less than 0,01 W/m2K during heating season. The system is as efficient as a conventionally insulated exterior wall of double thickness.

Table 5-7: Composition of Ecolar case envelope (wall, roof).

wall		**roof**		
material	**thickness** (mm)	**material**	**thickness** (mm)	
Lucido system	56	Polyethylene waterproofing membrane		
MDF board	15	OSB	15	
Thermo-Hemp WCG (between		Thermo-Hemp WCG 038	160	
Lignotrend U*PSI t 6/170 elements)	170	Thermo-Hemp WCG 038 (between Lignotrend elements)	135	
OSB panel	19	Vapour barrier		
Plasterboard	12,5	Clay board	25	
		Plasterboard	12,5	
Wall thickness	**273**	**Roof thickness**	**366**	
Uwall-value (W/m2K)	**0,10**	**Uroof-value (W/m2K)**	**0,13**	
Wall area external (m2)	**128,08**			
Wall insulation area (m2)	**114,52**			
Wall area internal (m2)	**91,39**	**Roof area (m2)**	**52,93**	

In the Table 5-7 the construction and energy system with basic data is presented. The walls have a thickness of 273 mm and a dynamic U_{wall} value with a calculated average of 0,10 W/m^{2}K. The flat roof (Figure 5-7), has a thickness of 366 mm and a U_{roof}-value of 0.13 W/m^{2}K. All other parameters are fixed and have a value as presented in chapter 4.2.

5.1.3.2 Energy evaluation numbers

The interior heated volume is 249,90 m^3 and the treated net floor area with 94,44 m^2. The gross floor is 112,40 m^2 and the glazing ratio is 23%. It has an average U-value rating (building shell and openings) of 0,31 W/m^{2}K.

The assessment of the energy evaluation shows following energy needs (Figure 5-8). Net heating energy value is 35,00 kWh/m^{2}a and annual energy demand for heating is 3305,3 kWh/a. The annual energy demand for service hot water and electricity are the same for all case studies, due to exact same parameters for scheduled residential use of the building.

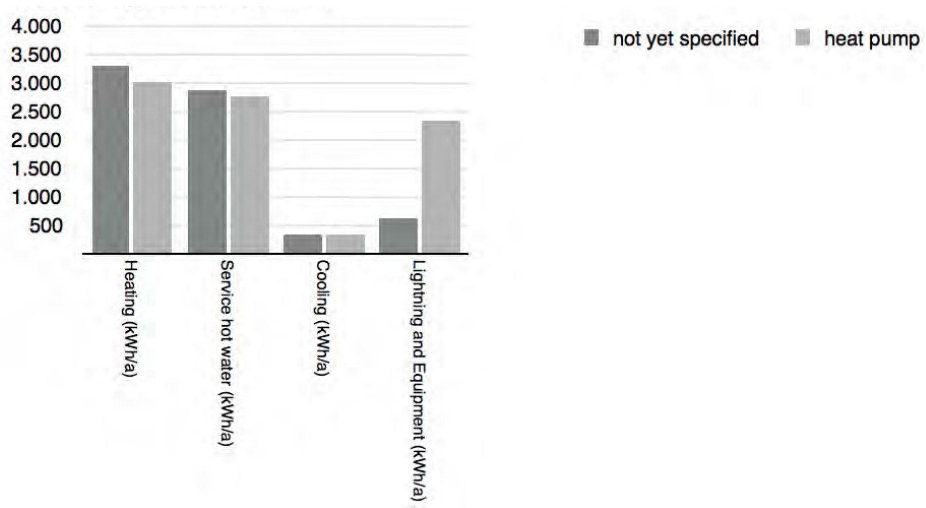


Figure 5-8: Energy evaluation results for Ecolar case.

The results of the evaluation of the 03 Ecolar case study using the energy air to water heat pump, the net heating energy is lowered to 31,67 kWh/m2a. Secondary electricity energy consumption for heat-pump operation is projected to be 1721 kWh/a, with annual heating demand dropping to 2991,3 kWh/a. In both case variations such building would be clarified as B2 energy class in Slovenia. According “dena-gutesiegel Effizienzhaus” described in Chapter 2.4 the both house variations would be considered a KfW Efficiency House 55.

5.1.3.3 Construction cost evaluation

Table 5-8 shows the results of the cost assessment for Ecolar case study by different MEP. The results for Ecolar match the results done for Lumar and show that lowest initial building construction cost for the house and outdoor facilities for the investor is variation with the gas stove. The gross building cost for case 01 pellet is 173.058,53 EUR, for case 02 with the heat pump it is 176.028,59 EUR and the lowest investment for the 03 gas with 166.929,21 EUR. The difference in gross cost for investor is 6.129,32 EUR for 01 Pellet and 9.099,38 EUR for 02 HP.

Table 5-8: Construction cost evaluation for Ecolar case.

	03 Ecolar 01 with pellet stove	**03 Ecolar 02 with heat pump air to water**	**03 Ecolar 03 with gas stove**
building construction	**115.963,85**	**115.963,85**	**115.963,85**
- exterior wall with windows and shading	74.856,15	74.856,15	74.856,15
- roof	12.849,40	12.849,40	12.849,40
01 technical equipment (MEP)	**25.811,09**	**28.523,47**	**20.213,54**
- heating	15.151,36	17.863,74	9.553,81
outdoor facility	**16.269,38**	**16.269,38**	**16.269,38**
Tax (9,5%)	**15.014,21**	**15.271,89**	**14.482,44**
Building cost (gross)	**€173.058,53**	**€176.028,59**	**€166.929,21**
delta	**€6.129,32**	**€9.099,38**	**€0**
Cost key value (€/m2)	**1.255,91**	**1.277,47**	**1.211,43**

5.1.3.4 LCC costs (50 years)

The LCC values for the 03 Ecolar case study for all 3 variations are presented in Table 5-9 according to DIN 276 + DIN 18960 + VDI 2067 which is a part of the certification (Steckbrief 4.1.1 (NaWoh)) report done by Legep LCC evaluation.

The assessment of LCC costs by MEP variation shows that the gas stove supply and disposal needs for 03 Ecolar case study are the highest and present a present value of 19.529,28 EUR for a period of 50 years. For 01 pellets stove the present value drops to 17.893,43 and to 15.980,28 for the heat pump variant. Maintenance cost for 03 variants with gas stove is 17.041,13 EUR in present value. The maintenance for the 02 HP has a lower present value of 15.108,56 EUR and the cheapest maintenance would be for 01 Pellet with 11.120,65 EUR.

Table 5-9: Life cycle costs for Ecolar case (50 years).

	03 Ecolar 01 Pellet			03 Ecolar 02 HP			03 Ecolar 03 Gas		
Overall cost	Net in EUR	% of construction cost	Present value in EUR	Net in EUR	% of construction cost	Present value in EUR	Net in EUR	% of construction cost	Present value in EUR
Construction cost (Cat. 300 and 400 acc. to DIN) (net value)	€141.775,30		**141.775,30**	€144.487,68		**144.487,68**	€136.177,75		**136.177,75**
Cleaning	€460,12	0,32%	**11.266,79**	€460,12	0,32%	**11.266,79**	€460,12	0,34%	**11.266,79**
Maintance	€314,33	0,22%	**15.626,99**	€341,46	0,24%	**17.625,88**	€258,35	0,19%	**11.502,24**
Regular service and repair (VDI2067)	**€321,85**	0,23%		**€376,10**	0,26%		**€209,91**	0,15%	
Service and repair (KGR300/ 400)	€3.144,61	2,22%	**57.537,30**	€3.212,14	2,22%	**58.794,84**	€2.778,68	2,04%	**50.682,39**
Supply and disposal	€872,87	0,62%	**18.653,21**	€759,87	0,53%	**16.634,80**	€969,46	0,71%	**20.378,98**
			6.854,91			**8.112,45**			
	Present value in EUR		**Present value/m² GFA**	Present value in EUR		**Present value/m² GFA**	Present value in EUR		**Present value/m² GFA**
Construction cost and LCC	244.859,59		1.945,80	248.809,99		1.977,19	230.008,15		1.827,78
Net difference	**14.851,44**			**18.801,84**					

The KGR 300/400 service and repair costs are estimated to have a present value of 50.880,17 EUR for 03 gas stove case, compared to 57.735,08 EUR and 58.992,62 EUR for the 01 Pellet and 02 HP cases.

The assessment of LCC evaluation shows that the most economical variation is the 03 Ecolar 03 Gas, its LCC and construction costs combined are evaluated to the present value of 230.008,15 EUR. Next would be 03 Ecolar 01 Pellet with 244.859,59 EUR. The most expensive solution would be the 03 Ecolar 02 HP with 248.809,99 EUR. This is a net present difference of 14.851,44 EUR and 18.801,84 EUR.

5.1.4 Med in Italy case study model construction system

As presented in Chapter 0. Med in Italy was chosen as a case study, because it uses an innovative low-tech solution. The typical panel walls have a cavity, that is filled with sand. Light elements in form of alloy pipes are transported, and on the site, filled with humid sand in order to get the inertial mass and to optimize thermal behavior.

5.1.4.1 Envelope system

The case study is according to Steib et.al.[218] a timber panel system built in timber framework construction principle (Figure 5-9).

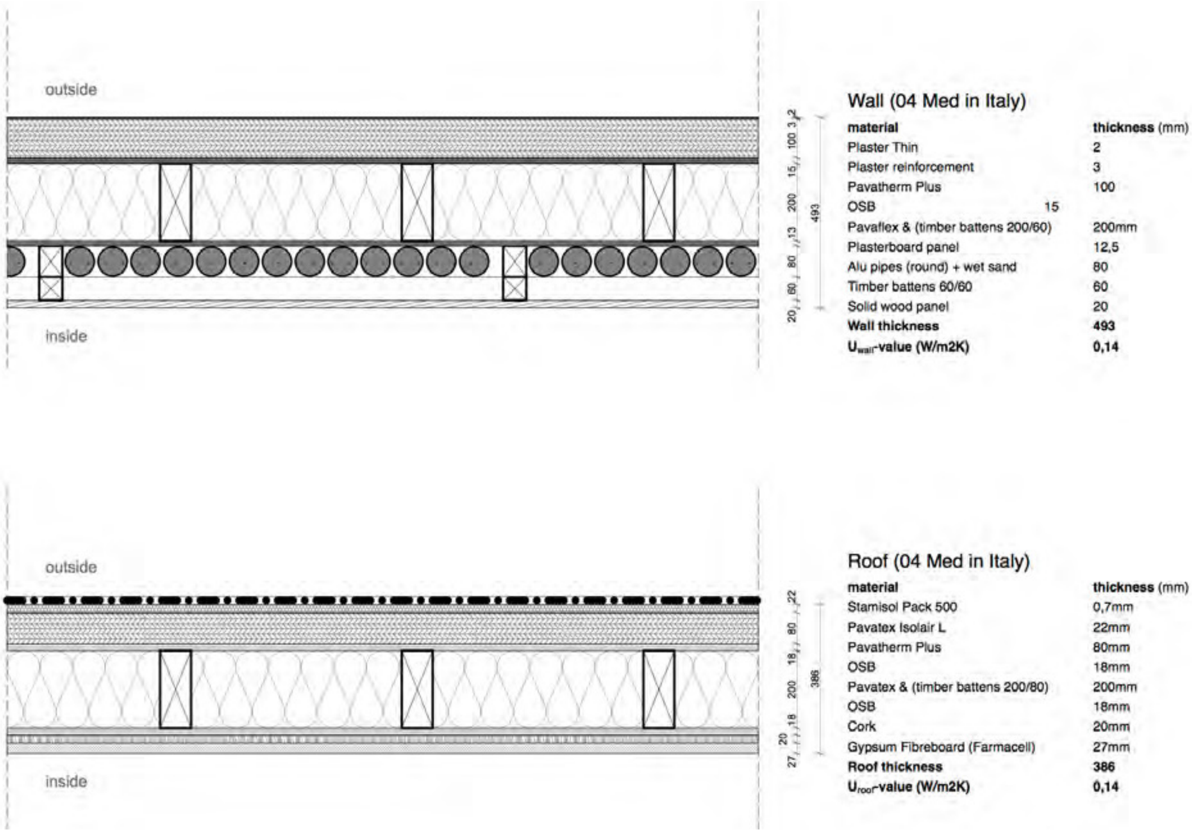


Figure 5-9: Composition of 04 Med in Italy wall (upper figure) and 04 Med in Italy roof (lower figure) external layer.

It has a low tech timber frame structure, where thermal mass of the wooden frame structure, was increased with sand in filled aluminum pipes, to achieve a better comfort. The reduction of the total weight of the structures is up to 30% less, compared to a homogenous layer of

[218] Staib/Dörrhöfer/Rosenthal 2008, 114.

dry sand and the whole thermal capacity was increased at least up to 20% thanks to increased surface exchanging the heat, due to a ventilation of the mass itself (according to team MED). It makes this wooden structure comparable with a traditional insulated brick wall.

In the table Table 5-10 the construction and energy system with basic data is presented. The walls have a thickness of 493 mm and U_{wall} value of 0,14 W/m^{2}K. The flat roof, has a thickness of 386 mm and a U_{roof}-value of 0.14 W/m^{2}K. All other parameters are fixed and have a value as presented in chapter 5.2.

Table 5-10: Composition of Med in Italy case envelope (wall, roof).

wall		roof	
material	**thickness** (mm)	**material**	**thickness** (mm)
Plaster Thin	2	Stamisol Pack 500	0,7
Plaster reinforcement	3	Pavatex Isolair L	22
Pavatherm Plus	100	Pavatherm Plus	80
OSB	15	OSB	18
Pavaflex/wood battens 62,5cm/200mm	200	Pavatex+wood battebs 0,4m	200
Plasterboard panel	12,5	OSB	18
Alu pipes (round) + wet sand (center to center > 120cm)	80	Cork	20
Wood battens c. to c. 120cm	60	Gypsum Fibreboard (Farmacell)	27
Solid wood panel	20		
Wall thickness	**493**	**Roof thickness**	**386**
Uwall-value (W/m2K)	**0,14**	**Uroof-value (W/m2K)**	**0,14**
Wall area external (m2)	**137,61**		
Wall insulation area (m2)	**127,65**		
Wall area internal (m2)	**90,99**	**Roof area (m2)**	**60,33**

5.1.4.2 Energy evaluation numbers

The interior heated volume is 249,90 m^3 and the treated net floor area 94,44 m^2. The gross floor area is 126,13 m^2 and the glazing ratio is 23%. It has an average U-value rating (building shell and openings) of 0,31 W/m^{2}K.

The assessment of the energy evaluation shows following energy needs (Figure 5-10). Net heating energy value is 35,80 kWh/m^{2}a and annual energy demand for heating is 3381,2 kWh/a. The annual energy demand for service hot water and electricity are again the same as for other case studies, due to exact same parameters for scheduled residential use of the building.

The results of the evaluation of the 04 Med in Italy case study using the energy air to water heat pump, the net heating energy is lowered to 33,54 kWh/m^{2}a. Secondary electricity energy consumption for heat-pump operation is projected to be 2348 kWh/a, with annual heating demand dropping to 3167,6 kWh/a. In both case variations such building would be clarified as B2 energy class in Slovenia. According “dena-gutesiegel Effizienzhaus” both house variations would be considered a KfW Efficiency House 55.

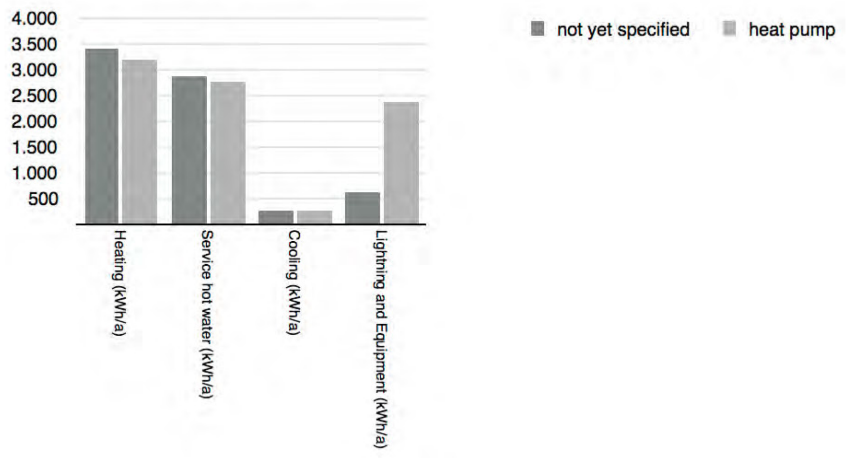


Figure 5-10: Energy evaluation results for Med in Italy case.

5.1.4.3 Construction cost evaluation

Table 5-11 assesses construction evaluation data for MED case study by different MEP. Again the evaluation was done with the same parameters as retrieved for reference case model.

Table 5-11: Construction cost evaluation for Med in Italy case.

	04 MED 01 with pellet stove	04 MED 02 with heat pump air to water	04 MED 03 with gas stove
building construction	**115.963,85**	**115.963,85**	**115.963,85**
- exterior wall with windows and shading	74.856,15	74.856,15	74.856,15
- roof	12.849,40	12.849,40	12.849,40
01 technical equipment (MEP)	**25.811,09**	**28.523,47**	**20.213,54**
- heating	15.151,36	17.863,74	9.553,81
outdoor facility	**16.269,38**	**16.269,38**	**16.269,38**
Tax (9,5%)	**15.014,21**	**15.271,89**	**14.482,44**
Building cost (gross)	**€142.662,96**	**€145.633,02**	**€136.533,64**
delta	**€6.129,32**	**€9.099,38**	**€0**
Cost key value (€/m2)	**1.035,33**	**1.056,88**	**990,85**

The results for MED show that the gross building cost for case 01 pellet is 142.662,96 EUR, for case 02 with the heat pump it is 145.633,02 EUR and the lowest investment for the 03 gas with 136.533,64 EUR. The difference in gross cost for investor is 6.129,32 EUR for 01 Pellet and 9.099,38 EUR for 02 HP.

5.1.4.4 LCC costs (50 years)

The LCC values for the 04 Med in Italy case study for all 3 variations are presented according to DIN 276 + DIN 18960 + VDI 2067.

The assessment of LCC costs by MEP variation shows that the gas stove supply and disposal costs in 50 years for 04 MED case study are the highest with 19.618,96 EUR net present value. For 01 pellets stove the number drops to 17.963,58 and to 16.017,85 for the heat pump variant. Maintenance present value for 03 variants with gas stove is 16.390,48 EUR. The maintenance for the 02 HP is 14.457,76 EUR and the cheapest maintenance would be for 01 Pellet and would have a net value of 10.469,90 EUR.

Table 5-12: Life cycle costs for Med in Italy case (50 years).

	04 MED 01 Pellet			04 MED 02 HP			04 MED 03 Gas		
Overall cost	Net in EUR	% of construction cost	Present value in EUR	Net in EUR	% of construction cost	Present value in EUR	Net in EUR	% of construction cost	Present value in EUR
Construction cost (Cat. 300 and 400 acc. to DIN) (net value)	€114.016,38		**114.016,38**	€116.728,76		**116.728,76**	€108.418,83		**108.418,83**
Cleaning	€237,26	0,21%	**5.792,52**	€237,26	0,20%	**5.792,52**	€237,26	0,22%	**5.792,52**
Maintance	€286,69	0,25%	**14.953,86**	€313,82	0,27%	**16.952,89**	€230,71	0,21%	**10.829,16**
Regular service and repair (VDI2067)	**€322,09**	0,28%		**€376,34**	0,32%		**€210,15**	0,19%	
Service and repair (KGR300/ 400)	€2.761,69	2,42%	**48.789,04**	€2.829,22	2,42%	**50.046,58**	€2.395,76	2,21%	**41.934,13**
Supply and disposal	€877,01	0,77%	**18.727,20**	€762,09	0,65%	**16.674,43**	€974,78	0,90%	**20.473,62**
			6.854,91			**8.112,45**			
	Present value in EUR		**Present value/m² GFA**	Present value in EUR		**Present value/m² GFA**	Present value in EUR		**Present value/m² GFA**
Construction cost and LCC	**202.279,00**		1.607,43	**206.195,18**		1.638,55	**187.448,26**		**1.489,58**
Net difference	**14.830,74**			**18.746,92**					

The KGR 300/400 service and repair net value is estimated to be 42.131,91 EUR for 03 gas stove case, compared to 48.986,82 EUR and 50.244,36 EUR for the 01 Pellet and 02 HP cases.

The assessment of LCC evaluation shows that the most economical variation is the 04 MED 03 Gas, its construction and LCC cost is evaluated to be 187.448,26 EUR. Next would be 04 MED 01 Pellet with present value of 202.279,00 EUR. The most expensive solution would be the 04 MED 02 HP with 206.195,18 EUR. These are differences in present value of 14.830,74 EUR and 18.746,92 EUR for a LCC period of 50 years.

5.2 Results and evaluation

The LCC of external envelope cases in the following chapters compares construction cost and operation cost. In chapter 5.2.1 the construction costs of KGR 300 and 400 of all case studies are compared. Followed by chapter 5.2.2 where we compare the Life Cycle Costs according to Steckbrief 4.1.1 - NaWoh, for each case. Finally, we evaluate the value of all cases using Value for money method in chapter 5.2.3.

5.2.1 Comparison of Construction Costs (KGR 300 and 400)

Table 5-13 shows the results of construction cost assessment for each case. The reference for the assessment was the construction cost for 01 Lumar case study. The construction cost difference arises from the alteration among material cost, labor cost and toll processing cost. The order of construction cost from lowest to highest is 01 Lumar, 04 MED, 02 Canopea and 03 Ecolar.

Table 5-13: Comparison of construction costs (KGR 300 and 400).

	01 Pellet		02 TP		03 Gas	
	Construction cost (Cat. 300 and 400 acc. to DIN) (net value in EUR)	Building cost (gross)	Construction cost (Cat. 300 and 400 acc. to DIN) (net value in EUR)	Building cost (gross)	Construction cost (Cat. 300 and 400 acc. to DIN) (net value in EUR)	Building cost (gross)
01 Lumar	€106.052,29	€133.941,47	€108.764,67	€136.911,53	€100.454,74	€127.812,16
02 Canopea	€116.747,15	€145.654,61	€119.459,53	€148.624,67	€111.149,60	€139.525,29
03 Ecolar	€141.775,30	€173.058,53	€144.487,68	€176.028,59	€136.177,75	€166.929,21
04 MED	€114.016,38	€142.662,96	€116.728,76	€145.633,02	€108.418,83	€136.533,64

As evaluated in Table 5-14 the construction cost (300 and 400) of the 04 MED is evaluated to be approximately 7% higher than 01 Lumar, the one for 02 Canopea case approximately 9% higher and the one for 03 Ecolar is with 25% more, the highest. The highest construction cost for Ecolar is due to high tech external wall envelope with a dynamic U-value and the highest material cost for its facade. All other envelopes have very good U-values which are achieved with insulation on a low-tech basis, with the exception of expensive vacuum insulation panels used in 02 Canopea case.

Table 5-14: Evaluation of Construction costs (Cat. 300 and 400) with difference value.

	01 Pellet		02 TP		03 Gas	
	difference (%)	Construction cost (Cat. 300 and 400 acc. to DIN) (net value in EUR)	difference (%)	Construction cost (Cat. 300 and 400 acc. to DIN) (net value in EUR)	difference (%)	Construction cost (Cat. 300 and 400 acc. to DIN) (net value in EUR)
01 Lumar	/	€106.052,29	/	€108.764,67	/	€100.454,74
02 Canopea	9,2%	€116.747,15	8,95%	€119.459,53	9,62%	€111.149,60
03 Ecolar	25,2%	€141.775,30	24,7%	€144.487,68	26,2%	€136.177,75
04 MED	7%	€114.016,38	6,8%	€116.728,76	7,3%	€108.418,83

5.2.2 Comparison of Life Cycle Costs

Table 5-15 shows the results of life cycle costs evaluation according to Steckbrief 4.1.1 - NaWoh, for each case. The reference for the assessment was the LCC for 01 Lumar case study. The LCC adds operational costs to the construction costs.

Table 5-15: Life cycle costs evaluation (construction cost and life cycle cost net present value).

	01 Pellet	02 TP	03 Gas
	Construction cost and LCC (present value) in EUR	Construction cost and LCC (present value) in EUR	Construction cost and LCC (present value) in EUR
01 Lumar	187.913,51	191.824,95	173.097,21
02 Canopea	200.511,45	204.361,12	185.567,95
03 Ecolar	244.859,59	248.809,99	230.008,15
04 MED	202.279,00	206.195,18	187.448,26

The comparison of the construction cost analysis is shown in Table 5-13. The different life cycle costs result from the difference between construction and operational costs through the life cycle (50 years) of the building. The order of LCC from lowest to highest is 01 Lumar, 02 Canopea, 04 MED and 03 Ecolar.

Table 5-16: Comparison of life cycle costs with the difference value.

	01 Pellet		02 TP		03 Gas	
	difference (%)	Construction cost and LCC (present value) in EUR	difference (%)	Construction cost and LCC (present value) in EUR	difference (%)	Construction cost and LCC (present value) in EUR
01 Lumar	/	187.913,51	/	191.824,95	/	173.097,21
02 Canopea	6,28%	200.511,45	6,13%	204.361,12	6,7%	185.567,95
03 Ecolar	23,3%	244.859,59	22,9%	248.809,99	24,7%	230.008,15
04 MED	7,102%	202.279,00	6,97%	206.195,18	7,66%	187.448,26

As revealed in Table 5-16 the LCC of the 02 Canopea 01 Pellet and 02 TP are evaluated to be approximately 6% higher, the one for 04 MED 01 and 02 cases approximately 7% higher and the one for 03 Ecolar 01 and 02 are with 22% more than 01 Lumar the highest. The difference in 03 Gas Cases are approximately 2% higher. The analysis revealed that when looking at the LCC the 02 Canopea has almost 1% lower LCC present value than 04 MED, whereas when looking at the construction costs Canopea was almost 2% more expensive than 04 MED. This is a result of lower operational costs, foremost lower maintenance and supply costs. For the potential investors, 01 Lumar would still mean lowest LCC costs.

The difference in supply and disposal present value as presented in Table 5-17 is because the demand costs vary depending on the energy performance of the external envelope. The highest supply costs are for Lumar case study with the Heat transfer coefficient (U-value) 0,11 W/m2K for external envelope that makes for 20.536,77 net present value in 50 years. The lowest supply costs has the 02 Canopea case with its U-value between 0,07-0,08 W/m2K. This case would cost the user app. 3% less then Lumar. The 02 Ecolar with its high tech envelope and a dynamic U-value of (0,01-0,1)-0,13 W/m2K 0,77% less. The 04 MED case has a U-value of 0,14 W/m2K but would cost the user app. 0,3% less than 01 Lumar due to its smart use of simple aluminum pipes filled with wet sand for heat capacity purposes.

Table 5-17: Difference in supply and disposal cost present value.

	01 Pellet		02 TP		03 Gas	
	difference (%)	Supply and disposal (EUR)	difference (%)	Supply and disposal (EUR)	difference (%)	Supply and disposal (EUR)
01 Lumar	/	18.775,88	/	16.718,39	/	20.536,77
02 Canopea	-2,41%	18.333,67	-3,11%	16.214,44	-2,85%	19.967,33
03 Ecolar	-0,66%	18.653,21	-0,5%	16.634,8	-0,77%	20.378,98
04 MED	-0,26%	18.727,20	-0,26%	16.674,43	-0,31%	20.473,62

The operational costs comparison is shown in Table 5-18. The highest operational costs for Ecolar are a result of the high-tech external wall envelope with dynamic U-value that does indeed lower the supply and disposal costs by app. 1% but has very high maintenance and service costs in 50 years, that are 20,6% to 22,6% higher comparing to 01 Lumar. The evaluation results show that high-tech equipment and high-tech materials lower the supply costs, but add to operational costs, due to much higher maintenance and service costs during its life period. That is why the results had to be reasserted also for shorter LCC periods.

Table 5-18: Difference in operational cost present value.

	01 Pellet		02 TP		03 Gas	
	difference (%)	Operational costs (NaWoh) in EUR	difference (%)	Operational costs (NaWoh) in EUR	difference (%)	Operational costs (NaWoh) in EUR
01 Lumar	/	81.861,22	/	83.060,28	/	72.642,47
02 Canopea	2,27%	83.764,3	2,17%	84.901,59	2,386%	74.418,35
03 Ecolar	20,6%	103.084,29	20,4%	104.322,31	22,6%	93.830,4
04 MED	7,25%	88.262,62	7,16%	89.466,42	8,08%	79.029,43

The results also show that the value varies when looking from user perspective (supply costs) and owner perspective (maintenance and service costs). From the user's perspective, the cases that have lover supply costs are better, however for owners less maintenance and service costs mean a better value. That is an important result, because according to Statistical office of Republic Slovenia[219] 77% of residential apartments in Slovenia are owned and not rented.

[219] Naseljena stanovanja, Slovenija, 1. januar 2011 - začasni podatki, http://www.stat.si/StatWeb/glavnanavigacija/podatki/prikazistaronovico?IdNovice=4420, 12.3.2016

5.2.3 Value for Money evaluation

As described in chapter 4.1.1, Value For Money (VfM) is a term used to refer to the highest value for a payment. The formula for Value for money method (Figure 5-11) divides the Function (value drivers) with Total costs (Life Cycle Costs).

$$\text{V (Value)} \qquad \frac{\text{F (Function)}}{\text{LCC (Life Cycle Costs)}}$$

Figure 5-11: The Value for money equitation.

The VfM formula reveals, that its main function is not to reduce cost but to improve value. Out of three major ways to improve Value, we decided to provide the required project function, but look at lower life cycle cost as as a parameter that provides greater Value. In our example, the function of the space of our residential house is to provide the same level of service but with different life cycle costs depending on the external envelope used. This results in a change in value.

The implemented function is set as a residential house, which is a space for living. Therefore, the functions for all studied cases were identical. The indoor environment used for this research is described in the chapter 4.2 where all the parameters that were used for the case studies are described.

In Table 5-19 value for money evaluation is presented according to different energy sources and is done for each energy source separately. The evaluation was done with life cycle cost present value being calculated for a period of 50 years. As the reference Value we used the Lumar case with each of the MEP variants. For each energy source, the highest value for money presents the 01 Lumar case, followed by 02 Canopea with 94% reference value and 04 MED with 93% reference value. The lowest results we got for the high-tech envelope 03 Ecolar.

Table 5-19: Value for money evaluation according to energy source.

	01 Pellet		02 TP		03 Gas	
	VfM	Construction cost and LCC (present value) in EUR	VfM	Construction cost and LCC (present value) in EUR	VfM	Construction cost and LCC (present value) in EUR
01 Lumar	100%	187.913,51	100%	191.824,95	100%	173.097,21
02 Canopea	94%	200.511,45	94%	204.361,12	93%	185.567,95
03 Ecolar	77%	244.859,59	77%	248.809,99	75%	230.008,15
04 MED	93%	202.279,00	93%	206.195,18	92%	187.448,26

According to overall value for money evaluation presented in Table 5-20 the highest valued option would be the 01 Lumar with gas stove heating. The lowest valued option is the 02

Ecolar with thermal air to water heat pump. Canopea and Med are valued same or similar in each of the variants.

Table 5-20: Overall value for money evaluation.

	01 Pellet		02 TP		03 Gas	
	VfM	Construction cost and LCC (present value) in EUR	VfM	Construction cost and LCC (present value) in EUR	VfM	Construction cost and LCC (present value) in EUR
01 Lumar	92%	187.913,51	90%	191.824,95	100%	173.097,21
02 Canopea	86%	200.511,45	85%	204.361,12	93%	185.567,95
03 Ecolar	71%	244.859,59	70%	248.809,99	75%	230.008,15
04 MED	86%	202.279,00	84%	206.195,18	92%	187.448,26

Following (Figure 5-12) we present the evaluation that was done for different LCC periods. This evaluation shows how value for money of evaluated cases changes through different life cycle periods. The evaluation was done for a period of 50 years in 5 year steps, starting with the initial construction costs. With such evaluation we wanted to elaborate how value changes through different life cycle periods of a house.

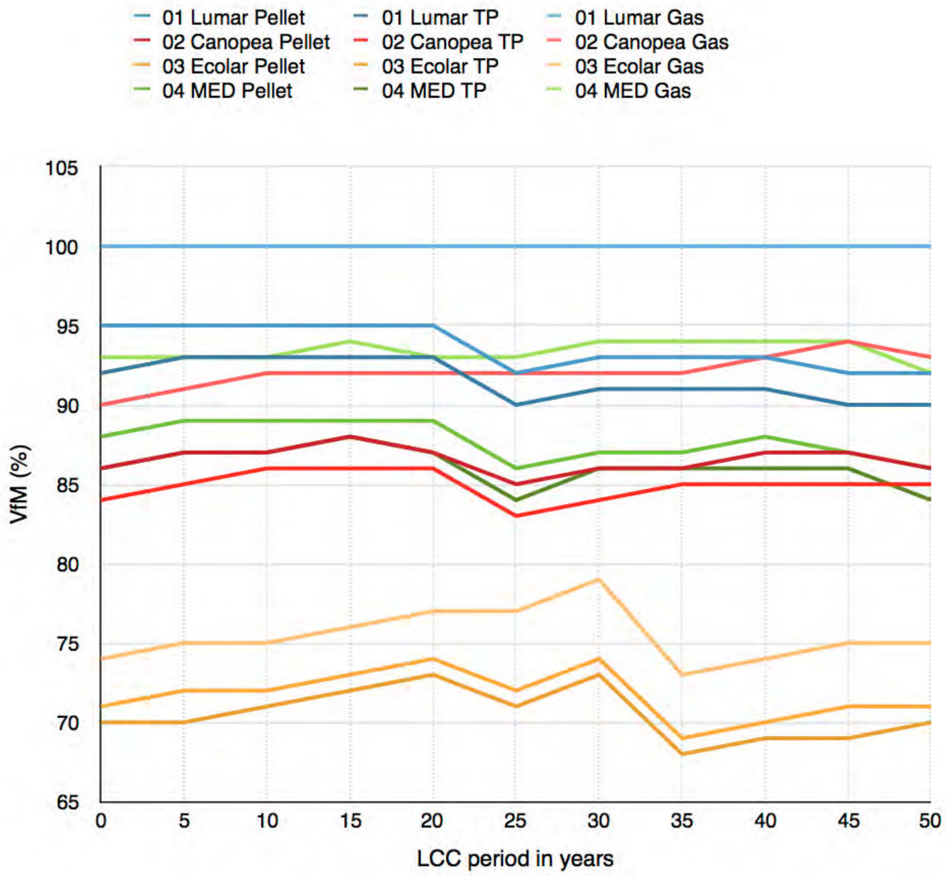


Figure 5-12: Value for money evaluation for different LCC periods (0-50 years).

As presented in Table 5-21, in the early period after the construction, the value of the 01 Lumar case is the highest. The 03 Ecolar case has the lowest value because of the extremely high construction costs. Its value is 26% lower. After construction phase 04 Med has a 7% lower value and 02 Canopea has a 10% lower value. The 02 Canopea and 04

MED have almost the same value with a difference of 2% in the early period. The difference in value between them drops to 1% after 25 years and the value of both cases comes together after 50 years for the pellet stove. For the other two MEP variants the difference in value drops from 2% to 1% after 50 years. Our data indicates that none of the variants has a higher value then 01 Lumar with gas stove. 04 MED comes closest after 15 years with 94% of the value. 02 Canopea has a value of 90% after the initial construction compared to 01 Lumar, but rises its value up to 94% after 45 years due to lower operation costs. From the perspective of owners/investors the 01 Lumar case with the gas stove can be considered most useful. From national resources management and user perspectives we would suggest 01 Lumar with the pellet stove, especially up to 20 years of usage.

Table 5-21: Value for money evaluation for different LCC periods (0-50 years).

		01 Pellet		02 TP		03 Gas	
		VfM	LCC (present value)	VfM	LCC (present value)	VfM	LCC (present value)
01 Lumar	0	95%	106.052,29	92%	108.764,67	100%	100.454,74
	5	95%	113.984,80	93%	116.559,10	100%	108.045,99
	10	95%	120.538,93	93%	123.037,84	100%	114.276,39
	15	95%	127.795,26	93%	130.262,01	100%	121.525,10
	20	95%	134.827,36	93%	137.291,27	100%	128.282,61
	25	92%	147.183,23	90%	150.854,20	100%	135.508,73
	30	93%	159.355,94	91%	162.514,70	100%	147.459,94
	35	93%	166.361,48	91%	169.554,53	100%	154.418,49
	40	93%	172.034,25	91%	175.264,57	100%	159.918,27
	45	92%	186.090,02	90%	189.964,68	100%	171.405,94
	50	92%	187.913,51	90%	191.824,95	100%	173.097,21
02 Canopea	0	86%	116.747,15	84%	119.459,53	90%	111.149,6
	5	87%	124.616,44	85%	127.175,15	91%	118.645,14
	10	87%	131.126,18	86%	133.597,48	92%	124.806,62
	15	88%	138.351,66	86%	140.781,73	92%	132.005,92
	20	87%	146.625,56	86%	149.045,83	92%	139.990,68
	25	85%	159.531,94	83%	163.153,90	92%	147.756,59
	30	86%	171.696,15	84%	174.801,88	92%	159.690,83
	35	86%	179.451,84	85%	182.588,74	92%	167.393,24
	40	87%	183.898,26	85%	187.070,00	93%	171.661,64
	45	87%	197.843,38	85%	201.657,66	94%	183.034,93
	50	86%	200.551,45	85%	204.361,12	93%	185.567,95
03 Ecolar	0	71%	141.775,3	70%	144.487,68	74%	136.177,75
	5	72%	150.885,12	70%	153.469,23	75%	144.937,20
	10	72%	158.436,26	71%	160.952,54	75%	152.157,62
	15	73%	166.539,06	72%	169.028,95	76%	160.248,26
	20	74%	174.109,10	73%	176.600,54	77%	167.539,55
	25	72%	187.069,68	71%	190.771,59	77%	175.367,47
	30	74%	199.756,47	73%	202.948,74	79%	187.830,33
	35	69%	222.832,95	68%	226.061,47	73%	210.858,10
	40	70%	228.877,52	69%	232.144,81	74%	216.728,25
	45	71%	242.847,17	69%	246.759,93	75%	228.128,78
	50	71%	244.859,59	70%	248.809,99	75%	230.008,15
04 MED	0	88%	114.016,38	86%	116.728,76	93%	108.418,83
	5	89%	121.973,79	87%	124.549,27	93%	116.030,89
	10	89%	128.550,10	87%	131.051,05	93%	122.280,67
	15	89%	135.828,12	88%	138.297,63	94%	129.549,12
	20	89%	144.266,21	87%	146.733,48	93%	137.711,09
	25	86%	156.965,62	84%	160.640,38	93%	145.279,58
	30	87%	169.153,55	86%	172.316,39	94%	157.245,08
	35	87%	177.005,55	86%	180.202,92	94%	165.049,51
	40	88%	182.693,45	86%	185.928,28	94%	170.563,76
	45	87%	196.529,04	86%	200.408,32	94%	181.830,91
	50	86%	202.279,00	84%	206.195,18	92%	187.448,26

5.3 Generalization of the problem on single variable

Previously presented analyses, where Value for money calculation was done according to LCC calculation based on “Steckbrief 4.1.1 (NaWoh)” with 3 different MEP systems, showed that operation costs are not dependent only on energy supply costs. The results presented in Table 5-22 show that supply and disposal cost for a 50-year life cycle period represent a net present value between 18% to 28% of total operational NPV costs. That is why we tried to generalize the functional dependence of Value for money on following single variables that are a part of operation costs: Supply and disposal, Maintenance cost and Service and repair costs.

Table 5-22: Comparison of ratio between Supply and disposal (net present value *EUR*) and operational costs (*net present value in EUR for a life cycle period of 50 years*).

Case study	PELLET (NPV EUR)	LCC no CC (NPV EUR)	Supply and disposal/Life cycle costs (%)	TP (NPV EUR)	LCC no CC (NPV EUR)	Supply and disposal/Life cycle costs (%)	GAS (NPV EUR)	LCC no CC (NPV EUR)	Supply and disposal/Life cycle costs (%)
01 Lumar	18.775,88	81.861,22	22,9	16.718,39	83.060,28	20,1	20.536,77	72.642,47	28,3
02 Canopea	18.333,67	83.764,30	21,9	16.214,44	84.901,59	19,1	19.967,33	74.418,35	26,8
03 Ecolar	18.653,21	103.084,29	18,1	16.634,80	104.322,31	15,9	20.378,98	93.830,40	21,7
04 MED	18.727,20	88.262,62	21,2	16.674,43	89.466,42	18,6	20.473,62	79.029,43	25,9

5.3.1 Functional dependence of Value for Money from Supply and Disposal

Based on the previous research we analyzed the relationship between Supply and disposal life cycle costs and the value for money from the perspective of users. The data presented in Table 5-23 shows the value for money reduced only to single operational cost for a life cycle period of 50 years. For the users who rent a house and have to pay operational cost of supply and disposal each month, but do not cooperate in initial investment costs, maintenance and service and repair costs, the best option would be the one with the greatest value presented in the table below (Table 5-23). The option where the value for money reaches the highest value, dependent on the life cycle costs of supply and disposal of the selected external envelope and heating option is the best from the perspective of users. The data shows that the highest VfM according to such perspective is the 02 Canopea option with thermal heat pump, with a value of 127%. The lowest VfM are for 01 Lumar and 04 MED with gas stoves 100%.

From the perspective of owners where we add the construction cost to the previously added supply and disposal operational costs the data shows opposite results. The highest value at such perspective has 01 Lumar with the gas stove. 04 MED with a value of 94% followed by 02 Canope with 92% are plausible options with the gas stove. The 03 Ecolar with the high tech facade has a value between 75 - 77% due to much higher construction costs, that are not compensated with low enough supply and disposal costs.

Table 5-23: Comparison of functional dependence of value for money (%) from supply and disposal costs (*net present value in EUR for a life cycle period of 50 years*) compared to the value for money (%) of construction costs with added supply and disposal costs (*net present value in EUR for a life cycle period of 50 years*).

		01 Pellet		02 TP		03 Gas	
		VfM	Supply and disposal	VfM	Supply and disposal	VfM	Supply and disposal
01 Lumar	VfM LCC S&D	109%	18.775,88	123%	16.718,39	100%	20.536,77
	VFM CC+LCC S&D	97%	124.828,17	96%	125.483,06	100%	120.991,51
02 Canopea	VfM LCC S&D	112%	18.333,67	127%	16.214,44	103%	19.967,33
	VFM CC+LCC S&D	90%	135.080,82	84%	143.389,59	92%	131.116,93
03 Ecolar	VfM LCC S&D	110%	18.653,21	123%	16.634,80	101%	20.378,98
	VFM CC+LCC S&D	75%	160.428,51	75%	161.122,48	77%	156.556,73
04 MED	VfM LCC S&D	110%	18.727,20	123%	16.674,43	100%	20.473,62
	VFM CC+LCC S&D	91%	132.743,58	91%	133.403,19	94%	128.892,45

5.3.2 Functional dependence of Value for Money from Maintenance costs

In further research we observed the relationship between Value for money and Maintenance costs. This is a value important from the perspective of owners. According to comparison results obtainable in Table 5-24, this values present approximately 50% lower present value for a period of 50 years than the present values for supply and disposal.

Table 5-24: Comparison of functional dependence of value for money (%) from maintenance costs (*net present value in EUR for a life cycle period of 50 years*) compared to the value for money (%) of construction costs with added maintenance costs (*net present value in EUR for a life cycle period of 50 years*).

		01 Pellet		02 TP		03 Gas	
		VfM	Maintance	VfM	Maintance	VfM	Maintance
01 Lumar	VfM LCC MC	72%	14.758,34	63%	16.757,35	100%	10.633,61
	VFM CC+LCC S&D	92%	120.810,63	89%	125.522,02	100%	111.088,35
02 Canopea	VfM LCC MC	71%	15.012,09	63%	17.011,07	98%	10.887,39
	VFM CC+LCC S&D	84%	131.759,24	77%	144.186,22	91%	122.036,99
03 Ecolar	VfM LCC MC	68%	15.626,99	60%	17.625,88	92%	11.502,24
	VFM CC+LCC S&D	71%	157.402,29	69%	162.113,56	71%	156.439,44
04 MED	VfM LCC MC	71%	14.953,86	63%	16.952,89	98%	10.829,16
	VFM CC+LCC S&D	86%	128.970,24	83%	133.681,65	93%	119.247,99

Consistent with the presented data, when looking only at Maintenance costs, the highest value for money again has the 01 Lumar with the gas stove, followed by 02 Canopea and 04 MED with a VfM of 98%. This data shows that the maintenance value is dependent on the MEP solution, due to higher maintenance costs for pellet stove and thermal heat pump. The results also show, that when adding construction cost to maintenance costs, the value ranking is the same but the difference in value is smaller, because initial construction cost difference for different MEP variants is higher than the present value difference for life cycle maintenance costs for a period of 50 years.

5.3.3 Functional dependence of Value for Money from Service and repair costs (KGR300/400)

Finally, the highest parameter for operational cost according to “NaWo” is analyzed. These are KGR300/400 service and repair costs and are approximately three times higher then the maintenance costs. According to the presented data in Table 5-25 again the highest VfM has the 01 Lumar case with the gas stove, followed by 04 MED and 02 Canopea with 98% with Service and Repair costs for KGR 300/400 without construction costs, as the only parameter for VfM. The 03 Ecolar case has a low VfM of 70% again, due to high service and repair costs of the high tech facade.

According to results when adding construction cost to service and repair costs the VfM ranking stays the same but the value delta margin is smaller.

Table 5-25: Comparison of functional dependence of value for money (%) from service and repair costs (*KGR300/400*, *net present value in EUR for a life cycle period of 50 years*) compared to the value for money (%) of construction costs with added service and repair costs (*net present value in EUR for a life cycle period of 50 years*).

		01 Pellet		02 TP		03 Gas	
		VfM	Service and repair (KGR300/400)	VfM	Service and repair (KGR300/400)	VfM	Service and repair (KGR300/400)
01 Lumar	VfM LCC RS&R	84%	42.534,48	81%	43.792,02	100%	35.679,57
	VFM CC+LCC S&D	92%	148.586,77	89%	152.556,69	100%	136.134,31
02 Canopea	VfM LCC RS&R	80%	44.626,02	78%	45.883,56	94%	37.771,11
	VFM CC+LCC S&D	84%	161.373,17	79%	173.058,71	91%	148.920,71
03 Ecolar	VfM LCC RS&R	62%	57.537,30	61%	58.794,84	70%	50.682,39
	VFM CC+LCC S&D	68%	199.312,6	67%	203.282,52	70%	195.619,59
04 MED	VfM LCC RS&R	73%	48.789,04	71%	50.046,58	85%	41.934,13
	VFM CC+LCC S&D	84%	162.805,42	82%	166.775,34	91%	150.352,96

According to the values presented in Table 5-24 and Table 5-25 we can assume that higher construction costs, produce higher service and repair costs and maintenance costs, a consequence of which is lower value for money.

6 Conclusions and outlook

In the following chapter a short introduction statement upon which the research was conducted is presented. It restates the research question, that the study set out to answer and justifies its necessity. Establishment of the context, background and importance of value for money evaluation of external envelopes for stakeholders involved in building construction process, is presented. The research gap in the value assessment is introduced (thorough LCC and not just energy supply costs). Key objectives are described. Following the introduction, the synthesis of empirical findings is presented. The results that were produced with developed Value for Money evaluation method using the BIM Use Purposes[220] and were disclosed and analyzed in previous chapter are summoned in key answers and findings. Theoretical and applicative implications of the results and the method are suggested next with the possibility of using the value for money method model used in this study, by stakeholders in the earlier construction stages, when deciding for a suitable envelope for their building. Finally, direction of further research is presented.

6.1 Introduction

The study was set out to explore a specific economic evaluation method for construction, to evaluate the prefabricated lightweight systems used for residential houses and to elaborate their suitability for Slovenian residential property market.

The study has also sought to develop a comparative model for evaluation, to be used in the design phase by the stakeholder when adopting an envelope system to their building.

The general theoretical literature on this subject and specifically in the context of construction system evaluation, regarding the suitability for a purpose is inconclusive on several vital questions within the life cycle costing discourse. Our general critic remark on existing studies is, that they only use parts of the operational costs. They generally use supply costs (energy related costs) for their LCC assessment, but mostly exclude maintenance, repair and replacement costs, cleaning and demolishing costs which add a considerable net value in the lifetime period of a building. However, according to the results presented in this study (Table 5-22), the supply and disposal costs represent between 18% and 28% of total operational costs for a 50-year life cycle period of the case model.

The study sought to answer two questions related to value evaluation of construction envelopes:

1. Are future construction systems and envelopes that connect research, knowledge, praxis and PR effect in form of Solar decathlon Europe 2012 competition suitable for the Slovenian prefabricated house property market?

2. Can stakeholders, already in the design phase, use an effective economic evaluation method when deciding for a construction system?

[220] Kreider/Messner 2013, 6.

6.2 Empirical findings

The main empirical findings are chapter specific and were summarized within the respective empirical chapters:

This section will synthesize the empirical findings to answer the study's two research questions.

6.2.1 Are future construction systems and envelopes that connect research, knowledge, praxis and PR effect in form of Solar decathlon Europe 2012 competition suitable for the Slovenian prefabricated house property market?

The comparison of construction costs showed that although all evaluated houses have very good U-values, that are between 0,07 – 0,14 W/m^2K which are far below legislation minimum (Figure 2-5) and could also be used for passive houses[221], the initial construction cost (for KGR 300 and 400) has a net difference of up to 25% between the case studies. It is significant to indicate that this difference comes only from different external construction envelopes excluding all openings and internal structures (also excluding the foundation plate), which were all fixed parameters for all the case models. The results show that a high tech envelope with prototype like elements brings a high increase of initial construction costs, that would have to be repaid through the advantage of very low life cycle costs in 50 years' life cycle period of a building. The much higher initial construction cost of the high tech solution present a high financial burden for the house builders and are therefore not suitable for current property market situation.

The comparison of life cycle costs adds operation costs to the construction costs. As we remarked after the study of current research regarding evaluation of construction, the main critic is that studies did not include thorough life cycle costs and mostly considered energy supply costs in the life period as LCC. Furthermore, some of them (Lee[222] et. al.) studied operational costs as sum of energy consumption through life period with a static calculation method, that does not include inflation or interest rates. We used dynamic LCC calculation method, with following values: building cost inflation 2%, energy price inflation 4% (data obtained from Statistical office RS[223]), real interest rate 3,5% and capital interest rate 5,5% (Legep software defaults). According to the presented results, when looking only at the Supply and disposal costs, the envelope case (02 Canopea) with the best U-value, indeed

[221] Hegger et.al. 2007, 87.
[222] Lee/Kim/Na 2015, 67-74.
[223] Cene in inflacija, http://www.stat.si/statweb, 12.12.2015

presents lowest supply costs, which are app. 3% lower than the reference case model. The low U-value of Canopea case is achieved through a combination of thick ("low-tech") cellulose insulation and ("high-tech") vacuum insulation panels. The 03 Ecolar model with its high tech dynamic u-value was expected to have good results, particularly in Supply and disposal category of operational costs, but produced only 0,77% lower costs in 50 years compared to our reference model and this by fabricating app. 25% higher initial construction costs. Furthermore, when assessing the LCC results including thorough operational costs, it becomes evident that only energy related supply costs do not generate comprehensive LCC evaluation. On one hand a high tech envelope lowered the energy supply costs, on the other hand due to very high maintenance and service costs in 50 years, it adds up to approximately 20% in the total operational costs compared to the lowest costing case, which was the reference 01 Lumar model. Moreover, we have to consider that concurring with the results presented in Table 5-22, the Supply and disposal costs represent merely between 18% to 28% of total LCC net present value in 50 years.

The thorough LCC analyses bring us to a conclusion that although higher initial construction cost as a future investment in lower operational costs seemed reasonable, the net present value result show that this is not accurate. The lower supply costs do not compensate for the higher replacement and maintenance costs in 50 years. According to Statistical office of Republic Slovenia[224] 77% of residential apartments in Slovenia are owned and not rented, therefore, from the perspective of owners lower initial construction and less operational costs mean a better net present value and therefore a better solution.

6.2.2 Can stakeholders, already in the design phase, use an effective economic evaluation method when deciding for a construction system?

After the preliminary study and state of the art research it was obvious to use Value for money evaluation method to assess our case studies. Since the main function of the VfM formula (VfM=F/LCC) is not cost reduction but improving value of an assessed object. The function of our case studies was a fixed parameter (residential living), an improved value, meant lower net present value of construction costs and all operational costs for a period of 50 years.

One of the questions for this study was if it is possible to evaluate a construction system already in the design phase. Namely approximately 80% of all investment and operating costs are determined in the initial design phase[225] as shown in Figure 4-6. The method used for our study was developed using BIM Use Purposes[226] presented in Figure 6-1. First step is

[224] Naseljena stanovanja, Slovenija, 1. januar 2011 - začasni podatki, http://www.stat.si/StatWeb/glavnanavigacija/podatki/prikazistaronovico?IdNovice=4420, 1.1.2011
[225] Hofer et.al. 2011, 1075.
[226] Kreider/Messner 2013, 6.

the **BIM generation**, where we **gather** (capture and/or quantify) the needed values (floor-plan area, shape, volume, external envelope and other quantities) and **generate** the **BIM** case model (prescribed, arranged and sized) using BIM software (Archicad). Further we created the **BEM** model, prescribing operational profiles, thermostat control, environment and building location to the BIM model. Second step is the **BIM Evaluation**. In this step we firstly **analyze** (forecast) the data using Energy evaluation software (Archicad, EcoDesigner Star). Further we **communicate** (visualize, document and transform) the analyzed data. We document it and transform it, so that it can be imported into LCC evaluation software (Legep). Third and final step is the **VfM Evaluation**. With help from SirADos database we create a building data model with comprehensive building data for a thorough **LCC analyze** (including initial construction cost and operational costs). Next we analyze the Value for Money of case models with the generated LCC data and according to VfM formula (VfM=F/LCC). Finally, we **realize** (**regulate**) the decision making process of future stakeholders. We namely compare the calculated values of different variations according to Value for money to choose a construction envelope which is most valuable for a stakeholder.

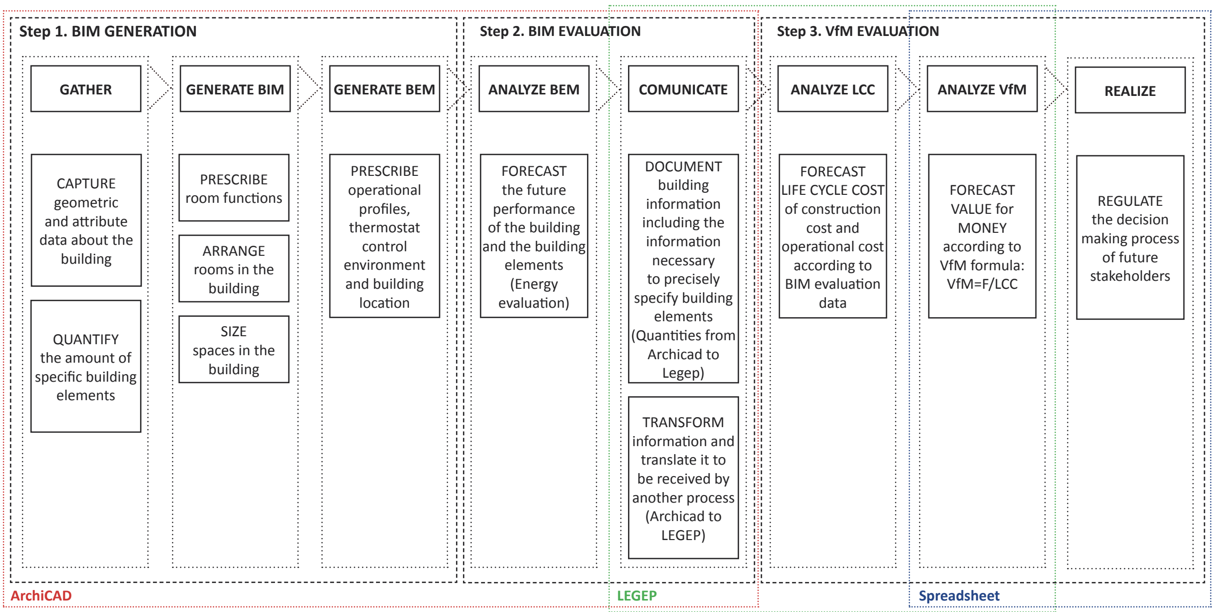


Figure 6-1: Extended Value for money evaluation method with used primary and secondary BIM use purposes.

Since SirAdos is a product which in last 25 years has developed to one of the market leaders in construction cost documentation[227] a breakdown of construction elements is possible with the use of its preset macro-elements, therefore a LCC analyze is already possible in earlier design stages before final detailed planning is developed.

The existing framework for our study has been updated during the development of the VfM evaluation method. We decided to further develop each of the case studies, applying three different energy sources to each of the models. Firstly we used a wood pellet stove, which has been widely used for residential houses in recent years because of the low prices for

[227] sirAdos, http://legep.de/uber-uns/sirados/, 12.1.2016

pellets (EUR/MWh) in Slovenia[228]. Secondly we added an air to water heat pump, which is included in the offers for very good low energy prefabricated houses by Lumar[229]. Finally, we used a conventional gas heater with a water tank. The VfM evaluation was done for each energy source separately and for a period of 50 years. For each energy source, the highest value for money presents the reference 01 Lumar case, followed by 02 Canopea with 94% reference value and 04 MED with 93% reference value and the lowest results we got for the high-tech envelope 03 Ecolar.

Although we had detailed plans for the different cases of our study, for the value for money evaluation that was developed, we needed only values of different layers of external envelopes. This implicates that this method can indeed be used in earlier design stages.

If we recapture findings presented in previous chapter, when considering the LCC and transfer them to the functional dependence of Value for Money from supply and disposal costs, they generate similar results. The data shows that the highest VfM from the perspective of users when considering LCC of only supply and disposal is the 02 Canopea option with thermal heat pump, with a value of 127%. The lowest VfM are for 01 Lumar and 04 MED with gas stoves 100%. 01 Lumar, with its value of 100%, was set as the reference value.

Further, we established when evaluating functional dependence of VfM from Maintenance costs, that they represent approximately 50% lower present value for a period of 50 years than the present values for supply and disposal. The highest value for money has the 01 Lumar with the gas stove, followed by 02 Canopea and 04 MED with a VfM of 98% (both with the gas stove).

Finally, when we look at the functional dependence of VfM from Service and repair costs we got following results. The highest VfM has the 01 Lumar case with the gas stove, followed by 04 MED and 02 Canopea with 98% and the 03 Ecolar case with VfM as low as 70%, due to high service and repair costs of the high tech facade. Net present values show us that service and repair costs and are approximately three times higher then the maintenance costs and up to two times higher than the supply and disposal costs.

All this data implies, that to get an accurate value for money evaluation of a building case study, it is important to asses thorough life cycle costs and not merely supply and disposal costs.

6.3 Theoretical Implication

The theoretical cases for evaluation of construction systems of buildings need to be revisited in order to further understand the possibility of application of VfM evaluation method when

[228] Sistem zagotavljanja kakovosti lesenih pellet, http://www.s4q.si/info, 15.1.2016
[229] Lumar super-niedrigenergiehäuser, http://www.lumar-haus.at/energiekonzepte.asp?m3=21, 13.1.2016

deciding for an investment in a future or prototype construction system or when deciding between different envelope solutions as a stakeholder.

Tam et.al.[230] suggest in their feasibility analysis in adopting prefabrication in construction activities, that even if the initial construction cost is higher, long-term construction costs can be reduced through reduction of wastage generation. It is however, noted from this study that such a benefit is more likely achieved with reduction of maintenance and replacement and repair costs, which means more sustainable and maintenance free materials and a reduction of initial investment cost, by not reducing the quality. This pattern is consistent with Pons[231], he claims that in the future it is expected that industrialized technologies will be most sustainable as long as their costs and logistics of production are rectified. Together with reduced life cycle costs as shown in this research such industrialized buildings would certainly have a great value for money if their function is not reduced.
Rakshsan[232] et. al. state that the balance between initial costs and operational costs is directly reflected in the building energy use. Moreover, noted from this research the balance is even more reflected between initial costs and service, replacement and maintenance costs.
After developing the value for money method used for this study we would concur with study by Mateus et. al.[233] assessing the sustainability of innovative lightweight building technology for partition walls, where they propose to include other life-cycle stages, like the maintenance, and the use of the specific Life Cycle Inventory (LCI) data from the chosen producers, for future evaluation of new technologies.
This study showed that a thorough life cycle cost analysis is necessary for a thorough value for money evaluation, which contradicts Matic[234] et.al. In their economic feasibility study they calculated operational cost savings solely as the reduction in the heating energy bill. We would therefore agree with Cabeza[235] et. al. on their review of Life cycle assessment, where they quote the National institute of Standards and Technology which defines life cycle costs as “the total discounted dollar cost of owning, operating, maintaining and disposing of a building or a building system” over a period of time. Our study concurs with them claiming that LCC is considered an economic evaluation technique, which was used as main parameter for Value for money evaluation. Furthermore, we applied the LCC as part of VfM method in decisions regarding construction envelope of a facility, as they recommended. As the results of our study demonstrate, it is barely possible to compensate for the higher initial construction costs even in a LCC period of 50 years. Therefore, we can partially agree with the authors about the operational phase contributing more than 80-85% share in the total life cycle energy of buildings and suggesting that future efforts should focus on reducing the operational phase, even on the cost of other less significant phases.

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[230] Tam et.al. 2007, 3642-3654.
[231] Pons 2014, 434-456.
[232] Rakhshan 2013, 105-110.
[233] Mateu et. al. 2013, 147-159.
[234] Matic 2015, 74-81.
[235] Cabeza et. al. 2014, 394-416.

Our findings suggest that Leckner and Zmeureanu[236] where consistent with our results claiming that to use a method that includes life cycle costs analysis it is very important to make every effort to compile accurate and realistic prices. Coherent with their claim we used SirADos database construction data. Secondly, we also agree with their second calculation method that used the effective interest rate, rising energy prices or the replacement cost for the economic evaluation. Finally, our pattern is consistent with them claiming that it is unlikely that average homeowner would accept the additional expanses for the construction of a NZEH or in our case a high tech envelope.
As noted from this study and by the study from Hasan et. al.[237] the designers should increasingly use simulation tools instead of guessing, when deciding on building envelope improvement or in our study building envelope variant. Further, consistent with Hasan et. al., when the objective is to reduce total building cost during its lifetime, the life cycle cost of the building is to be studied as is also done in the value for money method of our research. They also used net present value for their LCC calculations which we find is the most objective solution for economic evaluation. However, they used simplified LCC calculations and because of significance of all parts of LCC calculations as shown in chapter 5.3, where we generalized the problem on single variables of LCC, this could produce inaccurate results. We also concur with Najia[238] et. al. claiming the economic issues and saving money are among the most important challenges in all aspects of human life. However, although we also used a reference model for our study, for their operational cost calculations they only used energy consumption calculations excluding other significant parts of LCC, as explained earlier in this chapter.
Our evaluation method is consistent with that presented by Lee[239] et. al. Our LCC part of the VfM evaluation was also completed in three phases: implementation of function, cost analysis and quantification of operational costs. According to authors, the development of materials that satisfy LCC requirements and minimize the amount of energy used will be encouraged in considering the energy performance and cost of external walls. They also state that their study can be used as the basis for further simulation studies to easily and quickly calculate the LCC or VFM in cases of design change. However, for the operation cost, they only considered heating and cooling costs that varied depending on the energy performance of the external walls. Instead, for our VfM evaluation we also included cleaning, maintenance, service and repair and supply and disposal costs.

Consistent with presented theoretical implication we suggest using thorough Life Cycle Cost evaluation for a comprehensive Value for Money assessment.

6.4 Recommendation for future research

The scale of this debate is extensive and multifaceted at each level of upgrading the function or life cycle costs. To generate a general evaluation model for different building designs

[236] Leckner/Zmeuranu 2011, 232-241.
[237] Hasan/Vuolle/Siren 2008, 2022-2034.
[238] Najia et. al. 2014, 727-739.
[239] Lee/Kim/Na 2015, 67-74.

utilizable in the design phase, there is need for more case studies exploring different external parameters, to allow further assessment of the subject. Exploring the following as future research strategies can facilitate the attainment of this goal.

6.4.1 Comparison to non-prefabricated technologies

Some non-prefabricated technologies are more suitable than prefabricated ones. If construction time is not critical and if main parameter is initial cost. In further research we want to evaluate and compare the value of non-prefabricated massive construction principles (brick and concrete construction systems) to the prefabricated (wood and steel prefabricated systems). A lot of research was already done considering the difference of material behavior (massive and light) in terms of thermal capacity regarding energy efficiency. Therefore, we would like to evaluate and compare these non-prefabricated systems to prefabricated lightweight systems, with the VfM method with thorough LCC, including specifically maintenance and service and repair costs for a period of 50 years.

6.4.2 Comparison of VFM of timber panel and light steel frame (LSF) construction

Timber panel construction systems are widely used as favorite prefabricated house construction system in Slovenia (Lumar). However, Maribor and surroundings have a strong background in steel construction and prefabricated steel lightweight construction systems used for industry, with former industrial companies like Livarna, TAM and still successful companies like Meteorit and EXPO Biro as forerunners of steel industry in Maribor. Therefore, in future research we want to compare these two construction systems. However, the research would be concentrated on using steel and timber only for bearing construction. Same “external” envelope would then be applied on both types of bearing construction to be evaluated, for the use in the field of residential prefabricated houses. Such research would like to answer the question if steel prefabricated houses can also be sustainable.

6.4.3 Production cost reduction through industrialization

Since in the future it is expected that industrialized technologies will be most sustainable as long as their costs and logistics of production are resolved. More research should be focused on industrialization possibilities of prefabrication and cost reduction through quick industrialization of building parts or envelopes. The question, for this type of future study should be, what parameter is used for price reduction through industrialization of prefabricated building envelopes. Next question consistent with this parameter is the amount of industrialization that maintains the flexibility of the architecture.
As part of our preliminary research we looked into Industrialization and prefabrication (Chapter 2.5.1). The Canopea project manual[240] provides following values considering price reduction through industrialization of the envelope (for mass production):

[240] Team Rhone-Alpes, Project Manual #5 2012, 629.

- A prototype envelope for 1 unit has a cost factor of 100%.
- For a 10 units production, they estimate that the cost gain factor for the envelope would be 96%.
- For 100 units production they estimate that the gain factor would be 87%
- For a 1000 units production they estimate that the gain factor of envelope could be 82%.

In future research a generalization of the industrialization (mass production) parameter should be researched, that could be used when evaluating construction cost of prefabricated buildings.

6.5 Final thoughts

In spite of what is often reported about the benefits of sustainable high tech envelopes and their advantages in energy supply costs during the life cycle of buildings, our results offer a new look at the feasibility of such systems. Furthermore, we offer an evaluation method that can be used in the design phase, and where the main function is not cost reduction but the improvement of the value of a building.

Future smart efforts in architecture should therefore be focused on better architectural design and living quality and not so much on reducing energy consumption through technologically advanced envelopes.

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BEM	Building Energy Modeling
BIM	Building Information Modeling
DPB	Depreciated Payback period
EnEV	Energieeinsparverordnung
EPBD	Energy Performance of Buildings Directive (EU)
EPC	Energy Performance Certificate
Et. al.	From Latin, abbreviation of *et* (“and”) and *alii* (“others”)
etc.	et cetera
EUR	Euro
HP	Heat Pump air to water
HVAC	Heating, Ventilation & Air Conditioning
KfW	Kreditanstalt für Wiederaufbau
KGR 300/400	Construction costs according to DIN 276-1:2008-12, building construction (300) and technical installations (400)
LCA	Life Cycle Assessment
LCC	Life Cycle Costs
LCCA	Life Cycle Cost Analysis
LCEA	Life Cycle Energy Analysis
LCI	Life Cycle Inventory
MEP	Mechanical, Electrical, and Plumbing
MOM	Management, Operation, Maintenance
NaWoh	Verein zur Förderung der Nachhaltigkeit im Wohnungsbau (NaWoh), http://www.nawoh.de
NEP	National Energy Programme
NPV	Net Present Value
NZEB	Nearly Zero Energy Building
PR	Public Relations
PURES	Regulations on energy efficiency in buildings in Slovenia (“Pravilnik o Učinkoviti Rabi Energije v Stavbah”)

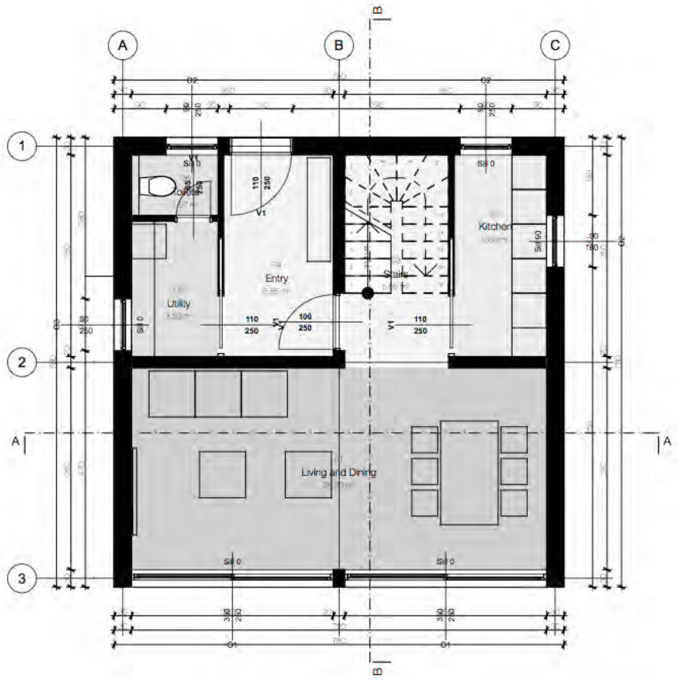
Q_h	Annual heating energy demand
Q_k	Cooling demand
Q_{l+e}	Electricity demand
RES	Renewable Energy Sources
SDE	Solar Decathlon Europe
SPB	Simple Payback period
Steckbrief 4.1.1	NaWoh Steckbrief mit Teilindikatoren, ökonomische qualität, Lebenszykluskosten (LCC), Ausgewählte Kosten im Lebenszyklus
U-value	Thermal transmittance
VfM	Value for Money
W/m^2K	Watts per meters squared kelvin (thermal transmittance)

Attachments

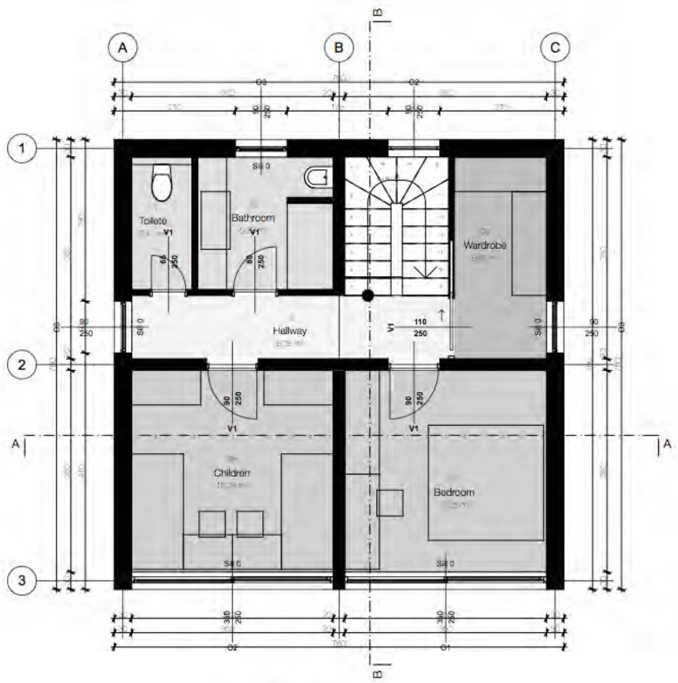
Attachment 1: Value for Money 0 – 50 years LCC

		01 Pellet			02 TP			03 Gas		
		LCC (present value)	300&400	BRUTOKOSTEN	LCC (present value)	300&400	BRUTOKOSTEN	LCC (present value)	300&400	BRUTOKOSTEN
01 Lumar	5	113.984,80	€106.052,29	€133.941,47	116.559,10	€108.764,67	€136.911,53	108.045,99	100.454,74	127.812,16
	10	120.538,93	€106.052,29	€133.941,47	123.037,84	€108.764,67	€136.911,53	114.276,39	100.454,74	127.812,16
	15	127.795,26	€106.052,29	€133.941,47	130.262,01	€108.764,67	€136.911,53	121.525,10	100.454,74	127.812,16
	20	134.827,36	€106.052,29	€133.941,47	137.291,27	€108.764,67	€136.911,53	128.282,61	100.454,74	127.812,16
	25	147.183,23	€106.052,29	€133.941,47	150.854,20	€108.764,67	€136.911,53	135.508,73	100.454,74	127.812,16
	30	159.355,94	€106.052,29	€133.941,47	162.514,70	€108.764,67	€136.911,53	147.459,94	100.454,74	127.812,16
	35	166.361,48	€106.052,29	€133.941,47	169.554,53	€108.764,67	€136.911,53	154.418,49	100.454,74	127.812,16
	40	172.034,25	€106.052,29	€133.941,47	175.264,57	€108.764,67	€136.911,53	159.918,27	100.454,74	127.812,16
	45	186.090,02	€106.052,29	€133.941,47	189.964,68	€108.764,67	€136.911,53	171.405,94	€100.454,74	127.812,16
	50	187.913,51	€106.052,29	€133.941,47	191.824,95	€108.764,67	€136.911,53	173.097,21	100.454,74	127.812,16
02 Canopea	5	124.616,44	116.747,15	€145.654,61	127.175,15	119.459,53	€148.624,67	118.645,14	€111.149,60	€139.525,29
	10	131.126,18	116.747,15	€145.654,61	133.597,48	119.459,53	€148.624,67	124.806,62	€111.149,60	€139.525,29
	15	138.351,66	116.747,15	€145.654,61	140.781,73	119.459,53	€148.624,67	132.005,92	€111.149,60	€139.525,29
	20	146.625,56	116.747,15	€145.654,61	149.045,83	119.459,53	€148.624,67	139.990,68	€111.149,60	€139.525,29
	25	159.531,94	116.747,15	€145.654,61	163.153,90	119.459,53	€148.624,67	147.756,59	€111.149,60	€139.525,29
	30	171.696,15	116.747,15	€145.654,61	174.801,88	119.459,53	€148.624,67	159.690,83	€111.149,60	€139.525,29
	35	179.451,84	116.747,15	€145.654,61	182.588,74	119.459,53	€148.624,67	167.393,24	€111.149,60	€139.525,29
	40	183.898,26	116.747,15	€145.654,61	187.070,00	119.459,53	€148.624,67	171.661,64	€111.149,60	€139.525,29
	45	197.843,38	116.747,15	€145.654,61	201.657,66	119.459,53	€148.624,67	183.034,93	€111.149,60	€139.525,29
	50	200.551,45	116.747,15	€145.654,61	204.361,12	119.459,53	€148.624,67	185.567,95	€111.149,60	€139.525,29
03 Ecolar	5	150.885,12	141.775,3	€173.058,53	153.469,23	144.487,68	€176.028,59	144.937,20	€136.177,75	166.929,21
	10	158.436,26	141.775,3	€173.058,53	160.952,54	144.487,68	€176.028,59	152.157,62	€136.177,75	166.929,21
	15	166.539,06	141.775,3	€173.058,53	169.028,95	144.487,68	€176.028,59	160.248,26	€136.177,75	166.929,21
	20	174.109,10	141.775,3	€173.058,53	176.600,54	144.487,68	€176.028,59	167.539,55	€136.177,75	166.929,21
	25	187.069,68	141.775,3	€173.058,53	190.771,59	144.487,68	€176.028,59	175.367,47	€136.177,75	166.929,21
	30	199.756,47	141.775,3	€173.058,53	202.948,74	144.487,68	€176.028,59	187.830,33	€136.177,75	166.929,21
	35	222.832,95	141.775,3	€173.058,53	226.061,47	144.487,68	€176.028,59	210.858,10	€136.177,75	166.929,21
	40	228.877,52	141.775,3	€173.058,53	232.144,81	144.487,68	€176.028,59	216.728,25	€136.177,75	166.929,21
	45	242.847,17	141.775,3	€173.058,53	246.759,93	144.487,68	€176.028,59	228.128,78	€136.177,75	166.929,21
	50	244.859,59	141.775,3	€173.058,53	248.809,99	144.487,68	€176.028,59	230.008,15	€136.177,75	166.929,21
04 MED	5	121.973,79	114.016,38	€142.662,96	124.549,27	116.728,76	€145.633,02	116.030,89	108.418,83	€136.533,64
	10	128.550,10	114.016,38	€142.662,96	131.051,05	116.728,76	€145.633,02	122.280,67	108.418,83	€136.533,64
	15	135.828,12	114.016,38	€142.662,96	138.297,63	116.728,76	€145.633,02	129.549,12	108.418,83	€136.533,64
	20	144.266,21	114.016,38	€142.662,96	146.733,48	116.728,76	€145.633,02	137.711,09	108.418,83	€136.533,64
	25	156.965,62	114.016,38	€142.662,96	160.640,38	116.728,76	€145.633,02	145.279,58	108.418,83	€136.533,64
	30	169.153,55	114.016,38	€142.662,96	172.316,39	116.728,76	€145.633,02	157.245,08	108.418,83	€136.533,64
	35	177.005,55	114.016,38	€142.662,96	180.202,92	116.728,76	€145.633,02	165.049,51	108.418,83	€136.533,64
	40	182.693,45	114.016,38	€142.662,96	185.928,28	116.728,76	€145.633,02	170.563,76	108.418,83	€136.533,64
	45	196.529,04	114.016,38	€142.662,96	200.408,32	116.728,76	€145.633,02	181.830,91	108.418,83	€136.533,64
	50	202.279,00	114.016,38	€142.662,96	206.195,18	116.728,76	€145.633,02	187.448,26	108.418,83	€136.533,64

Attachment 2: Case study model plans



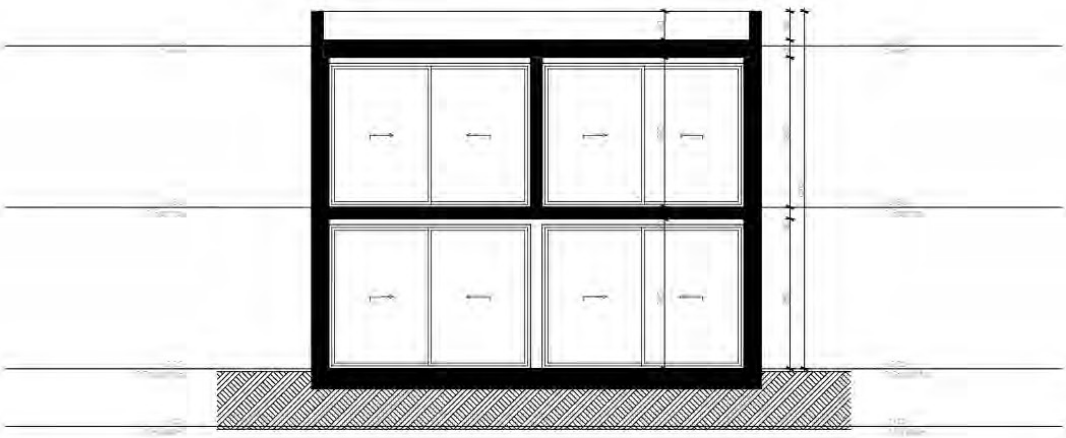
ground floor



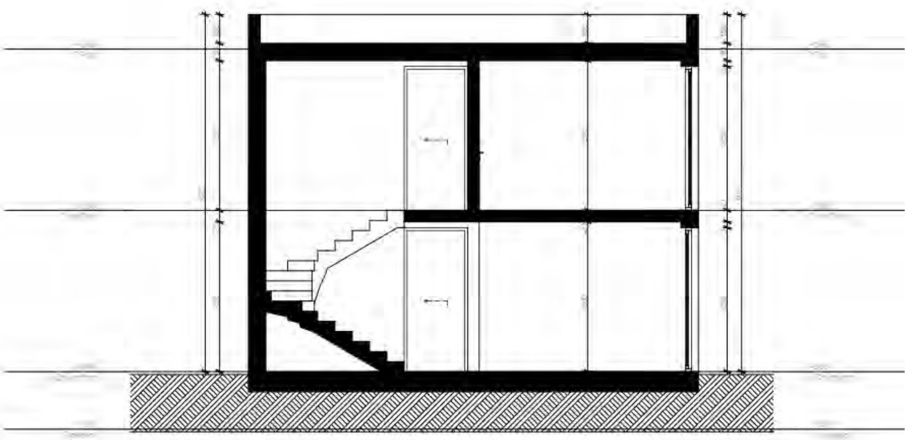
first floor

Recapitulation of spaces - Netto

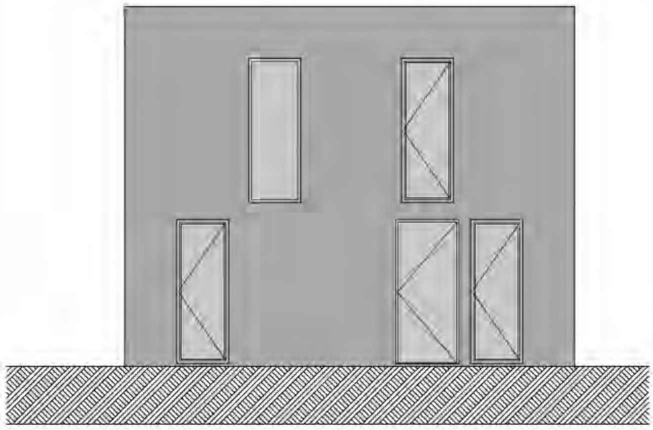
Floor	Nr. sp.	Name	Floor area
Ground floor	01	Living and Dining	31,86
Ground floor	02	Kitchen	5,60
Ground floor	03	Stairs	6,66
Ground floor	04	Entry	6,65
Ground floor	05	Utility	3,53
Ground floor	06	Toilete	1,58
			55,88 m²
First floor	07	Bedroom	12,25
First floor	08	Children	12,25
First floor	09	Wardrobe	5,60
First floor	10	Bathroom	5,33
First floor	11	Toilete	2,42
First floor	12	Hallway	10,37
			48,22 m²
			104,10 m²



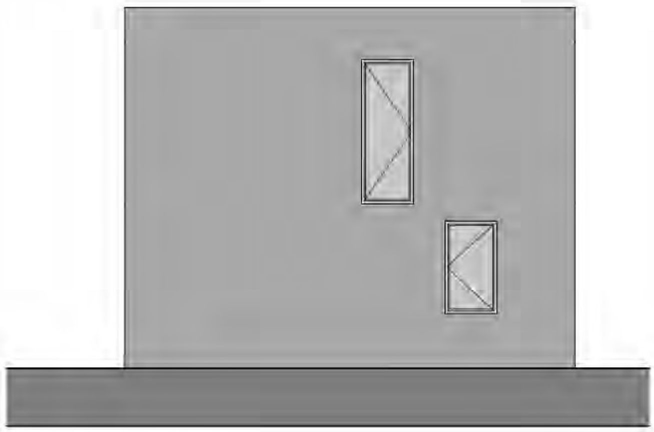
section A-A



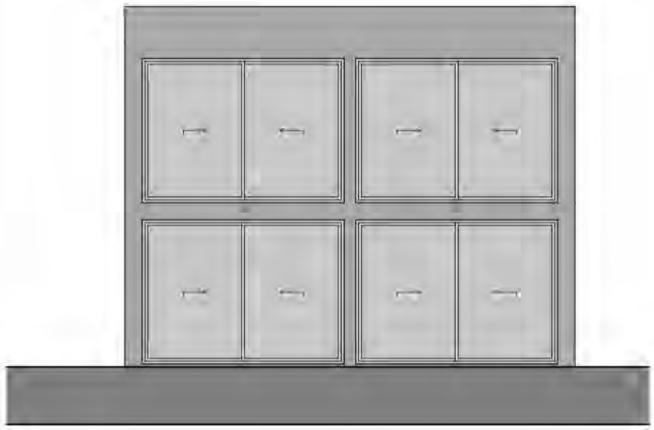
section B-B



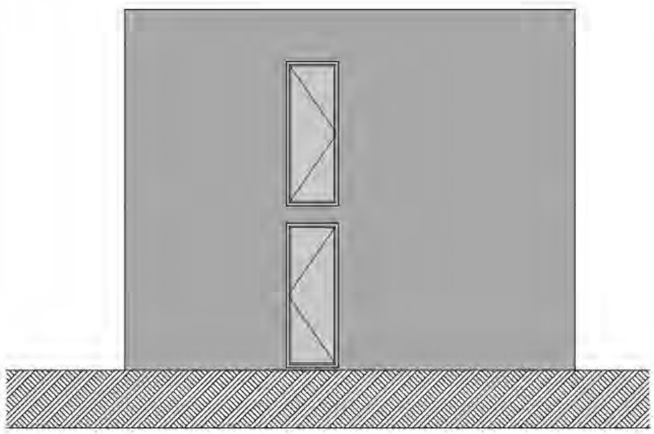
elevation North



elevation East

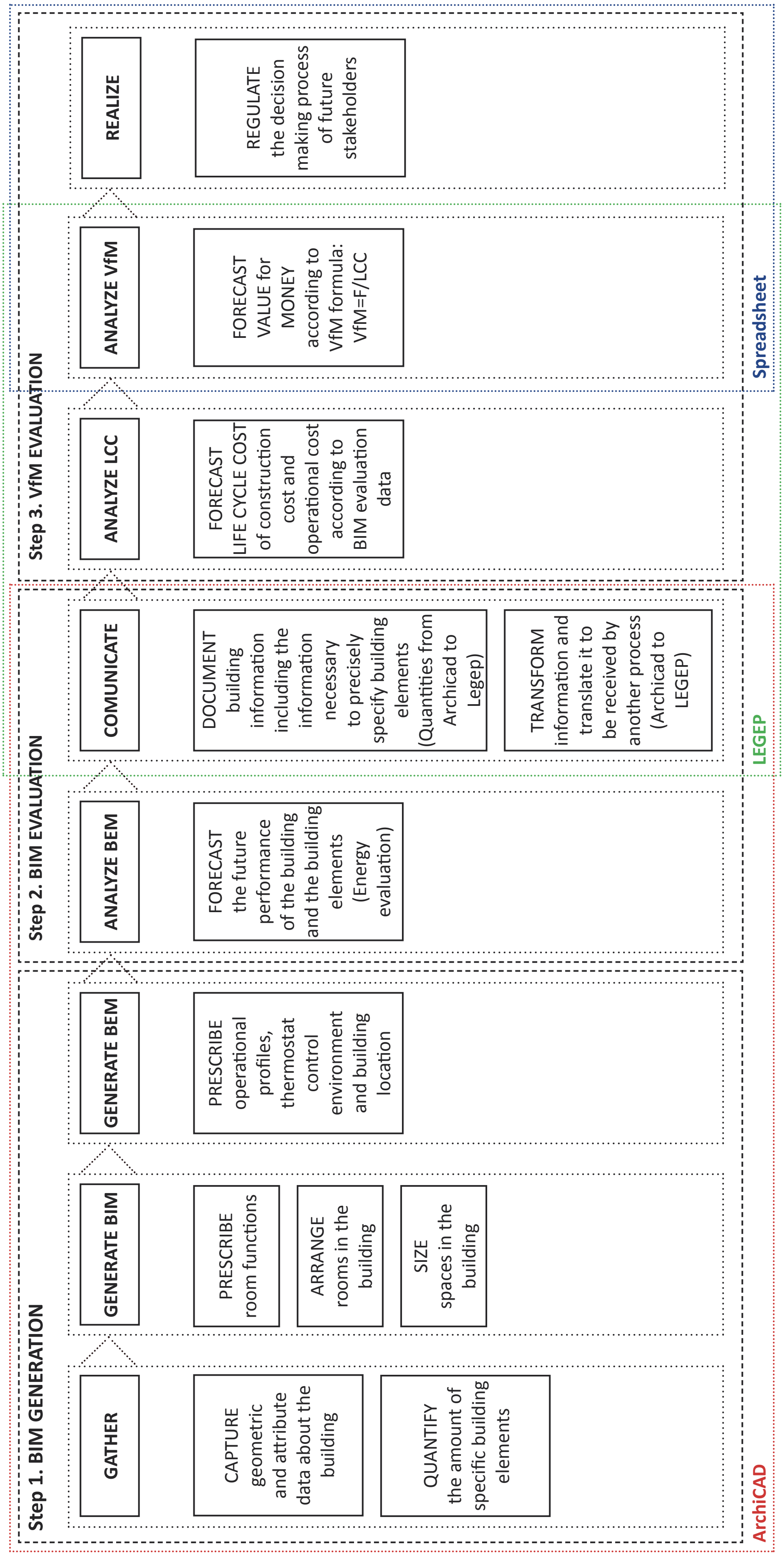


elevation South



elevation West

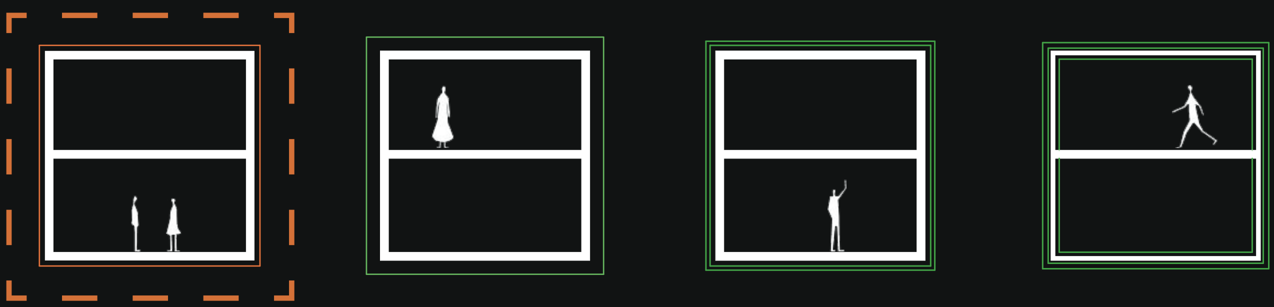
Attachment 3: Extended Value for money evaluation method with used primary and secondary BIM use purposes.



Attachment 4: Curriculum Vitae

Name	Marko Jausovec
Born	15.5.1979
In	Maribor, Slovenia
Address	Sernceva 5 2000 Maribor, Slovenia
Education	1998 Graduated on First Gymnasium Maribor 2004 Graduated with honor on Faculty for Architecture, Technical University Graz 2004 PhD inscription, Faculty for Architecture, Technical University Graz
Practice	Ekohrup s.p. and Urbis d.o.o., Maribor 1998-2007 Plan B d.o.o., Maribor, 2003 – 2005 Zadravec arhitekti d.o.o., Maribor, 2006 Faculty of Civil Engineering, Transportation Engineering and Architecture, University of Maribor, Department for architecture, since 2007 as teaching assistant House of Architecture Maribor (HAM), since 2012 as member of the founding committee and project coordinator 2007 – 2013 Cooperation with following architectural offices as architect: Boris Debenjak AU arhitektura Urbis d.o.o. Stojan Skalicky Arhilab Milorad Labus Arhitektura četri, d.o.o. (Croatia) Vjekoslav Gale (Croatia) Bipro d.o.o. Since 2013 ARHISOL d.o.o., expert for architecture

TU Graz
Graz University of Technology



Graz, July 2016