DIPLOMARBEIT

Performance-based optimization potential of a widely used prefabricated building type: A case study of Zagreb

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DISCLAIMER

I hereby declare that this dissertation is my own original work and has not been submitted before to any institution for assessment purposes.

Further, I have acknowledged all sources used and have cited these in the reference section.

Matea Flegar   Date

KURZFASSUNG

Es gehört zu den weithin bekannten Fakten, dass Gebäude zu einem wesentlichen Teil an Emissionen treibhausschädlicher Gase beitragen, sowie für einen großen Teil des globalen Energieverbrauchs verantwortlich sind. Für Zwecke einer verbesserten Performance der Gebäude reicht es nicht aus, nur neue Gebäude zu optimieren, vielmehr muss auch der Gebäudebestand fundamental verbessert werden. In vielen europäischen Ländern kann ein umfangreicher Bestand an vorgefertigten Gebäuden gefunden werden. Diese Gebäude wurden aufgrund bestimmter Vorteile hinsichtlich erforderlicher Investitionskosten und der Fertigstellungsgeschwindigkeit in vorgefertigter Weise errichtet, entsprechen oftmals jedoch nicht unbedingt den heutigen Anforderungen Ein Schwachpunkt von historischen Fertigkonstruktionen – trotz oft großer architektonischer Qualität und ansprechenden Nutzerkomforts weithin als Plattenbauten herabgewürdigt - ist ihr Energiebedarf. In vielen Ländern wurden Anreize gestartet um bestehende Gebäude – und somit auch solche Prefabricates – thermisch zu sanieren und entsprechend den heutigen Anforderungen herzurichten und auszustatten. Im Juli 2014 wurde von der kroatischen Regierung ein Programm ins Leben gerufen, welches in den Jahren 2014 – 2020 die thermische Optimierung von bestehenden Mehrfamilienhäusern adressiert. Dabei werden spezifisch Gebäude mit schlechten Energiekennzahlen adressiert. Die Mehrheit der Bauwerke, die nach dem zweiten Weltkrieg und vor 1989 (dem Fall der Sovietunion) auf kroatischem Gebiet errichtet wurden, dürften in diese Kategorie fallen. Städte wie Zagreb haben daher einen großen Bedarf an Nachrüstung solcher Bauwerke.

Die Masterthese verfolgt das Ziel ein Sanierungs-/Nachrüstungsmodell von vorgefertigten Bauwerken aus dieser Zeit zu entwickeln. Diese modularen Gebäude wurden aus vorgefertigten Betonelementen und nicht-tragenden Fassadenplatten errichtet, was es erforderlich macht, bei der Planung von Sanierungsvarianten nicht zu unterschätzende hochbautechnische, statische und bauphysikalische Herausforderungen spezifisch zu adressieren.

Verschiedene Sanierungsvarianten, welche Verbesserungen an Dach, Boden, Fenstern und Fassaden beinhalten wurden untersucht, und zwei Fassadensanierungsvarianten wurden im Detail angesehen und bewertet. Dabei wurden Kosteneffizienz, Energieeinsparung und Wärmebrückenbewertung als Bewertungsaspekte herangezogen. In einem ersten Schritt wurden jeweils die prinzipiellen Energieeinsparungen mit einer numerischen Simulationsumgebung für Gesamtgebäudesimulation ermittelt, sowie eine Kostenabschätzung und eine

Kosten-Nutzen-Abschätzung der vorgeschlagenen Sanierungsvariante durchgeführt. Anschließend wurde im Detailmaßstab mit numerischer thermischer Wärmebrückensimulation eine Analyse der kritischen Punkte der vorgeschlagenen Sanierungsmethodik vorgenommen. Auf diese Weise kann gut beurteilt werden, ob eine Sanierungsvariante entsprechend geeignet ist. Die Ergebnisse dieser Arbeit können dazu herangezogen werden, Sanierungsideen für solche Bauwerke holistisch zu beurteilen. Die untersuchten Details können auch als Wissensbasis für die Fortentwicklung von solchen Sanierungen herangezogen werden. Damit erlauben die Ergebnisse dieser Arbeit eine Abschätzung über die Wirkung von Sanierungsmaßnahmen für Bauherrenschaft und Gebäudenutzer / Mieter.

Keywords: Fertigteilbauten, numerische Wärmebrückensimulation, Gebäudeenergieverbrauch, holistischer Zugang zu Sanierungsvarianten, Energieeffizienz, Kosten-Nutzen-Abschätzung.

ABSTRACT

It is a widely known fact that buildings contribute to a large scale of both emissions and energy consumption. In many European countries an extensive stock of prefabricated buildings can be found. These buildings had benefits regarding investment cost and speed of completion, but do not necessarily meet today's demands. One weak part of these structures is their energy demand. Internationally, many incentives can be found that address the retrofit of these buildings. In July 2014 Croatian Government developed a program of thermal retrofit of apartment buildings valid from 2014 to 2020. This program specifically addresses buildings with an energy certificate category C or lower. The majority of the socialist buildings that were built after the World War II fit that description and have not been sufficiently retrofitted. Therefore, cities such as Zagreb need to develop precise scale retrofit programs for their building stock.

The goal of this case study is to establish a model for the envelope retrofit of prefabricated building type JU-61. These modular buildings were built out of prefabricated concrete panels and non-bearing façade panels which create difficulties while designing a retrofit project. That being said, this contribution analyses various retrofit options that include roof, floors and window improvements, together with a detailed evaluation of 2 different façade systems. This is being done in three stages of calculations: energy savings, cost effectiveness and thermal bridge assessment. Firstly, energy savings are estimated via dynamic energy simulations with a state of the art tool - EnergyPlus. Secondly, a cost evaluation is performed through a cost-benefit analysis of the proposed retrofit options to establish the most profitable ones. Lastly, a thermal bridge assessment is performed with a software tool- AnTerm to ensure the chosen details are eligible for implementation. The results seem to suggest that relying on evaluations of only one parameter can be misleading in the direction of less favourable retrofit option. Therefore, a holistic approach is implemented in this study to determine the most feasible improvements.

At the end, this work serves as a guideline for a comprehensive refurbishment of a particular type of building with a repository of details that promise a beneficial solution for the planers and the investors, i.e. the tenants.

Keywords: Envelope retrofit; Panel Buildings; Thermal bridges; Energy efficiency; Cost efficiency

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Matea,

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CONTENTS

ABBREVIATIONS

EPBD	Energy Performance Building Directive
SFRJ	Socialist Federal Republic of Yugoslavia
CTREEHRB	Croatian Technical Regulation on Energy Economy and Heat Retention in Buildings
EPEEF	The Environmental Protection and Energy Efficiency Fund
ECMs	Energy Conservation Measures
IS	Improvement Scenario
SHGC	Solar Heat Gain Coefficient
ACH	Air Change Rate
KPIs	Key Performance Indicators
ES	Energy Savings
EER	Energy Efficient Retrofit
NPV	Net Present Value

NOMENCLATURE

Q	Heat flow rate, [W]
R	Thermal resistance, [$m^2K.W^{-1}$]
U-Value	Thermal transmittance, [$W.m^{-2}K^{-1}$]
L^{2D}	Thermal coupling coefficient
Θ_{min}	Minimum interior surface temperature, [°C]
Θ_{i}, Θ_{e}	Air temperature of inside and outside space, [°C]
c	Specific heat capacity, [$J.kg^{-1}K^{-1}$]
d	Thickness, [m]
l	Length, [m]
λ	Thermal conductivity, [$W.m^{-1}K^{-1}$]
μ	μ-factor, [-]
ρ	Density, [$kg.m^{-3}$]
ψ	Linear heat transmittance value, [$W.m^{-1}K^{-1}$]
f_{Rsi}	Temperature factor, [-]

1 INTRODUCTION

1.1 Objective

In the years after the World War II, a great residential crisis occurred in Europe and also in former Yugoslavia. There were 2 main reasons for this crisis: on the one hand there was a great amount of buildings destroyed in the war and on the other hand strong urbanization caused by industrialization. In the first 5 Year plan (1947.-1952.) for industrialization in Yugoslavia a goal was set to build as much as possible factories throughout the country (Mattioni 2007). They were built in city areas, resulting in a strong need for inexpensive residential space (*Figure 1*). The answers to those needs were massive prefabricated buildings. There were 22 prefabricated systems in Yugoslavia in the second half of 20th century. The most famous types in Zagreb were 3 systems manufactured by Jugomont enterprise, JU-59, JU-60 and JU-61 (manufactured in the years 1959, 1960 and 1961). The last one was developed as an enhancement of the previous two and was the most commonly used one. The firstly JU-61 buildings were the ones built in residential neighbourhoods Borongaj and Remetinečki gaj in Zagreb (Mlinar 2007). Later, the system was widely used in other areas of Zagreb as well as the whole country. For instance, these systems can be found in Skopje, Sarajevo, Kranj, Maribor and other parts of former Yugoslavia where Jugomont sold their license. In the best working years of the company (1960ies), 800 workers built approximately 800-1000 apartments, based on this type, per year (Mlinar & Bobovec 2015).

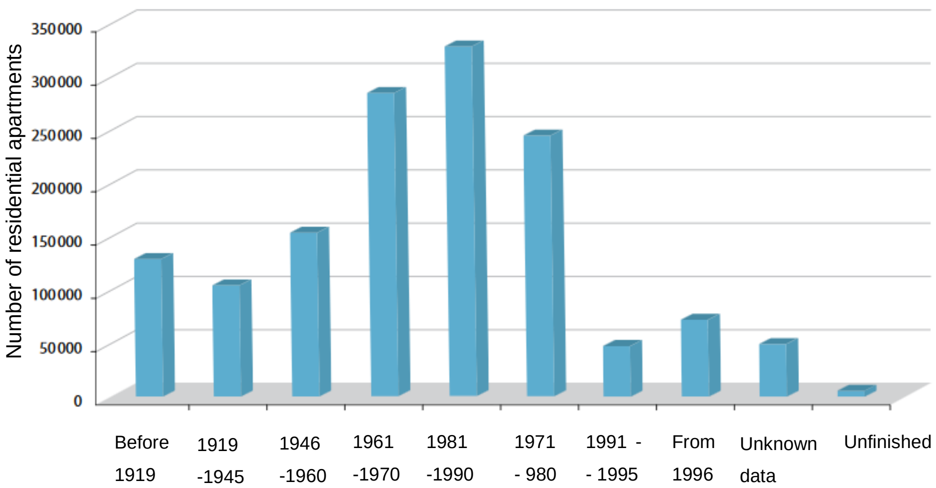


Figure 1 Number of residential apartments depending on the year of built (Energy Institute Hrvoje Požar 2017)

Considering the large number of these buildings (Table 1) and the similarities to the different types of Jugomonts prefabricated buildings – JU-59 and JU-60, this research could be beneficial for a whole range of refurbishment in Zagreb and other parts of former Yugoslavia.

Table 1. A review of Jugomonts "cans" per settlement- number and type (Prosinečki 2015)

SETTLEMENT IN ZAGREB	NUMBER OF BUILDINGS	NUMBER OF FLOORS	TYPE OF BUILDING
Folnegovićevo naselje	28	3 or 5	JU-60 and JU-61
Remetinečki gaj	14	3 or 4	JU-60 and JU-61
Borongaj	26	4 or 5	JU-61
Zapruđe	20	4 or 8	JU-61
Utrina	10	4 or 8	JU-61
TOTAL	98 buildings built with JU-60 and JU-61 system		

With privatization of apartment buildings in the 90ies and the lack of maintenance, these buildings can be found in a bad shape. In order to fulfil the EU´s long-term goal of reducing greenhouse gas emissions by 80-95 % (when compared to 1990 levels) by 2050, significant improvements need to be made.

The base case model of this study represents an example of the JU-61 type which has not yet been retrofitted. Even though Croatia has adopted all of the EU regulations and standards when joining the Union in July 2013, a lack of methodological approach for energy efficient improvements of buildings can be found. Improvement of the energy efficiency via retrofits of building envelopes will result in reduction of both total yearly energy consumption and emissions.

The high-level objective of this contribution is to perform a thermal building performance assessment aimed to retrofit an existing building. The exact goal is to evaluate the efficiency of the buildings envelope and propose a retrofit model which results with future energy and money savings.

In the second part of the thesis, the focus is directed to the analysis, representation and interpretation of the results given by the simulated model based on the collected data and assumptions of the buildings characteristics. Furthermore, simulation of more than one retrofit option will provide a conclusion that represents the best energy and cost efficient retrofit model for this type of buildings.

1.2 Motivation

With the Europe 2020 agenda, which states for 20 % increase of energy efficiency and the rise of energy prices, high energy consumption buildings from this research have to be subjected to reconstruction. Needless to say, the existing buildings do also show issues regarding indoor thermal comfort. Thus, retrofit efforts also need to address this quality that affects a significant amount of people living in these buildings.

Despite the low reputation amongst the population, the JU-61 buildings represent a historical and architectural heritage of socialism in Croatia. Recognizable by the metal flashing beneath the windows, so called ”*cans*” are currently in deteriorated shape, with only few records of refurbishment.

This contribution will focus on retrofit strategies for buildings JU-61 type. Thereby, a 6 storey building build in 1961 and located in Remetinečki gaj 24, Zagreb, Croatia, will be used as a case study building.

1.3 Structure

This research is divided into 5 major sections. Each of the main section has a couple of subsections. Some general information about the legislation, the building type and the need for this research is explained in the first two chapters, the Introduction and Background. The method chapter, in one hand, gives an insight of the chosen case study building and on the other hand, explains the usage of simulation software in this research. At this point all segments of the thermal simulations are explained into detail, following the chosen improvement scenarios, the cost assessment of this scenarios and the thermal bridge simulations of the problematic details. In the fourth chapter all of the given results are collected and discussed. This chapter is the basis for the last one, the conclusion, where all of the findings of the research are collected and summarized.

2 BACKGROUND

2.1 Energy and buildings

We are witnesses of significant climate changes partially caused by human behaviour and exploitation of the natural resources. It is a widely known fact that buildings have a great environmental impact, they are responsible for 40 % of the total energy consumption and 36% of the EU CO2 emissions. In May 2013 the EU parliament recognized this problem and adopted an Energy Performance Buildings Directive (EPBD), as a main legislative agent towards the reduction of energy consumption. It is said that together with an increased use of energy from renewable sources and measures taken to reduce energy consumption, the Union could comply with the Kyoto Protocol. To recall, in the Protocol the members of EU have obliged to maintain the global temperature rise below 2 °C and to reduce, by 2020, overall greenhouse gas emissions by at least 20 % below 1990 levels (Kaderják, et al. 2012).

Recent impact assessment done for the European Commission shows that EU will meet the overall -20 % of greenhouse gas emissions target in 2020 but, like the renewable energy targets, some Members of state will have to make additional efforts to meet their national requirements. Additionally, EU is likely to miss the energy efficiency target, what is a result of non-legally bounding measures for the Members of State. To achieve those goals this Directive has appealed to the Members of State to apply the requirements of minimum energy usage for new and existing buildings. Furthermore, the Directive 2012/27/EU on energy efficiency from October 2012 states: "*The rate of building renovation needs to be increased, as the existing building stock represents the single biggest potential sector for energy savings. Moreover, buildings are crucial to achieving the Union objective of reducing greenhouse gas emissions by 80-95 % by 2050 compared to 1990.* " (Official Journal of the European Union 2012)

The building sector is a major drawback in the renewable energy consumption and should be dealt with on a national basis. In EU households, heating and hot water alone account for 79 % of total final energy use (European Commission 2016). European Commission states that cutting the energy consumed by heating and cooling in buildings and industry can be achieved through scaling up the use of advanced construction and design techniques and high-performance insulation materials when renovating buildings. It is essential to decrease non-renewable energy usage, thereby CO2 emissions and fossil fuel consumption, by energy efficient improvements of existing buildings and with new regulations.

In an on-going upturn in energy assessment technologies, new low-energy standards can be reached by retrofits based on building simulations of energy performance. Thus, improvements made in such matter will have a positive aftermath on the climate change and the environment for the next generations.

2.2 Building legislations then and now

Technical advances in the 50ies such as production of masonry materials and the use of concrete and reinforced concrete enabled the development of "thin" constructions that meet the static requirements but do not have any energy efficient concepts (Peulić, 1973). The consequence of these actions is a large building fund which is extremely disadvantaged from the thermal energy conservation point of view.

The first regulations on thermal conservation of buildings in the Republic of Croatia (then Socialist Federalist Republic of Yugoslavia) were adopted in 1970 (Regulations for Technical Measures and Conditions for Thermal Building Conservation - Official Journal of SFRJ 35/70) (Vrcek 2012). Firstly, the state territory was divided into three building-type climatic zones. Secondly, the maximum values of the heat transfer coefficient k ($W.m^{-2}.K^{-1}$) (today U) were prescribed for different elements of buildings envelope for each zone. That was the beginning of a modest thermal insulation application with thicknesses in a range of 2 to 4 cm. The glass surface area had increased but with poorly made sealing and severe thermal bridge problems.

These residential buildings, that are now older than 50 years, hold a significant share of the overall primary energy consumption in Croatia. As it can be found in the literature, these buildings are estimated to spend 230-250 $kWh.m^{-2}$ of primary energy per year, which accounts for about 20 % of the total housing stock (Marđetko-Škoro, et al. 2005). In this matter, primary energy stands for energy used for heating, cooling, ventilation and hot water preparation. According to Croatian Technical Regulation on Energy Economy and Heat Retention in Buildings (CTREEHRB), todays requirements demand a maximum of 180 $kWh.m^{-2}$ of primary energy use per year in case of refurbishment in Zagreb area. In case of a new building, planed primary energy demand must not exceed 120 $kWh.m^{-2}$ per year.

Considering the legal obligations, enhancement of energy efficiency by retrofits of existing buildings represent an opportunity to reduce present and future operation costs and improve users comfort. Thereby, upgrading existing buildings will not only contribute to the decrease of primary energy use but also will positively affect the users.

2.3 The JU-61 buildings

Remetinečki gaj is the first residential area of Novi Zagreb that was built according to a specific urban plan. The urban development of this area was conducted in three phases, beginning in 1955. The second phase began in 1960 and encompassed the central urban area with the montage apartment buildings constructed by Jugomont enterprise (Figure 2). This stretch was defined by the JU-60 building type, followed by an almost experimental usage of the JU-61 montage constructions. Altogether three buildings of JU-60 type, three five-storey buildings JU-61 and eight six-storey buildings JU-61 type were built in this neighbourhood (Mattioni 2007).

Figure 2 Building the neighbourhood Remetinački Gaj, 1961 (personal collection of architect Bogdan Budimirov)

This montage building system was designed by three architects, Bogdan Budimirov, Željko Solar and Dragutin Stilinović. The JU-61 apartments consist of modular units, each room 360 x 480 cm, which was a result of the calculation for the most simplified production of montage elements in a series. Furthermore, these modular units were simultaneously shifted for a third in the ground plan (Figure 3) so the necessary function links between the units could be ensured. This made it possible to connect the staircase unit with the apartment entrance unit which was the hall. The hall led to the kitchen, the bathroom and to one to three rooms depending on the apartment type. (Mlinar 2007)

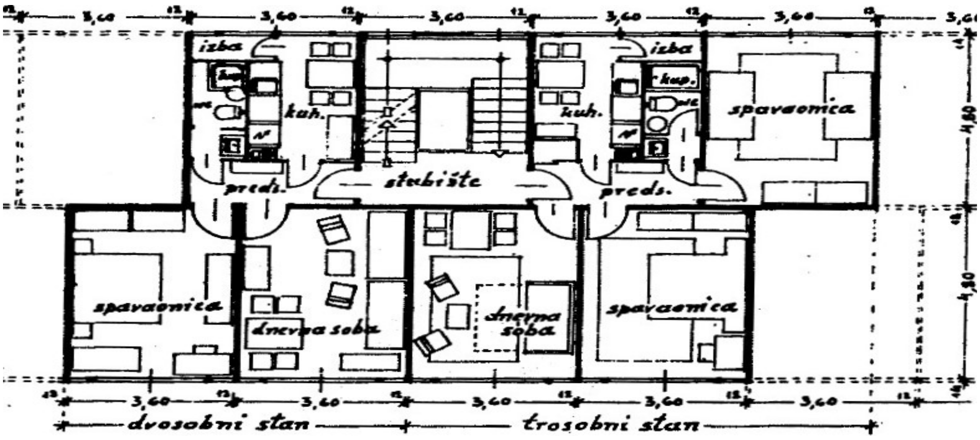


Figure 3 Ground plan of 2 units accessible from one staircase JU-61 type (Peulić 1973)

3 METHOD

The main problem while performing retrofit optimization of a building is to balance the cost efficiency with the energy performance while satisfying the occupants thermal comfort levels and the technical legislation constraints.

A few researchers in the field have developed five major phases in the whole retrofit optimization process (Ma, et al., 2012). As it can be seen in the figure 4, the first phase is the project setup and pre-retrofit survey where the building owners or agents should define the scope of the work and set project targets. In the second phase, energy auditing and performance assessment, building energy data should be analysed so that no-cost and low-cost energy conservation measures (ECMs) could be proposed. The third phase is the identification of retrofit options. The retrofit options can be prioritized based on energy-related and non-energy-related factors, the key performance indicators (KIPs). The fourth and fifth measure are site related. After implementation and tuning of the chosen measures, post validation and verification of energy savings should be done via occupant survey and measurements.

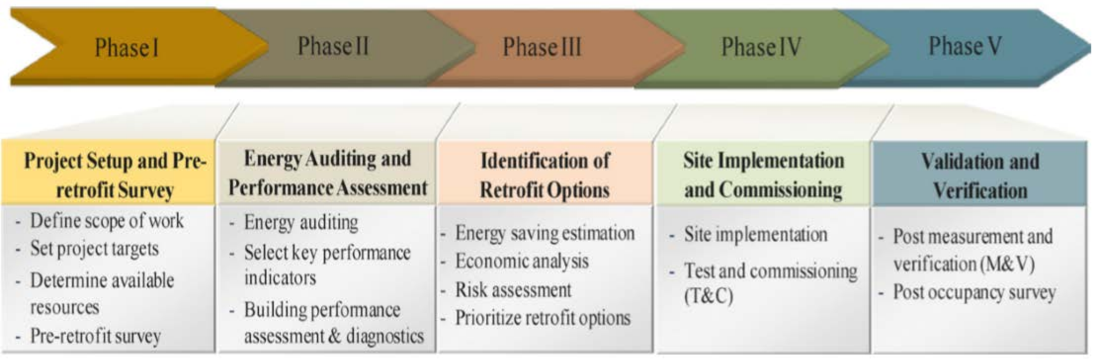


Figure 4 Key phases in a sustainable building retrofit program (Ma, et al. 2012)

This research is based on the first three key phases in the retrofit optimization process. For the first phase some general targets are defined:

- Meet the technical requirements for energy conservation measures
- Lower the heating and cooling load in an economically profound way
- Meet the thermal comfort parameters.

Steps of the method start with building auditing in the section 3.1, whereas section 3.2 is devoted to performance assessment and identification of the retrofit options. To conclude, a single retrofit strategy is chosen as optimal via evaluation of ECMs through the KPIs.

3.1 Sample Building

As it was mentioned before, an existing dwelling dating from 1961 was selected for this analysis. This building serves as a showcase of a large prefabricated building stock that represents an issue in the energy department due to the long period of usage without any conclusive renovation method.

The sample building is located in the district Remetinečki gaj with the address Remetinečki gaj 24a, 1010 Zagreb, Croatia. Figure 4 shows the exact position of the building in Zagreb City area.

Figure 5 Location of the building (Google Maps)

3.1.1 Building information

To produce a digital model with realistic properties, some general information about the building is needed. The original plans and data about the building were found in the Croatian State Archives. The collected and measured on site data such as location, orientation, dimensions and envelope characteristics are provided in the table below.

Table 2 Building characteristics

Location	Latitude: 45°46´8.14´´ N Longitude: 15°56´41.08´´ E
Orientation	11.5° (NW angle of the north façade)
Elevation (m)	114.39
Floor height (m)	2.8
Gross wall to outside area (m^2)	1784.77
Total gross building area (m^2)	2229.12
Glazing area (m^2)	633.80
Window to wall ratio (%)	35.51

This residential building with a total gross building area (GBP) 2675 m² and heated net area (Ak) of 1814 m² is a detached building consisting of 2 dilatations, each with a total surface area of approximately 44,76 x 4,92 m. The total height of the object is 16,8 m which contains a ground floor area and 5 floors. The ground floor incorporates storage rooms for tenants and is considered unheated. The remaining floors are exclusively residential, each floor with 7 residential units which makes a total of 35 residential apartments.

The building is a residential block extending mostly from north to south. On the east side there are 3 entrances to the building glazed from the bottom up. From the entrance area there is an access to the ground floor or to the staircase to the higher floors. The unheated ground floor rooms consist of storages, entrance space and stairwell to the upper floors.

The building was built in 1961 so the typology of construction, in the regulations, belongs to the group of buildings built in the period 1940-1970. According to the characteristics of the structure, the outer covering corresponds to the construction period. The supporting structure of the building is a system of reinforced concrete columns and panels, among which there are prefabricated façades or partition elements, 20 cm, 16 cm or 5 cm thick.

The vertical bearing elements are reinforced concrete wall panels (1,2 x 2,6 x 0,12 m) and columns (2,6 x 0,12 x 0,12 m). Horizontal load bearing elements are 12 cm thick reinforced concrete panels with the dimensions 3,6 x 1,2 m, used for the floor areas. The sides of the building are constructed out of prefabricated façade panels and the front side façade elements are wooden non-load bearing frames. This prefabricated panel was filled with a layer of mineral wool (4 cm), an air layer (8 cm) and finished with a corrugated metal flashing on the outside (Figure 6). The side façade panel on the other hand, is a load bearing element with 15 cm of reinforced concrete, 4 cm of mineral wool and a layer of the metal flashing, as it is shown in Figure 7. Currently, the finishing of the facade is overdue, which is visible on the lower parts of the façade.

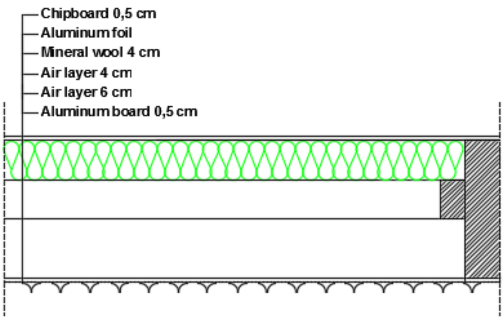


Figure 6 Non-bearing facade panel (Peulić 1973)

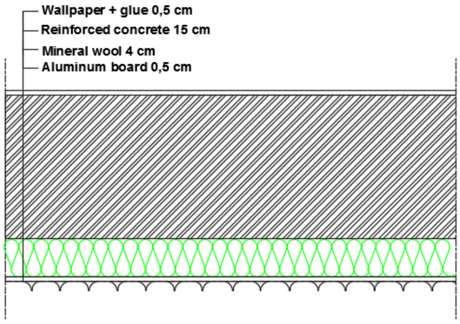


Figure 7 Load bearing facade panel (Peulić 1973)

The load-bearing structure between the heated and unheated space is constructed as a prefabricated ceiling panel. The staircases are prefabricated reinforced concrete elements with horizontal floor planes. The roof structure begins with a flat prefabricated reinforced concrete panel and continues with a sand layer, a layer of reed, a concrete screed, a waterproof membrane and finishes with a layer of gravel.

The walls of the apartments to the unheated staircase are precast reinforced concrete cores covered with wood wool panels and plaster, 0,125 m thick. The original exterior fenestrations are wooden windows with single glazing double wings. They have only one operation to open and that is to open fully. In the design of the carpentry, there is no adequate protection from insolation, but all of the windows subsequently received external shutters. The apartment entrance doors are wooden structures with frosted glass on top. Windows in common areas and storage in the ground floor are the metal single glazing windows with a smaller surface. The staircase glass wall is metal framed with single glazing, where only the middle window in each floor is able to open. Original heating system was based on local firewood burning units for each of the apartments. Currently the tenants have switched to electric heaters, with built-in appliances of different manufacturers and the heating effect. Also, there is no centralized hot water production. Electrical energy is the main energy source and electric boilers serve as appliances. There are no central air conditioning or ventilation systems either, in the building ventilation takes place naturally through the windows. For cooling purposes in the summer periods some of the apartments use singular built-in split systems, thus disrupting the façade look with outside air units.

3.1.2 Current state and damages

The current appearance of the building envelope has changed in comparison to the original plans. Firstly, negligence and secondly nonprofessional, even illegal renovations of the front façade has led to an unappealing look as it is shown in the figures below (Figure 8 – 10).

On the first hand, the unaltered original joinery is outdated, not sealed properly, and contributes to large thermal losses and moisture leakages through it. On the other hand, some of the fenestration has been replaced by tenants with new PVC profiles, but these works were not systematically made. Also, some of the originally glazed areas have been closed and turned into walls.

The roof of the building has been partially repaired and altered several times and the initial ground floor use has been changed. Figure 9 shows unprofessional alterations on the envelope. Needless to say, some of these alterations do not fulfill basic requirements and can be considered to be far from lege artis.

Due to the age of the building, the outer envelope is in bad condition. This is primarily related to the dilapidation of the original external joinery and the damaged metal coverings. The insufficient heat-insulated outer shell, as well as the mostly unsatisfactory exterior joinery, generates great thermal losses. There were no major works on the building, apart from the individual replacement of the residential windows and one staircase window wall.

The building requires a systematic renovation of all envelope elements to meet the Croatian Technical Regulations, the Environmental Protection and Energy Efficiency Fund (EPEEF) regulations and to improve the thermal characteristics of the building.

As this research is focused on making a general retrofit model, the alternations of the building envelope will not be taken into account. The “Base Case” model will be based on the original plans of the building.

Figure 8 Current state of the front façade (Photo collection of the author)

Figure 9 Partial renovations of the façade (Photo collection of the author)

Figure 10 Damages of the metal coverings (Photo collection of the author)

3.2 Performance assessment

3.2.1 Modelling and Simulation

A thermal simulation software (EnergyPlus V8.4.0 2016) was used to determine the thermal behaviour of the building with current characteristics and the retrofit options which could contribute to more efficient operation of the building itself. EnergyPlus is an energy analysis tool that uses dynamical simulations for sizing the HVAC equipment, retrofit studies for life and cost analyses and for optimizing energy performance of buildings (Department of Energy 2016). Since this software package doesn't include a graphical interface, the geometrical model of the building was developed using Openstudio 2.0.0, 2016 a plugin for Sketchup software (Sketchup 2016). This Plug-in allows users to quickly create geometry needed for EnergyPlus. Additionally, OpenStudio supports import of gbXML and IFC for geometry creation, thus, this tool was chosen to create the geometry and for zoning of the spaces (Openstudio 2.0.0 2016).

3.2.2 Weather data

For building performance simulations some metrological data is needed, such as air temperatures, humidity levels, sun radiation and wind speed and direction. As there are no hourly measured data for this area, the weather files used in this simulation were generated by Meteonorm 7.0 software tool (Meteonorm 7.0 2012). The given information is a result of an interpolation between the measured data of 6 nearby stations. Figure 11 shows the fluctuation of the site outdoor air temperatures given by the interpolation. The maximum of 37 °C is achieved in July and the lowest -9 °C on the 24th of January.

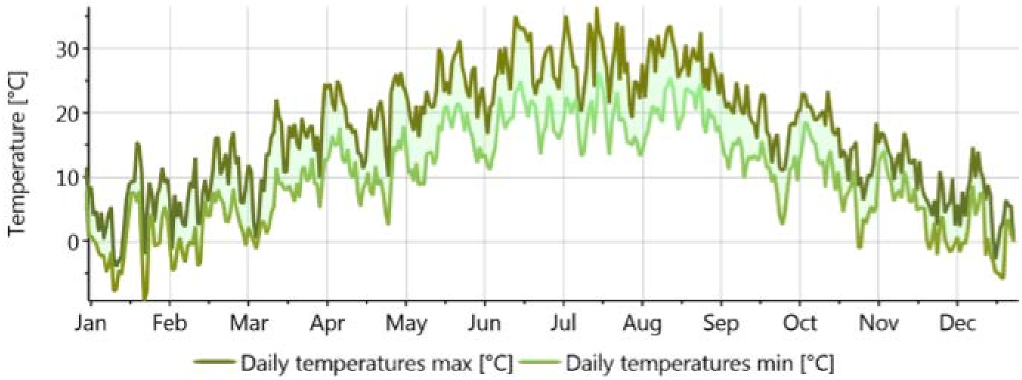


Figure 11 Minimum and maximum daily temperatures (Meteonorm 7.0 2012)

Figure 12 is a representation of mean monthly insolation in this area in kWh.m^{-2}. As expected, the highest values occurred in the summer period, Jun and July. Accompanying Figure 13 coincides with those values, showing that the longest sunshine duration, in hours per day, occurs in the same months.

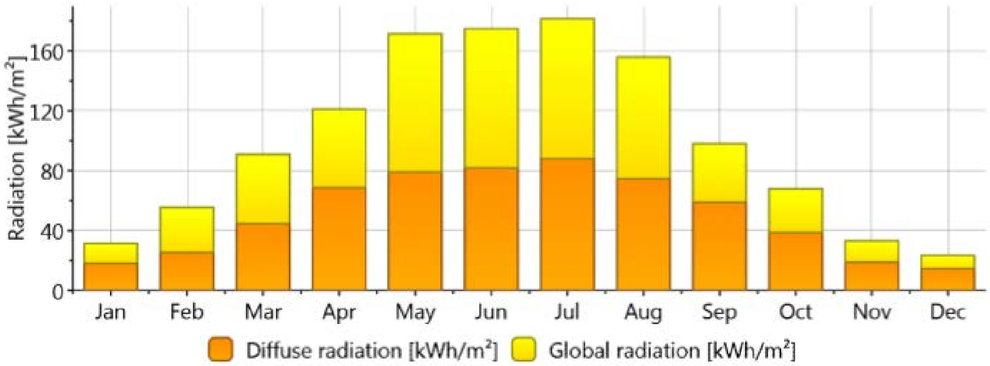


Figure 12 Mean monthly values of solar radiation (Meteonorm 7.0 2012)

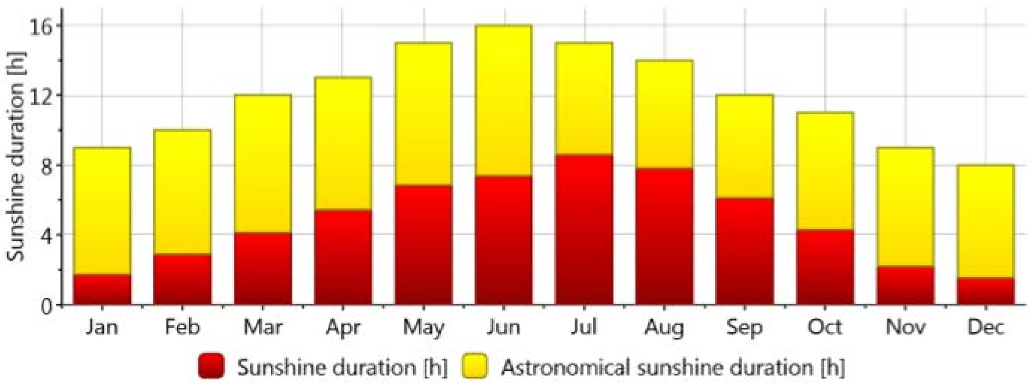


Figure 13 Monthly sunshine duration (Meteonorm 7.0 2012)

3.2.3 Geometry and technical specifications of the building

As mentioned before, the “Base Case” model was constructed according to the original plans of the building. Figure 14 and Figure 15 show the model in OpenStudio plugin (Openstudio 2.0.0 2016) where the orange label represents real North, 78,5° counter clockwise to the North axes in the starting model.

Figure 14 Base Case model- East façade (Openstudio 2.0.0 2016)

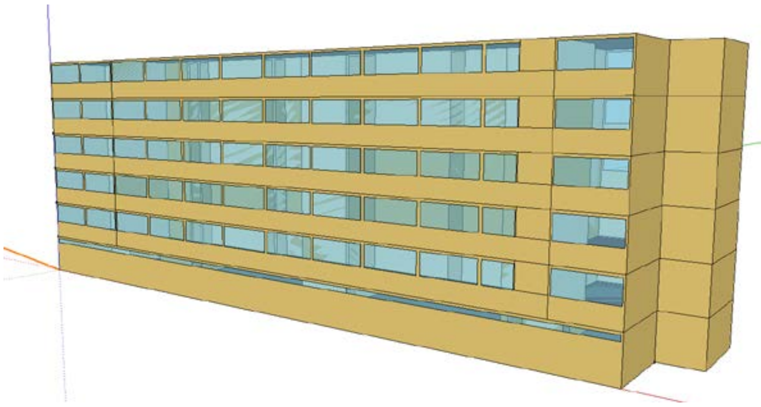


Figure 15 Base Case model- West façade (Openstudio 2.0.0, 2016)

All together 29 thermal zones were assigned to the building (Figure 16). These zones were attached according to the space orientation, conditioning features (heated/unheated space) and schedules. In this way, the building was divided into groups of almost uniform internal conditions in order to get a precise estimation of the overall energy demand.

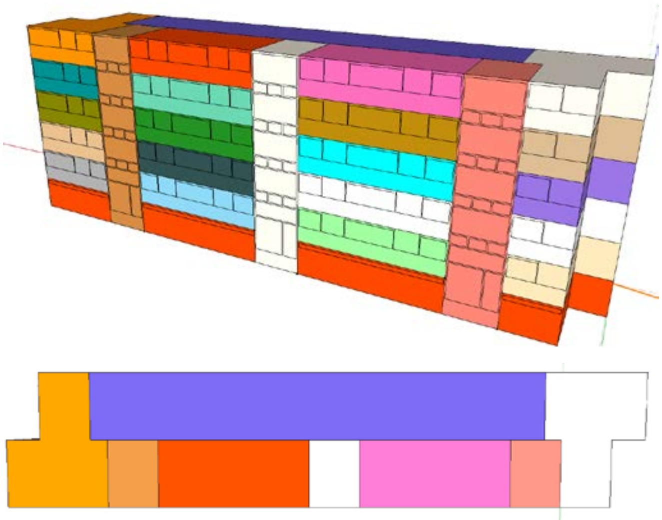


Figure 16 Base Case model- Thermal Zones (Openstudio 2.0.0 2016)

The unheated spaces were classified as zones of their own, ground floor as thermal Zone 1 and the staircases areas (shafts) as thermal Zone 2,3 and 4 (Zone 4 positioned the most north). The other zones were divided according to their orientation and apartment position.

Each of the upper floors consists of 5 uniform spaces and each space has its own Zone. Looking at the east façade, zones 5,9,13,17 and 21 are applied to the left corner apartments group (most South), shown in the plan of Figure 14, where zone 5 is on 1. Floor and Zone 17 on the 5th. Zones 6,10,14,18 and 22 are apartments between the staircase zoned 2 and staircase zoned 3, also spreading from bottom up. The same goes for Zones 7,11,15,19 and 23 which are placed between staircase 3 and 4. The North corner apartments group contains zones 8,12,16,20 and 24, Zone 24 being on the last floor. Lastly, Zones from 25 to 29 represent the spaces oriented west, Zone 25 being on the 1. Floor and Zone 29 on the last. Table 3 shows the areas and the volumes of different zone groups.

Table 3 Thermal zones- areas and volumes

Zone name	Zone Group	Area (m^2)	Volume (m^3)
THERMAL ZONE 1	Ground Floor	362,88	943,49
THERMAL ZONE 2/3/4	Corridors	17,28	269,57
THERMAL ZONE 5/9/13/17/21	S Corner Apartments	51,84	142,79
THERMAL ZONE 6/10/14/18/22	E Apartments 1	51,84	150,9
THERMAL ZONE 7/11/15/19/23	E Apartments 2	51,84	150,9
THERMAL ZONE 8/12/16/20/24	N Corner Apartments	51,84	142,79
THERMAL ZONE 25/26/27/28/29	W Apartments	155,52	404,35

3.2.4 Internal gains

Model input data for internal heat gains such as equipment, lighting and people were based on the recommendations and assumptions. Internal gains were assigned to zone groups shown in Table 3. As Croatian legislation has not yet developed recommendations for hourly input of internal gains, some Austrian and German norms were chosen for further modelling.

The Austrian norm (ÖNORM B 8110-6 2014) recommends a constant value of 3,75 W.m^{-2} for the calculation of winter internal heat gains. These gains include heat emitted from people, lights and electrical equipment. As the recommendations for summer calculation (ÖNORM B 8110-3:2012 2012), give separate values for the heat gains from people and gains from equipment, these values were combined. Values from the Table 4 show internal load in W.m^{-2} per hour that were assigned to the heated areas of the building. Heat gains for the summer calculations were added together to represent a single number for all internal gains per hour. In the second column are the values created as an average number of all the gains to get the values per hour for the winter calculation. Summer conditions are set to be from 31th of March until 30th of October and the winter season from 1st of November to 30th of March (Norm EN 15251:2012-12 2012).

Table 4 Internal gains per hour

Daytime (until h)	*Internal Load [W.m⁻²]* Summer (ONORM 8110-3:2012)	Winter (ONORM 8110-6:2014)
1:00	5,52	2,80
2:00	5,43	2,75
3:00	5,56	2,82
4:00	5,56	2,82
5:00	6,37	3,23
6:00	9,52	4,82
7:00	8,85	4,48
8:00	9,00	4,56
9:00	7,78	3,94
10:00	7,24	3,67
11:00	6,61	3,35
12:00	5,04	2,55
13:00	4,41	2,23
14:00	6,15	3,12
15:00	8,18	4,14
16:00	9,12	4,62
17:00	10,52	5,33
18:00	10,47	5,31
19:00	10,02	5,08
20:00	9,12	4,62
21:00	8,08	4,09
22:00	6,87	3,48
23:00	6,46	3,27
0:00	5,74	2,91
Average	7,40	**3,75**
Max value (100%)	**10,52**	5,33

Different values were assigned to the unheated ground floor and the corridors. As these spaces are not constantly used, a constant value of 2,5 $W.m^{-2}$ was chosen to represent those gains.

3.2.5 Base Case simulation assumptions

After generating the geometry and classifying the internal gains, the model was introduced with the input data regarding the physical properties of the embedded materials. The material properties for this “Base Case” model are based on assumptions and the collected information from the literature regarding these buildings. Table 5 provides the simulation assumptions for the walls, floors, roof and fenestration constructions that were used in the model. The thermal properties of materials used in the simulations were found in the Croatian technical regulations (CTREEHRB) annex B.

Table 5 Simulation assumptions regarding construction data and the minimum U values

Building constructions	***Thickness (mm)***	***U-value (W.m-2.K-2)***	***Heat flow direction***	***Minimum U-value (W.m-2.K-2) CTREEHRB, annex B***
GF EXTERIOR WALL	150	3,46	*(Unheated)*	/
GF FLOOR	420	2,15	*(Unheated)*	/
PARAPETT	150	0,76	horizontal	0,3
WINDOW WALL	150	0,69	horizontal	0,3
SIDE FACADE WALL	200	0,98	horizontal	0,3
GF SLAB	190	0,72	down	0,4
FLOOR SLAB	150	2,49	*(heated to heated)*	0,6
INTERIOR WALL (wall to unheated)	130	2,83	horizontal	0,4
WINDOW GLAZING (single glazing)	3	5,9	horizontal	1,1
WINDOW FAME AND DIVIDER				/
wood	7	2,2	horizontal	
aluminium	7	3,2	horizontal	
STEEL DOORS	80	5,97	horizontal	2
FLAT ROOF	270	1,4	up	0,25

Infiltration rates were designed to correspond the current loose and leaky state of the outdated building elements, with air change rate set on 0,6 h^{-1}.

The natural ventilation was represented using the “ZoneVentilation:DesignFlowRate” object. Using a specially designed schedule for the modelling of ventilation, different air change rates (ACH) were assigned to each zone group – Heated and unheated spaces, as shown in the Table 6. A difference was made for summer and winter period ventilation.

Table 6 Natural ventilation schedule in air changes per hour

<table>
<tr><th colspan="3">Heated spaces</th><th colspan="2">Unheated spaces</th></tr>
<tr><th colspan="3">ACH (h^{-1})</th><th colspan="2">ACH (h-1)</th></tr>
<tr><td>Until:</td><td>Summer</td><td>Winter</td><td>Summer</td><td>Winter</td></tr>
<tr><td>9:00</td><td>6</td><td rowspan="3">0</td><td rowspan="3">6</td><td rowspan="3">0</td></tr>
<tr><td>21:00</td><td>0</td></tr>
<tr><td>0:00</td><td>6</td></tr>
</table>

According the Croatian Technical Regulations and recommendations, minimum fresh air supply indoors should be 0,5 air changes per hour. In some cases, the infiltration rate (0,6 h^{-1}) fulfils the minimum requirements so there is no need for additional ventilation (Beko, et al. 2011). During the summer it is assumed the ventilation occurs mostly during the night, ergo a value of 6 h^{-1} was assigned having in mind the possibility of cross ventilation in the apartments (Bukarica, et al. 2008). The unheated spaces have constant values dependent on the year seasons. Summer ventilation is 6 h^{-1} to avoid overheating, whereas in winter 0 (infiltration is considered enough).

As far as shading is concerned, the building is equipped with outside plastic blinds that are operated according the schedule shown it the Table 7 depending on the orientation. Besides the schedule, shading is modelled to be on if zone air temperature exceeds a Set point of 24 °C and/or if insulation is more than 100 W/m^2. The Shading material was picked from the ASHARE database, with medium reflectance and medium transparencies.

Table 7 Shading control schedule

<table>
<tr><th>Shading Control:</th><th colspan="2">East Side</th><th colspan="2">West Side</th></tr>
<tr><td>Winter
(31st Sept - 30th March)</td><td colspan="2">Off</td><td colspan="2">Off</td></tr>
<tr><td rowspan="2">Summer
(31st March- 30th Sept)</td><td>Morning (7:01-14:00)</td><td>On</td><td>Morning (7:01-12:00)</td><td>Off</td></tr>
<tr><td>Afternoon (14:01-24:00)</td><td>Off</td><td>Afternoon (12:01-21:00)</td><td>On</td></tr>
</table>

The building heats on electric space heaters which operate in the winter period. The cooling of conditioned spaces is done by separate air conditioning units in each of the apartments that are also connected to the grid.

For the purpose of this study, the heating and cooling systems were modelled as ideal systems that provide enough energy to meet the required set points. Therefore, calculating the heating and cooling load was sad to be sufficient. The set points were designed as recommended in the European norm for apartment buildings (Norm EN 15251:2012-12 2012). A constant heating set point was set at 22 °C and cooling at room temperatures bigger than 27 °C while in the range of the schedule shown in the Table 8. The cooling schedule corresponds the ventilation schedule explained earlier in the text, it is set on during the day when the windows are closed.

Table 8 Cooling schedule

HVAC_Cooling		
Until:	Summer	Winter
9:00	Off	Off
21:00	On	
0:00	Off	

Following the EN 15251:2012-12 norm, the comfort room temperature $\theta_{Ra,C}$ is 22 °C, at external temperatures $\theta_{Au,C}$ below 16°C and 26 °C, at ambient temperatures $\theta_{Au,C}$ above 32 °C. Figure 15 shows the permitted comfort room temperature range, where X coordinate states hourly average of the outdoor temperature and Y the operative room temperatures. It can be seen; the inside room temperatures should not exceed 28 °C in the summer period and get below 20 °C in the winter.

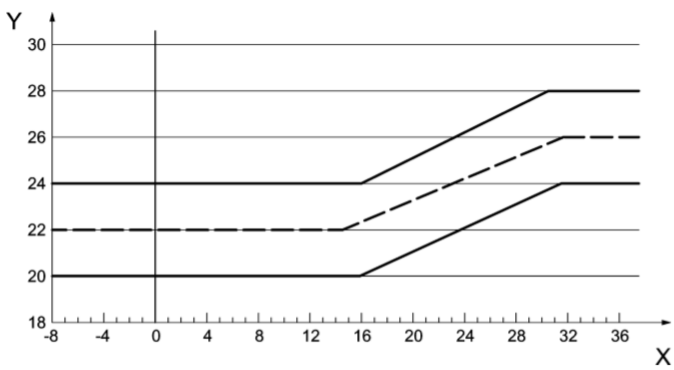


Figure 17 Comfort room temperature θ Ra, C (dashed line) with the permitted tolerance (EN 15251:2012-12 2012)

3.2.6 Improvement Scenarios

To demonstrate the feasibility of building refurbishment, five different envelope improvement scenarios were proposed.

Harvey (2009) states that "*The effectiveness of the thermal envelope depends on (1) the insulation levels in the walls, ceiling, and other building parts; (2) the thermal properties of windows and doors; and (3) the rate of uncontrolled exchange of inside and outside air which, in turn, depends in part on the air tightness of the envelope.*"

Following these steps, a wide range of retrofit options can be found. In this paragraph energy and technical factors will be considered to determine the best envelope improvements. To distinguish the most feasible measures, investment costs and thermal bridge simulations will be included in the next paragraphs.

The retrofit improvements suggested in this contribution pertain to different combinations of optimization of insulation improvement, infiltration rates, technical restrictions and occupant thermal comfort habits (Harvey 2009). These improvement scenarios were designed to follow the thermal requirements of building elements according to the CTREEHRB and to meet the low energy standards. Five different retrofit options were investigated and summarized in Table 9. Explanations of the improvement scenarios are provided below.

Table 9 Description of the improvement scenarios

Abbreviation	Scenario	Description
IS_01_a	Improved façade- type A	**Replacing old front facade:** 10 cm of PUR foam panels and 5 cm of mineral wool insulation; **U_{wall1}=0,157 W.m-^{2}K^{-1};** **Replacing single glazed windows:** *a) Apartment windows*: 4-16 -4 -16-4 Argon filled LowE glass and outside shading; **U_g= 1,06 W.m-^{2}K^{-1}, SHGC= 0,576;** *b) Corridor windows:* 4 -16-4 Argon filled LowE glass and outside shading; **U_g= 1,546 W.m-^{2}K^{-1}, SHGC=0,646** new exterior door **U=1,275 W.m-^{2}K^{-1};** **Side facade wall:** 15 cm of mineral wool ; **U_{wall2}=0,224 W.m-^{2}K^{-1};** **Ground floor walls:** 15 cm of mineral wool ; **U_{wall3}=0,222 W.m-^{2}K^{-1};** **ACH = 0,5 h-1**
IS_01_b	Improved façade- type B	**Replacing old front facade:** 20 cm aerated concrete blocks and 15 cm of mineral wool insulation; **Uwall1=0,157 W.m-^{2}K^{-1};** **Replacing single glazed windows with:** *a) Apartment windows:* 4-16 -4 -16-4 Argon filled LowE glass and outside shading **Ug= 1,06 W.m-^{2}K^{-1}, SHGC= 0,576;** *b) Corridor windows:* 4 -16-4 Argon filled LowE glass and outside shading **Ug= 1,546 W.m-^{2}K^{-1}, SHGC=0,646;** new exterior door **U=1,275 W.m-^{2}K^{-1};** **Side facade wall:** 15 cm of mineral wool **Uwall2=0,224 W.m-^{2}K^{-1};** **Ground floor walls:** 15 cm of mineral wool ; **Uwall3=0,222 W.m-^{2}K^{-1};** **ACH = 0,5 h-1**
IS_02	Improved Roof and Basement ceiling	**New roof construction:** 16 cm of mineral wool insulation; **U_{Roof}=0,221 W.m-^{2}K^{-1}** **New floor construction:** *a) 1. Floor to unheated basement: 12 cm of insulation;* **U_{floor}=0,246 W.m-^{2}K^{-1};** *b) Apartment floors: 4 cm of insulation;* **$U_{ceiling}$=0,562 W.m-^{2}K^{-1};** **ACH = 0,5 h-1**
IS_03_a	All together – Type A	IS_01_a together with IS_02
IS_03_b	All together– Type B	IS_01_b together with IS_02

It should be emphasized this research involves a prefabricated building with a specific construction where a large part of the façade is non load bearing – I.e. the retrofit options have to be carefully planned. Because of the deteriorating state of the front façade construction, these building elements cannot undertake partial replacements. That means the windows cannot be replaced if the whole front facade wall system that supports it is not replaced with a new structure.

For that reason, the Improvement scenarios IS_01 accommodates reconstruction of the whole façade together with the fenestration. In this case, instead of single glazed wooden windows, new PVC framed triple glazed low emissivity windows were applied for apartments (U_g= 1,06 W.m-^{2}K^{-1}, SHGC= 0,576) to satisfy the CTREEHRB requirements. The corridors were assigned with double glazed lowE windows and shading to reflect the intensive solar gains through the east and west side oriented fenestration (U_g= 1,546 W.m-^{2}K^{-1}, SHGC=0,646).

Furthermore, with the purpose of finding the most feasible solution, two different façade wall systems were examined, type A and type B. The construction of this two systems are explained below:

a) Wall type A introduces a commercially used panel system (Figure 18) that was already implemented in a nearby building of the same type. It consists of a prefabricated stainless-steel casing filled with 10 cm of polyurethane foam. This highly insulating (λ_{PUR}=0,021 W.m^{-1}K^{-1}) panel system is placed on metal framing (Kingspan 2017). The inside of the frame construction is filled on site with 5 cm of mineral wool insulation (λ=0,036 W.m^{-1}K^{-1}) and closed to the inside with gypsum boards.

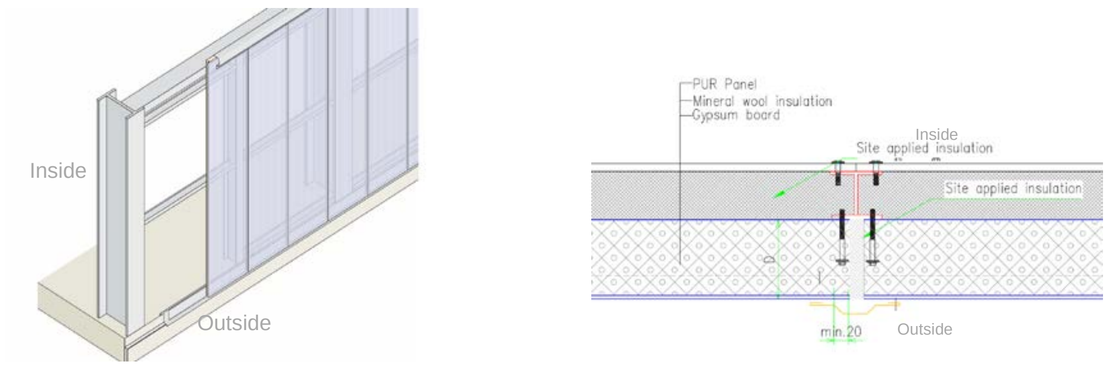


Figure 18 IS_02_a Construction method and detail of panels on a frame structure (Kingspan Construction Details 2017)

b) For the measure IS_01_b a new wall system was designed to meet the thermal requirements for outside walls (U_{wall} ≤ 0,3 $W.m^{-2}.K^{-1}$). It is suggested a new wall construction should be made out of aerated concrete blocks (20 cm thick). This blocks are much lighter than the regular bricks and as so can be supported by the original concrete structure. Additionally, with a fairly low thermal conductivity of λ=0,11 $W.m^{-1}K^{-1}$ they contribute to a better thermal insulation. This system is finished with additional 15 cm thick mineral wool ETICS façade (Figure 19) constructed to the new wall (Xella Group, 2017).

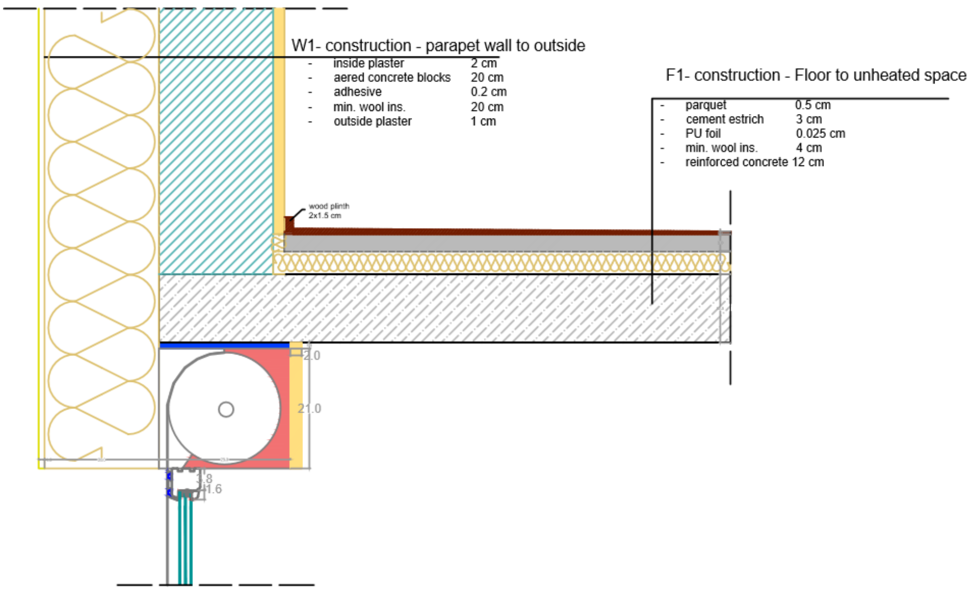


Figure 19 IS_02_b Wall to floor detail

Side façade walls are made out of reinforced concrete panels so a conventional façade with 15 cm thick mineral wool insulation (λ=0,035 $W.m^{-1}.K^{-1}$) and a plaster finish can be executed in both scenarios. The ground floor 12 cm thick reinforced concrete walls were also enhanced with 15 cm of the same mineral wool insulation.

IS_03 is the third scenario with roof and floor improvements. New roof construction suggests adding 16 cm of mineral wool which results with a U value of 0,22 $W.m^{-2}K^{-1}$. Ceiling of the unheated basement should be covered with 12 cm of insulation to prevent downwards heat loss.

Considering a new and improved envelope of the building, the air exchange rate was set to 0.5 h^{-1} for each IS.

The third improvement scenarios, IS_03_a and IS_3_b, are a combination all improvements and serve as an example of a whole envelope retrofit. The next chapters are dedicated to finding the most viable solution. All scenarios will be evaluated over the chosen key performance indicators that are explained in the next chapter. Furthermore, the two systems will be assessed via thermal bridge simulation to prove if they can be executed to satisfy the requirements.

3.3 KPI´s

Using computer software and equipment is beneficial while designing or evaluating energy efficient buildings. Various measures can be perceived as energy efficient, but only a few can be realized as practical, desirable and adequate. They key performance indicators (KPIs) are the indicators which show the best performance of one measure regarding a certain standpoint (economical, environmental, quality, etc.) (Xu, et al. 2012). In this research, simulation tools and manual calculations are used to assess the following indicators:

- Heating load
- Cooling load
- Energy savings
- Return period (P_t)
- Net Present Value (NPV)
- Temperature factor (f_{rsi})
- Linear thermal transmittance (Ψ)

3.3.1 Energy load and savings

By applying different boundary and weather conditions, computer tools are able to analyse the energy consumption of a building. In this case, energy simulations are performed on the Base Case model and improvement scenarios to estimate the energy consumptions. The outputs of these simulations are then heating and cooling load that are needed to satisfy the foreseen thermal comfort parameters.

First level of evaluation will be done via heating load. Croatian Energy efficiency guidelines (Croatian Technical Regulations 2010) characterize a building according to the annual heating demand in $kWh.m^{-2}$, Table 10.

While there are no efficiency guidelines for cooling load, these will be evaluated in terms of cooling energy savings. That means the measure with the highest cooling energy reduction will be evaluated most appropriate.

Table 10 Energy performance certificate ranking

Energy class	**Q''$_{H,nd,ref}$ – specific annual energy needs for heating for reference climatic data in kWh/m².year**
A+	≤ 15
A	≤ 25
B	≤ 50
C	≤ 100
D	≤ 150
E	≤ 200
F	≤ 250
G	> 250

In accordance with obtained annual consumptions, computing energy savings (ES) in this retrofit project is crucial for further comparison. Based on the difference between the pre-retrofit and post-retrofit yearly energy consumption, ES can be calculated in the following manner:

$$ES = Epre - Epost \qquad (1)$$

Where

- ES – estimated energy savings in one year [kWh.a^{-1}]
- E_{pre} –estimated energy use from a pre-retrofit model of the building [kWh.a^{-1}]
- E_{post} –estimated energy use in the facility after implementing the retrofit options [kWh.a^{1}]
  (Asadi, et al. 2012)

3.3.2 Cost assessment

This case study takes into account a multi-objective strategy of an energy efficient retrofit (EER). Therefore, a financial evaluation method will be used to compute the economic cash flow parameters of an EER project. By implementing above mentioned retrofit scenarios the investment cost and obtained benefits increase. This evaluation will analyse the costs and the benefits (energy savings cost) of each measure respectively in order to show the economic effects of EERs (Liu, et al. 2018). Two indexes were selected to represent the financial evaluation, investment payback period (P_t) and the Net Present Value (NPV). The method of calculation will be explained below.

The investment cost for each measure is calculated by adding the retrofit costs corresponding each action as follows:

$$Investment = \sum_{i=1}^{I} C_i^{Fen} \times x_i^{Fen} + \sum_{j=1}^{J} C_j^{Wall} \times A_j^{Wall} + \sum_{k=1}^{K} C_k^{Roof} \times A_k^{Roof} + \sum_{m=1}^{M} C_m^{Dem} \times X_m^{Dem} \qquad (2)$$

- C_i^{Fen} - cost in [€] for installation of one fenestration type i;
- x_i^{Fen}- number of fenestrations type i;
- C_j^{Wall} - cost in [€/m2] for installation of external wall system type j;
- A_j^{Wall}- exterior wall surface area type j;
- C_k^{Roof} - cost in [€/m2] for installation of roof system type k;
- A_k^{Roof} - roof surface area type k;
- C_m^{Dem} - cost in [€] for demolition and disposal of old construction type m;
- x_m^{Dem}- quantity of waste type m;

(Asadi, et al. 2012)

Tables below shows the approximate cost estimation of the possible retrofit options. Each of the improvements incorporate the overall cost of implementation. That means the finish price includes material supply, removal of old elements and material disposal, installation of new system and manual labour (Unit price). All of the prices are intuitional and are based on average prices of some private contractor companies. They are converted from Croatian Kuna to Euros where 1 EUR is equal to 7,6 Kuna. *Table 11* shows unit prices that are then multiplied with the quantity to get the renovation cost (ReCost), as proposed in equation 2. This cost is then divided with the net conditioned area (1814 m2) of the whole building to get the price of the investment per square meter of inhabited area (ReCost per m2). The sum of the total Investment per net conditioned area of the improvement scenarios are given at the end (Total ReCost). Table *11* shows the calculation of prices for each element.

Table 11 Cost calculation

ELEMENT	Description	Unit	Quantity,	Unit price [€]	ReCost [€]	ReCost per m2 [€.m^{-2}]	Total ReCost per m2 [€.m^{-2}]
Windows	Installation of triple glazed low-E windows with shading	pieces	175	533	93275	51	67
Staircases	Installation of double glazed PVC windows	m^2	119	150	17775	10	
	Installation of entrance doors	m^2	3	180	540	0	
Front façade type A	Assembly of new metal substructure with 5 cm insulation and gypsum boards	m^2	521	70.4	36643	20	31
	Installation of new PUR panels 100 mm thick	m^2	521	38	19779	11	
Side facade	Installation of new 15cm mineral wool ETICS façade	m^2	318	39	12411	7	7
Front façade type B	Construction of 200 mm thick aerated concrete block wall	m^2	521	40,9	21288	12	23
	Installation of 15 cm of mineral wool ETICS façade	m^2	521	39	20300	11	
Ground floor	Installation of 15cm mineral wool ETICS façade	m^2	415	39	16174	9	13
	Installation of 12cm mineral wool ceiling insulation	m^2	415	19,5	8087	4	
Roof	Installation of new roof system with 16 cm of mineral wool ins.	m^2	415	53,9	22353	12	12

A breakdown of the costs for each retrofit option is shown in *Table 12*. As it can be seen the investment for a whole façade and fenestration renovation with a panel system is 206486 €, respectively. Divided by the area of the building (1814 m^2) it results with a cost of 113,8 €.m^{-2}. The same calculation applies to other improvement scenarios in the table.

Table 12 Cost assessment of improvement scenarios

ABREVIATION	Description	ReCost [€]	ReCost per m^2 [€.m^{-2}]
IS_01_A	Improved Façade_Type A	206 426	113,8
IS_01_B	Improved Facade_Type B	191 591	105,6
IS_02	Improved Roof and Basement ceiling	53 665	29,6
IS_03_A	All together_Type A	260 090	143,3
IS_03_B	All together_Type B	245 256	135,2

First criterion for an economic evaluation of the offered improvements is the payback time or return period. The return period (T_p) is the simplest criterion for financial decision-making on investments. Once the investment return period has been reached, the cash flows of the project in the remaining time are the earnings of the investor (Bukarica, et al. 2008). It doesn't consider the time value of money and lifetime of an energy saving measure is not taken into account. The mathematical criterion of the return period is written:

$$T_p = \frac{Investment}{Anual\ savings} = \frac{ReCost}{V}\ [a] \qquad (3)$$

- ReCost - Investment [EUR]
- V- Annual benefits [EUR/a]

Annual savings or benefits in general represent the total savings in euros achieved annually by the project. In this case, the simulation outputs are heating and cooling load that stand for thermal energy needed to retain certain comfort values. As both heating and cooling equipment in the building are powered via electrical energy, these values need to be transformed for further calculations. The transformation of thermal energy load to electrical energy is done with the coefficient of performance (COP). This coefficient shows how many kWh of thermal energy is obtained for each kWh of electrical energy consumed by the device (Pavković, et al. 2012), which means:

$$Electrical\ energy\ (kWh) = \frac{required\ thermal\ energy\ load\ (kWh)}{COP} \quad (4)$$

This equation is applicable to the calculated ES for heating and cooling load where the COP for electrical heaters is 1 and COP for split air conditioning units is 3,2, respectively. The electrical energy savings is then calculated with the following equation:

$$ES_{el} = \frac{ES}{COP} \quad (5)$$

Total annual savings (V) are then calculated by multiplying the electric energy savings in kWh with the unitary energy price (EUR.kWh^{-1}):

$$V = ES_{el} * E; \quad (6)$$

Where:

- ES_{el} is the electrical energy savings in a year [kWh.a^{-1}]
- E is the unit energy price [EUR.kWh^{-1}]

Table 13 shows the annual benefits (V) formed with the appropriate COP values. Thermal energy consumption shown in the table is the sum of the heating and cooling load for each measure. The unit energy price is a mean value of the daytime and night time tariff model taken from the national energy company (HEP Group 2017).

Table 13 Electrical energy consumption and annual savings for each measure

Abbreviation	**Thermal energy consumption (kWh.a^{-1})**	**Energy Savings, ES [kWh.a^{-1}]**	**Electricity savings, ES_{el} [kWh.a^{-1}]**	**Unitary electrical energy price (€.kWh^{-1}.a^{-1})**	**Total annual savings, V (€.a^{-1})**
BC	287,042			0,10575	
IS_01_a	164,919	122,123	114,698		12,129
IS_01_b	166,477	120,565	112,836		11,932
IS_02	243,202	43,839	42,340		4,478
IS_03_a	131,935	155,106	146,884		15,533
IS_03_b	132,668	154,374	145,340		15,370

The second criterion is the net present value (NPV). The net present value is the present value of all future savings realized during the project implementation time (from year 1 to year t), minus the investment cost (Pavković, et al. 2012). NPV value of zero means that the proposed measure is capable of returning invested capital, and measures with a purely positive present value have a higher profitability than those required on the market. Therefore, a positive NPV is a good indicator of eligibility for a certain measure and It can be concluded, higher NPV values indicate more adequate options. However, the biggest difficulty in applying this method is to select a discount rate that can significantly affect the size of the net present value. The net present value is determined by future energy savings and is calculated in a following manner:

$$NPV = V * \frac{1-(1+k)^{-t}}{k} - ReCost \qquad (7)$$

Where:

- ReCost is the initial investment.
- V is the yearly savings represented as the energy savings costs.
- t is the expected lifetime of the measure.
- k is the discount rate.

Other assumptions are:

The predicted economical lifetime of all measures is assumed to be 20 years which is an average of all measures proposed by EU regulation (European Commission June 2010).

Discount rate used is 4 % as suggested in Guide to Cost-benefit Analysis of Investment Projects, Economic appraisal tool for Cohesion Policy 2014–2020 (Europa.eu 2015).

3.3.3 Thermal bridge simulation

Thermal bridges represent “weak points” of the envelope through which heat can escape from the interior, thereby lowering the surface temperature. This can directly influence the thermal comfort of the inside space and can lead to moisture condensation or even mould growth near the thermal bridge. In general, thermal bridges appear at junctions between building components or at places of structural differences.

In this study, 2 wall systems are suggested as retrofit solutions for a specific type of building. Considering the particularity of the proposed solutions, there is a need for properly designing the details for minimizing thermal bridge problems. This will be determined via 2 parameters, the f_{Rsi} factor and the ψ (psi) value. The temperature factor, f_{Rsi}, is used to establish the risk of surface condensation or mould growth and is calculated from:

$$f_{Rsi} = \frac{\theta_{si} - \theta_e}{\theta_i - \theta_e} \qquad (8)$$

Where:

- θ_{si} - surface temperature,
- θ_i - internal environmental temperature
- θ_e - the temperature of the external environment.

The f_{Rsi} depends only on the structure and is defined by steady state conditions (Ward & Sanders 2007). In order to avoid condensational risk, the f_{Rsi} value should satisfy the minimum requirements (OENORM B8110-2, 2003-07). The values are shown in Table 14 (standard indoor conditions 20 °C; 55 %; exterior temperature around -10 °C):

Table 14 Minimum – Requirements for f_{Rsi}-Values

Minimum requirements

$f_{Rsi} \geq 0{,}71$	for avoidance of mould grow
$f_{Rsi} \geq 0{,}69$	for avoidance of surface condensation

The linear thermal transmittance ψ ($W.m^{-1}K^{-1}$) represents that extra heat flow that goes through the thermal bridge. It is calculated in accordance to the equation 9, where L^{2D} ($W.m^{-1}K^{-1}$) represents the total heat flow through the element. This factor is the thermal coupling coefficient between the internal and external environment and is used to define two-dimensional junctions (Pont 2016). In the equation, the U value ($W.m^{-2}K^{-1}$) times l (m)– element length, stands for the heat flow of the flanking element which is then subtracted from the total heat flow amount:

$$\psi = L^{2D} - \sum U x l \qquad (9)$$

A software tool is being used to estimate both values through numeric thermal bridge simulation. AnTherm (Analysis of Thermal behaviour of Building Construction with Thermal Bridges) serves as a reliable tool for evaluating thermal bridges comprehensively and precisely, therefore has been chosen in this study. License for this tool has been provided by Ms. Kornicki, the creator of the software.

There are two main parameters that are defined before the simulation:

1. The **surface thermal resistance** R_s for internal and external spaces that are defined by the HRN EN ISO 6946:2008 depending on the direction of the heat flow.
2. The **boundary conditions** – temperatures for the simulated spaces.

In this case details with only horizontal heat flow from the heated inside space to the outside are examined so the chosen values are:

Table 15 Input parameters for AnTherm

Heat flow direction	R_{si} ($m^2K.W^{-1}$)	R_{se} ($m^2K.W^{-1}$)
Horizontally	0,13	0,04
	Boundary conditions (˚C)	
Heated rooms	+20	
Outside	-10	

Boundaries were set to follow the outside line of the last inside layer. Figure 20 shows the principle of defining boundaries conditions in a model. The same concept was applied to the simulation models in this study.

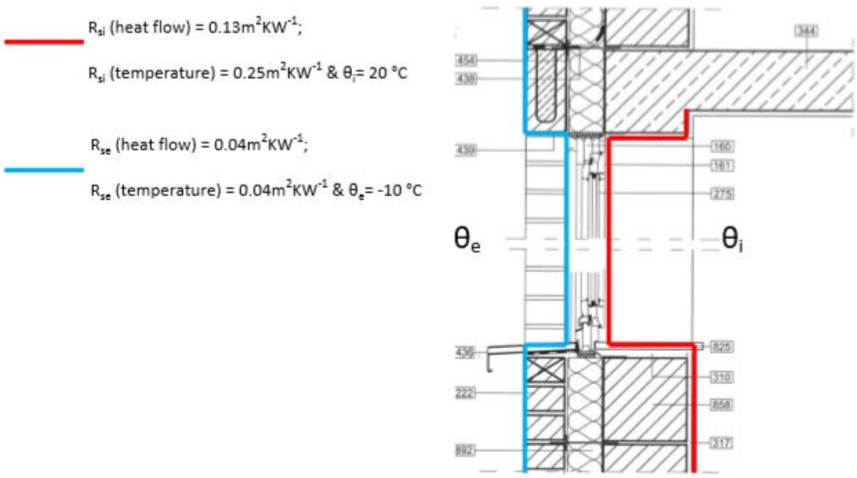


Figure 20 Example of defining boundaries in AnTherm (Buceva, 2016)

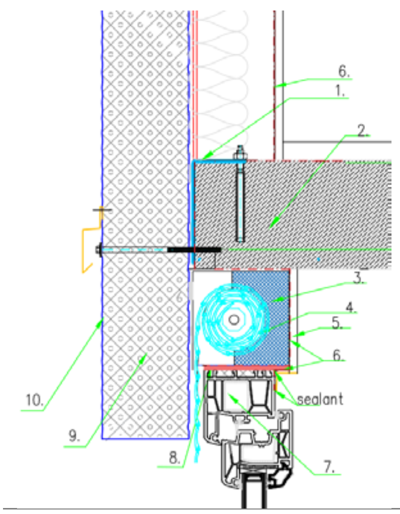
For each of the two arguable wall systems two details are modelled, window head and window sill, with one additional detail of the panel system (system A) – panel to panel junction. Altogether 5 thermal bridges are examined.

Each of the following tables includes a drawing of the construction detail with a description of the materials used in the simulation. All of the materials and their characteristics are taken from the AnTherm material library and are related to the materials used in the energy consumption simulation.

The first 3 tables represent thermal bridge solution details for the panel system A.

Table 16 shows a detail of the Window-frame-glass and roller shutter box construction detail. The panels are mounted in the concrete slab with fasteners over a metal L shaped plate at the top of the slab. The window frames are mounted sideways and on the window sill, whereas the roller shutter box connects directly in the slab, sideways and to the window head. The shutter box is insulated to the inside. It should be noted that the whole system is considered tightly shut from the inside due to the usage of vapour barriers behind the finishing gypsum boards. The vapour barriers should be carefully connected and overlapped at junctions. A special care should be given to the sealing of window frames to ensure there is no air or moisture permeability. The wall construction above the slab will be explained in a detail below.

Table 16 Wall system A- vertical section of the window head



Construction detail– Window-frame-glass_system A	Layers						
		Name	d (mm)	λ (W.m^{-1}.K^{-1})	μ (-)	ρ (kg.m^{-3})	c (J.kg^{-1}.K-1)
	1	Aluminium substructure	4	160	-	2800	0,88
	2	Concrete Slab	120	2,6	100	2500	1,06
	3	XPS	60	0,034	160	25	1,45
	4	Roller shutter	80	0,17	-	1390	0,9
	5	Gypsum board	9.5	0,21	10	852	1,044
	6	Vapour barrier (PE foil)	0.2	0,23	1000	0	0,792
	7	PVC shutter box and frame	80	0,17	-	1390	0,9
	8	PUR foam	10	0,2	100	30	0
	9	Insulated panels	100	0,02	100	30	-
	10	Aluminium covering	5	0,1877	-	-	0,92
		Air cavity	30	0,166	1	1,2	1,008

Table 17 describes a detail of the window sill. As there is no fixed wall construction, the window is mounted on a metal frame (U profile) that is then secured in the side walls of the room. The panels are mounted to the same metal framing beneath the window. Waterproof membrane should be added from the outside of the window sill beneath the flashing. As mentioned before, the airtightness is ensured with a vapour barrier and proper sealing from the inside space.

Table 17 Wall system A – vertical section of the window sill

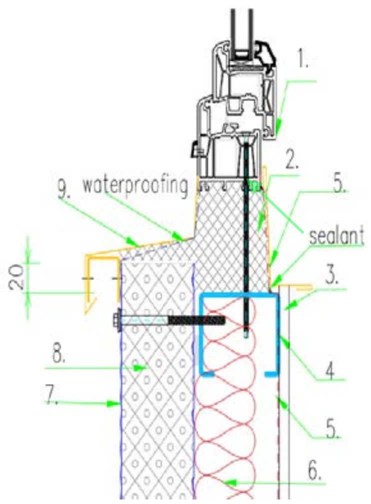
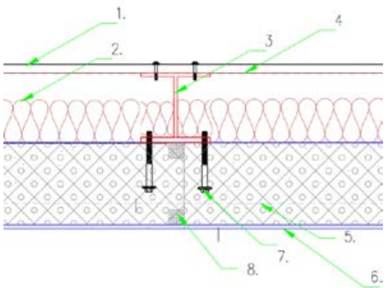
Construction detail– Window sill_system A	**Layers**						
		Name	d (mm)	λ ($W.m^{-1}.K^{-1}$)	μ (-)	ρ ($kg.m^{-3}$)	c ($J.kg^{-1}.K^{-1}$)
	1	PVC frame	80	0,17	-	1390	0,9
	2	XPS insulation	70	0,034	160	25	1,45
	3	Gypsum board	9,5	0,21	10	852	1,044
	4	Aluminium substructure (U-profile)	4	160	-	2800	0,88
	5	Vapour barrier (PE foil)	0,2	0,23	1000	0	0,792
	6	Mineral wool	50	0,036	1	140	0,84
	7	Aluminium covering	5	0,1877	-	-	0,92
	8	PUR insulated panels	100	0,02	100	30	-
	9	Aluminium sheet	2	160	-	2800	0,88
		Air cavity	30	0,166	1	1.2	1,008

Table 18 is a horizontal section of a vertical junction of two panels. The panels are mounted on a metal construction and connected with fasteners. This panels are produced with embedded sealant on the connection joint to secure a perfect weather and vapour barriers from the outside. To the inside there is a 5 cm layer of site applied mineral wool insulation to increase the thermal quality of the system. Due to the structural needs, the metal framing should be wider than 5 cm which results with unventilated air layer that is closed with gypsum boards (air cavity). To secure the airtightness, a vapour barrier is stretched behind the gypsum board and over the metal frames.

Specifically, this detail was modelled as a layered 2D model because of the modelling of fasteners that have a dimension of 4 millimetres.

Table 18 Wall system A - horizontal junction of two panels

Construction detail– vertical junction_system A



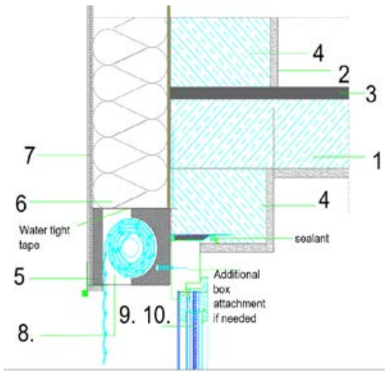
	Name	d (mm)	λ (W.m^{-1}.K^{-1})	μ (-)	ρ (kg.m^{-3})	c (J.kg^{-1}K^{-1})
1	Gypsum board	9,5	0,21	10	852	1,044
2	Mineral wool	50	0,036	1	140	0,84
3	Aluminium substructure	4	160	-	2800	0,88
4	Vapour barrier (PE foil)	0,2	0,23	1000	0	0,792
5	PUR insulated panels	100	0,02	100	30	-
6	Aluminium covering	5	0,1877	-	-	0,92
7	Metal fastener	5	60	-	7800	0,88
8	Sealant		0,8	40	1450	1,13
	Air cavity	30	0,166	1	1,2	1,008

The next 3 tables demonstrate detail solutions for the thermal bridge problematics of the aerated block system, system B. This retrofit measure suggests a new wall structure should be build out of aerated concrete blocks to support the window weight and the outside 15 cm thick façade.

Table 19 Wall system B- Vertical section of the block wall system and window junctions

Construction detail– Window-frame-glass_system B

Layers

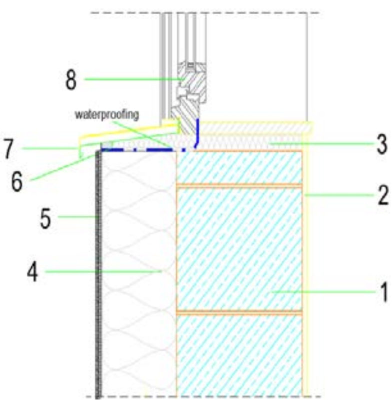


	Name	d (mm)	λ (W.m^{-1}.K^{-1})	μ (-)	ρ (kg.m^{-3})	c (J.kg^{-1}K^{-1})
1	Concrete Slab	120	2,6	100	2500	1,06
2	Internal plaster	15	0,2	3	1800	-
3	Mortar	20	1,4	-	2000	-
4	Aerated concrete	200	0,18	8	700	1,21
5	XPS	60	0,034	160	25	1,45
6	Mineral wool	150	0,036	1	140	0,84
7	External plaster	15	0,19	10	800	.
8	PVC shutter box and frame	80	0,17	-	1390	0,9
9	Glass	4	0,8	-	2500	.
10	Argon	16	0,017	1	1,7	0,518

The window-frame-glass and shutter box detail is presented in the *Table 19*. As it can be seen, the shutter box is positioned to the outside, to minimize the thermal bridging in that area. This insulated box is mounted in the window lintel. It is suggested by the manufactures of this blocks, a specialized window lintel should be used to support this construction. The shutter box is than closed with outside plaster as the rest of the façade. The window is mounted as the details before, sideways with special care for the air tight sealing.

The next table shows a vertical section of the window sill. The window is positioned slightly to the outside, on the edge of the concrete blocks to reach better thermal performance. It should be emphasized that the waterproof foil has to be placed in such manner so that it ensures no moisture comes through from the outside. The sill from the outside should be closed with a sloped metal cladding that finishes over the façade.

Table 20 Wall system B- vertical section of the window sill

Construction detail– Window sill system B	**Layers**						
		Name	d (mm)	λ ($W.m^{-1}.K^{-1}$)	μ (-)	ρ ($kg.m^{-3}$)	c ($J.kg^{-1}.K^{-1}$)
	1	Aerated concrete	200	0,18	8	700	1,21
	2	Internal plaster	15	0,2	3	1800	-
	3	XPS insulation	60	0,034	160	25	1,45
	4	External insulation (Mineral wool)	150	0,036	1	140	0,84
	5	External plaster	15	0,19	10	800	-
	6	Waterproof membrane	1	0,5	-	980	-
	7	Aluminium sheet	2	160	-	2800	0,88
	8	PVC frame	80	0,17	-	1390	0,9

4 RESULTS AND DISCUSSION

The main purpose of this thesis was to create a comprehensive retrofit solution for a specific type of buildings in order to give guidance to the investors in the decision making. Energy conservation measures were evaluated through energy savings and investment costs. Details of the constructions were assessed via thermal bridge simulation and the results are shown at the end.

4.1 Performance assessment results

The base case model and the improvement scenarios were simulated via EnergyPlus simulation software to estimate the most viable retrofit solution energy wise. The results will be evaluated according the heating and cooling load of each measure compared with the base case estimations. An overview of the energy outcomes is given in Table 14.

The following aspects can be documented regarding the impact of the application of different retrofit scenarios.

- The results from the first improvement scenarios, IS_01, show significant energy load reduction. Both façade options (type A and B) reveal more than 40 % heating load savings and almost 30 % cooling load reduction. As it can be seen in Table 21, IS_01_a shows slightly better heating results whereas IS_01_b performs moderately better in the cooling period.
- With 113,32 kWh.m^{-2}a^{-1} of heating energy demand (17 % reduction) and 20,72 kWh.m^{-2}a^{-1} for cooling, IS_02 shows much worse results compared to the other scenarios.
- The third retrofit option includes a combination of the previous and shows an increase in the envelope effectiveness. Up to 58 % of heating load and 33 % of cooling load reduction plays an important role in decision making.

Table 21 Overview of energy load depending on the improvement scenario

Abbreviation	Improvement Scenario	Heating demand $kWh.m^{-2}a^{-1}$	Cooling demand $kWh.m^{-2}a^{-}1$	Heating load reduction (%)	Cooling load reduction (%)
BC_00	Base Case	136,28	21,92	/	/
IS_01_a	Improved Façade-Type A	74,93	15,97	45 %	27 %
IS_01_b	Improved Façade-Type B	76,03	15,72	44 %	28 %
IS_02	Improved Roof and Basement ceiling	113,32	20,72	17 %	5 %
IS_03_a	All together-Type A	57,39	15,33	58 %	30 %
IS_03_b	All together-Type B	58,44	14,68	57 %	33 %

To recall from the chapter 3.3, based on the Croatian Energy Efficiency guideline, with an assumed heating demand of 136,28 $kWh.m^{-2}a^{-1}$, Base Case is considered to be class C. Improving the roof and floors (IS_02) would result with a demand of 113,32 $kWh.m^{-2}a^{-1}$ for heating, in which case the Efficiency category would stay unchanged – C. Lower categories are reached with other improvements and all fall to category B.

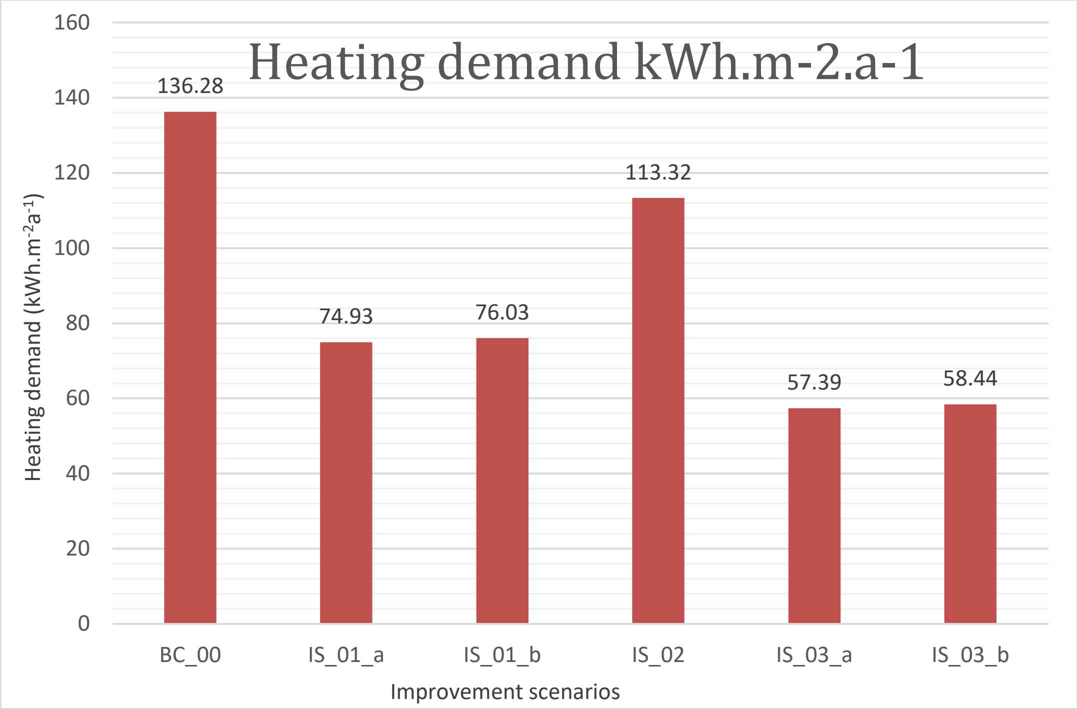


Figure 21 Predicted heating load for different scenarios

Figure 21 shows the heating demand for each of the improvement scenario. It can be seen, there are no significant difference in heating load between the façade systems A and B. The same can be confirmed in Figure 22, comparing the cooling load of the improvements.

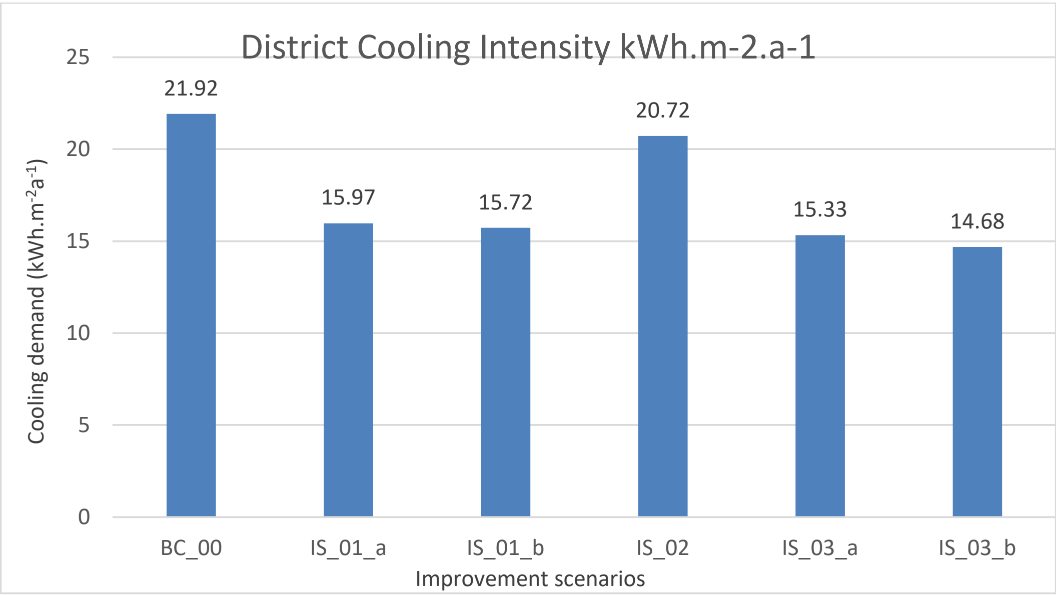


Figure 22 Predicted cooling load for different scenarios

As expected, the most improved measures (IS_3) give the most heating and cooling load reduction due to the overall improvement of the building envelope. Even though the cooling load are reduced with the insulation incensement, it is obvious in Figure 23, heating load reduction is much more influenced by these measures. During the cooling season heat flows, resulted from conduction, passes through building elements in a smaller range than in the heating period. This also accounts for the location of the building, considering the building is located in the continental part of Croatia where the weather conditions are less favourable.

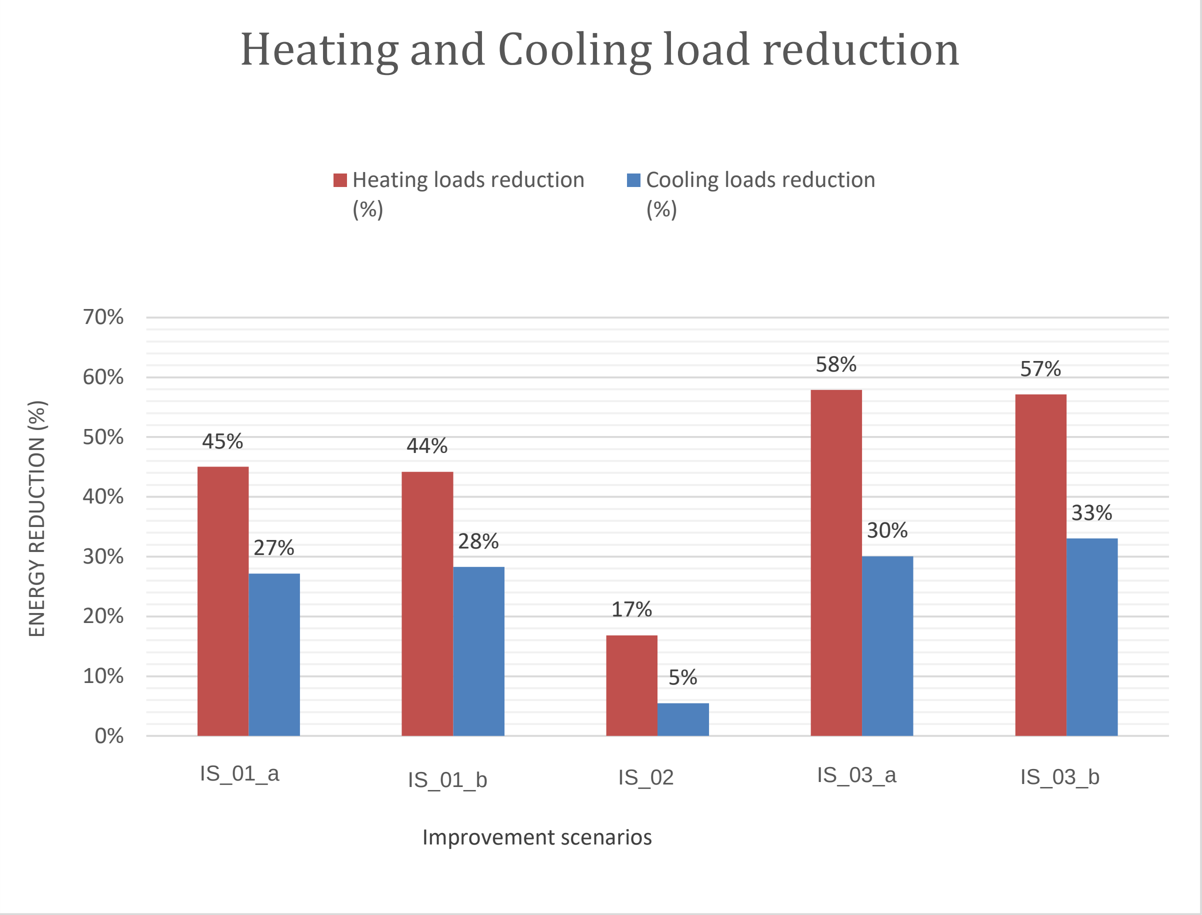


Figure 23 Heating and cooling load reduction for each improvement scenarios

By comparing the energy load it has become obvious there is a need for a holistic approach towards selecting the best retrofit option, thereby a cost evaluation will be presented in the paragraph below.

4.2 Cost efficiency results

Based on the 5 selected improvement scenarios, a financial estimation was carried out with a focus on prioritizing the potential benefits that can be obtained with the realization of the ECMs. The results of the cost-benefit analysis are displayed in Table 22.

Table 22 Cost-benefit analysis of the chosen IS's

Scenario	ReCost (€.m^{-2})	Annual savings V (€.m^{-2}a^{-1})	Return Perion T_p (a)	NPV (€)
IS_01_a	113,8	6,7	17	-21,8
IS_01_b	105,6	6,6	16	-15,3
IS_02	29,6	2,5	12	4,2
IS_03_a	143,3	8,6	17	-25,5
IS_03_b	135,2	8,5	16	-18,9

It can be observed the least investment is needed in the reconstruction of roof and floor areas, 29,6 € per square meter. The low investment costs are followed with the lowest annual savings, 2,5 €.m^{-2} but also the lowest return period. This can be explained in retrospective with the energy savings, where this measure shows the least energy reductions.

When comparing the two wall systems, IS_01_a and IS_01_b, with an investment of 105,6 €.m^{-2} system B is more economically justified as opposed to system A, which needs an investment of 113,8 €.m^{-2}. This accounts for a difference of 14834 euros in total. For that reason, the return period favours measure IS_01_b with one year less than the IS_01_a. Annual savings in euros per square meter are similar, 6,7 for system A and 6,6 for B.

Logically, the same ratio of cost efficiency is observed while comparing the two models of complete refurbishment (IS_3_a and IS_03_b). With less investments, 135,2 €.m^{-2}, the option B requires a smaller payback period (16 years). However, the annual savings of the first systems are 8,6 €.m^{-2}a^{-1}, which is slightly better than the second (8,5 €.m^{-2}a^{-1}). Still, both options result with the same payback time in a partial retrofit and an overall one. This would mean that a bigger initial investment into a complete refurbishment with more energy savings is equally efficient to the partial one. Considering this criterion doesn't include inflations and lifetime of a project, the results are evaluated with another parameter.

The forth criterion to determine cost efficiency is the net present value. It can be seen NPV is negative in all measures except IS_02, which holds a value of 4. The negative values indicate these improvements are not capable of returning the invested capital in the said period (20 years). If so, that could mean there is no economic justification for the initiation of such project. It should be emphasized, the calculation of this value is depended on the assumptions for economic lifetime of a project and the discount rate. Better results can be obtained while choosing a bigger lifetime or smaller discount rate. That being said, for further evaluation the NPV values will be taken into account solely for the purpose of prioritizing the results, less negative ones are considered better.

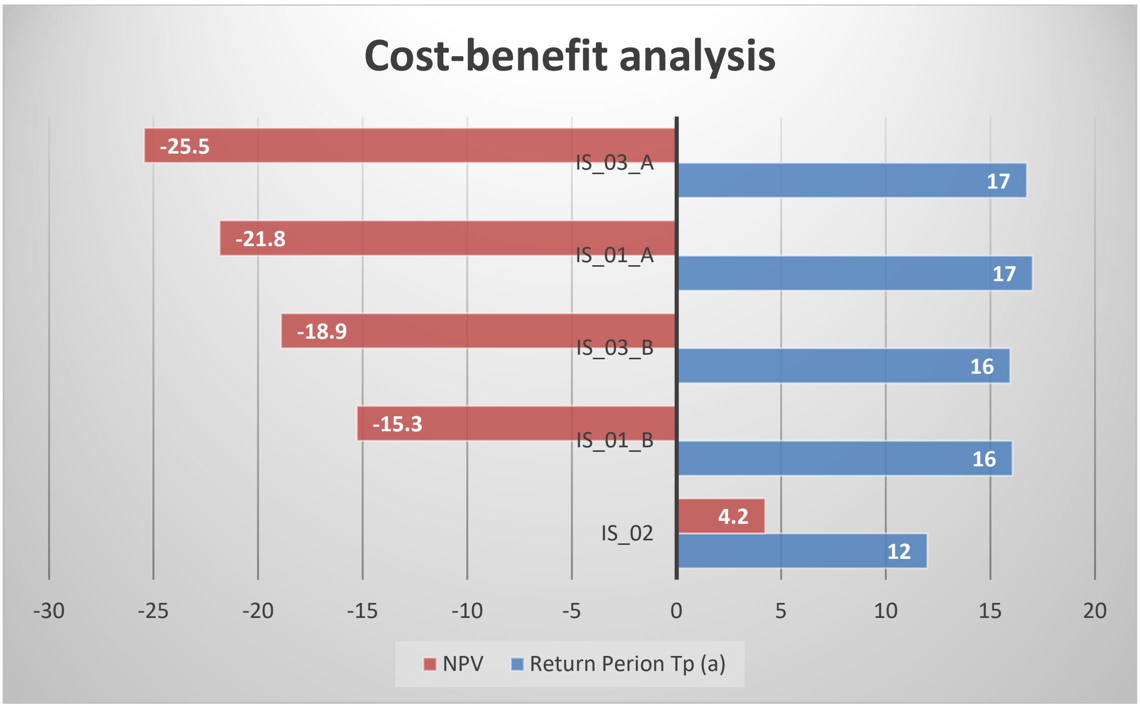


Figure 24 Economic KPI´s comparison

Figure 24 represents a comparison of the two KPI´s from the economic evaluation. This results can be observed in 2 approaches: in an overall ranking and in terms of comparing the two exanimated options (A and B).

In the first evaluation the IS_02 could be considered the most reasonable option, with a positive NPV value and the lowest return period. On the other hand, this observation is disputable while taking the energy savings into account. The next in line is the option IS_02_b with the lowest NPV value and return period, while the worst option seems IS_03_A.

When comparing only the two retrofit options, it can be seen option B results with a smaller return period and NPV value. Either considered as a partial renovation (IS_01_b) or a complete one (IS_03_b), the cost-benefit analysis places a priority on this improvement scenario.

Looking at the results from an owner's perspective, relatively long return period and low NPV values, combined with low income and credit restrains make it repelling to initiate with such ECM´s. In that reason, the Croatian Government adapted a program to promote energy efficient renovations of buildings in the period to the year 2020. This program offers irreversible grants for investments in measures that reduce the energy consumption of multi-family buildings. Grants up to 60 % of the whole project investment value is eligible for all households, whereas households in less-developed areas ca be funded up to 80 % of the investment value which makes this ECM´s achievable (Mikulić, D., Rašić Bakarić, I. & Slijepčević, S. 2016).

While the energy savings in both cases are similar, the cost-benefit analyses favours option B, an evaluation of the thermal bridges in the next chapter will give definite results on choosing the best option.

4.3 Thermal bridge simulation results

To conclude the uncertainty regarding the 2 queried systems, a thermal bridge evaluation was carried out to determine if such structures could be implemented in a real building without impairing the thermal comfort in spaces.

The results are shown in tables with two figures, one representing the simulation model and other the temperature profile given by the software. The output results are given at the end of the table starting with the psi-value, flowing the minimum inside surface temperature and the f_{Rsi} value. All of the simulated details have met the minimum requirements- i.e. the temperature factor is bigger than 0,71 in all cases. Thereby, there should be no risk of condensation or mould grow in elements implemented in above explained manner.

Window-frame-glass-construction detail was the first to be evaluated.

Table 23 and Table 24 show the results of both simulations. Slightly better results are achieved with the system B which requires the shutter box to be mounted from the outside. In this way, the f_{Rsi} value rises to 0,77. The same can be concluded while looking at the linear thermal transmittance, system B has a smaller value which means less energy is lost through this thermal bridge.

Table 23 Output results of a thermal bridge simulation - System A – window-frame-glass

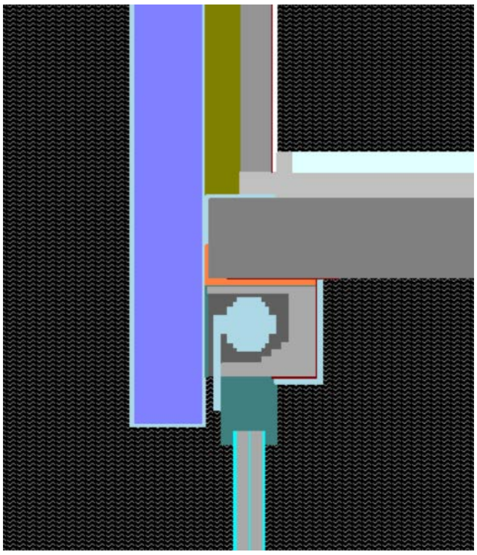
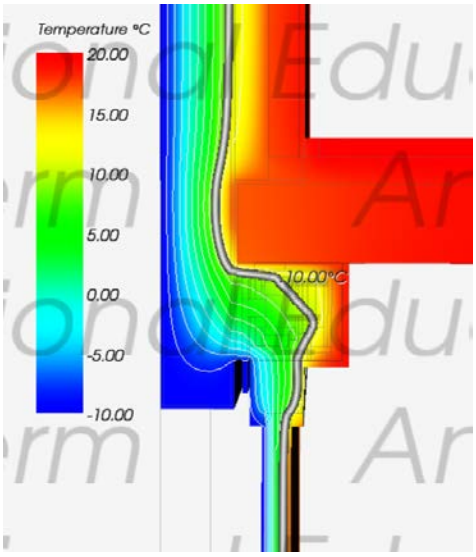
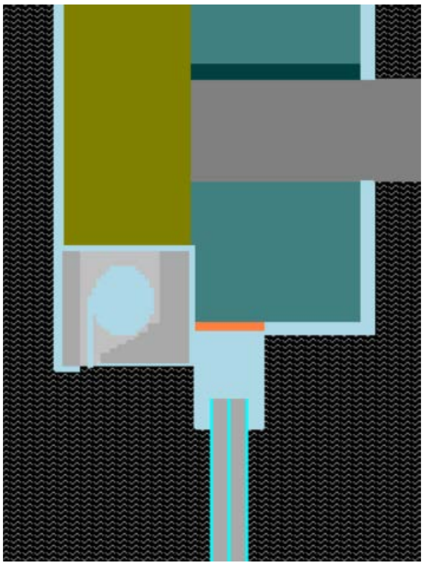
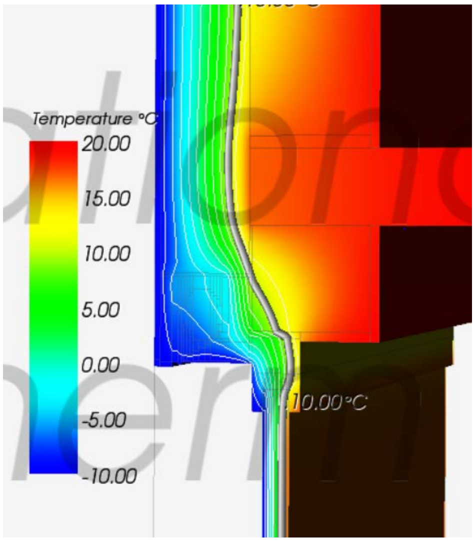
Wall system A - Window-frame-glass		
Simulation model	Temperature profile	
		
Output results		
ψ- value (W.m^{-1}.K^{-1})	**Θmin (˚C)**	**fRsi (-)**
0,0957	11,92	0,73

Table 24 Otput results of a thermal bridge simulation - System B –window-frame-glass

Wall system B - Window-frame-glass		
Simulation model	Temperature profile	
		
Output results		
ψ- value (W.m^{-1}.K^{-1})	**Θmin (˚C)**	**fRsi (-)**
0,0628	13,15	0,77

Simulation results for window sill sections are represented in Table 25 and Table 26. The first table shows temperature distribution of the panel system and the second for the block system. Even though both systems satisfy the requirements, system A shows slightly worse results. A psi value of 0,36 $W.m^{-1}.K^{-1}$ in the first case is a greater value, as appose to 0,068 $W.m^{-1}.K^{-1}$ from the second one. The temperature factor results support that claim also, with slightly higher minimum temperature in case of system B. It is obvious from the temperature distribution that the weakest point in both cases is the junction of the window frame and the wall system so this detail should be carefully executed.

Table 25 Output results of a thermal bridge simulation - System A - window sill

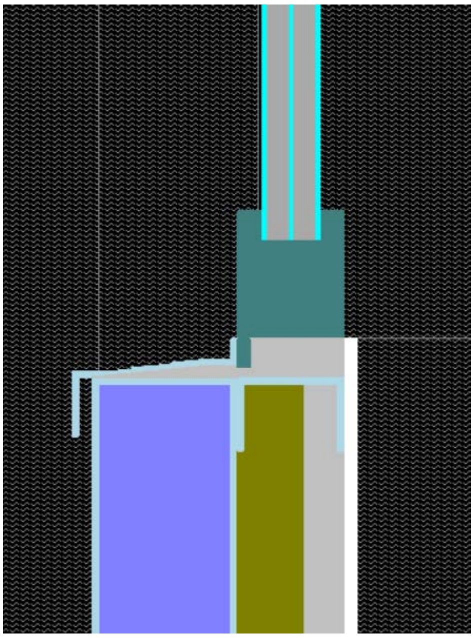
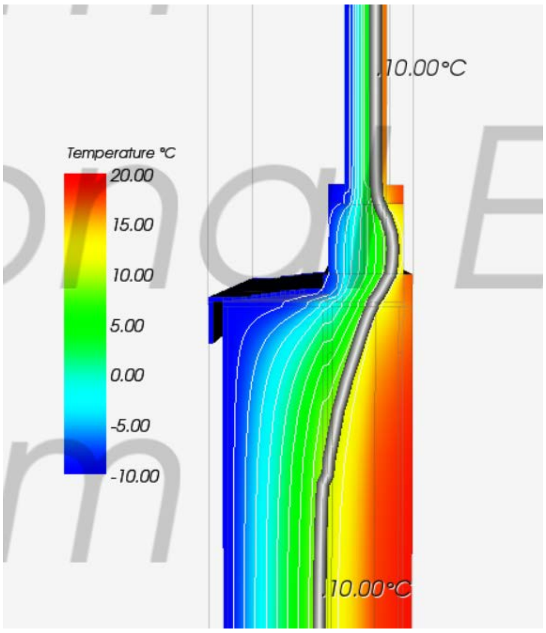
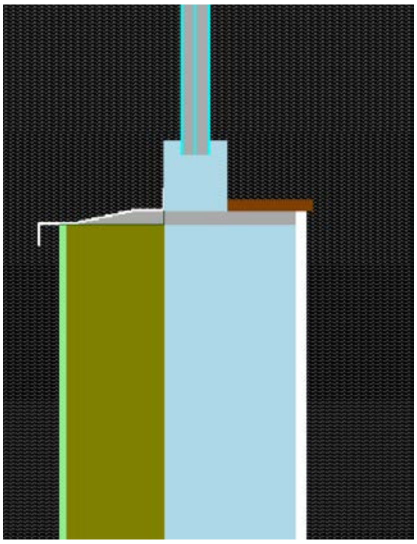
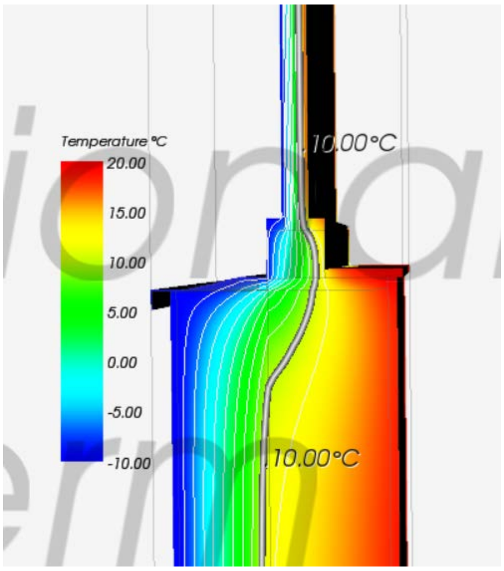
Wall system A - Window sill		
Simulation model	Temperature profile	
		
Output results		
ψ- value ($W.m^{-1}.K^{-1}$)	**θmin (°C)**	**fRsi (-)**
0,6617	12,33	0,74

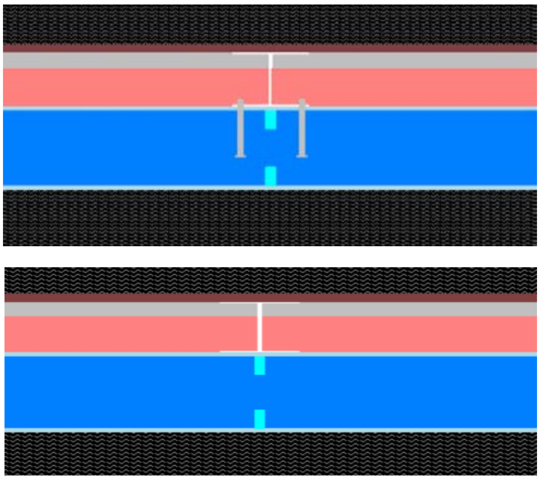
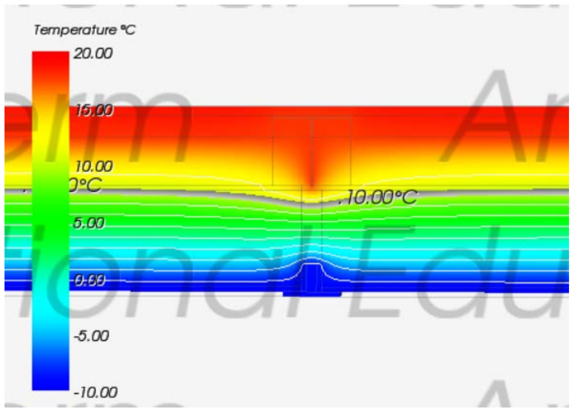
Table 26 Output results of a thermal bridge simulation - System B - window sill

Wall system B - Window sill		
Simulation model	**Temperature profile**	
		
Output results		
ψ- value (W.m^{-1}.K^{-1})	**Θmin (˚C)**	**fRsi (-)**
0,0682	12,96	0,77

A horizontal section of a vertical joint was modelled for the panel system (Table 27). This detail was modelled as a layered 3D project for the reason of modelling fastening screws in the middle. The point was to assess if there is a risk for condensation or mould growth in the critical area of the construction joint (the metal substructure behind the panels). Due to its position to the inside and a significant thermal conductivity, the metal structure conducts heat from the inside to the middle of the element. In this way the temperature rises and minimizes the influence of this thermal bridge. The f_{Rsi} value is more than satisfactory, 0,94.

Given the assumptions and connected uncertainties regarding boundary conditions (temperature, relative humidity, surface resistance coefficients), it seems that the constructions are rather well-thought in terms of surface condensation and mould-growth risk. However, more detailed assessment, for instance of the window details, should be considered if uncertainties regarding the used fenestrations remain.

Table 27 Output results of a thermal bridge simulation - System A – horizontal joint

<table>
<tr><td colspan="2">Wall system A - Window sill</td></tr>
<tr><td>Simulation model</td><td>Temperature profile</td></tr>
<tr><td></td><td>
</td></tr>
<tr><td colspan="2">Output results</td></tr>
<tr><td>Ѳmin
(˚C)</td><td>fRsi
(-)</td></tr>
<tr><td>18,11</td><td>0,94</td></tr>
</table>

5 CONCLUSION

5.1 Conclusions

This work attempts to provide appropriate envelope retrofit measures for a specific building stock, while simultaneously comparing two different wall improvement techniques. This includes an investigation of three main components that are most influential in the decision-making: energy consumption, economic evaluation and thermal bridge assessment.

Examining the thermal behaviour of the improvements, results have proven that most reductions in energy demand come from a whole envelope retrofit. Both retrofit systems have shown a great potential in improving the buildings thermal performants in the winter and in the summer period. An overall improvement with the panel system has demonstrated slightly better results in lowering the heating load - up to 58% of reduction, whereas the block system shows somewhat more positive impact on the cooling load (33 % cooling reduction compared to 30% with system A).

However, these positive effects on the building energy load do not completely correspond to the cost-benefit analysis. Calculating and comparing the return period and the net present value of the improvements has led to the conclusion that while some improvements show more energy reduction they do not necessarily mean they are economically justified. Improvement of the roof and floors shows the least energy savings but also require the smallest investment. This improvement has also resulted with a positive NPV and the smallest return period. On the other hand, the improvement with the biggest heating energy reduction (system A) has proven to be most uneconomical.

Moving on and assessing the thermal bridge parameters has demonstrated the eligibility of the proposed solutions. Two-dimensional sections of both systems were evaluated with a thermal bridge simulation tool which proved they can satisfy the minimum requirements set by the norms. Each of the simulated sections has resulted with a temperature factor greater than 0,71, therefore condensation and mould grow risks should be avoided if the details are performed in the proposed way. Considering the thermal transmittance via linear thermal bridges, system B resulted with slightly better results which is manifested, at the end, with a smaller heat transfer through this element.

Finally, it can be concluded that performing an envelope refurbishment of on unconventional building type is a very complex and variable process that is highly dependable on the choice of decision-making parameters. While entering the European Union, Croatia has obliged to follow the initiative in reducing energy consumption and environmental impact. With that, the Croatian government offered a program for promoting energy efficient renovations in dwellings with non-refundable grants up to 60 % of the whole project cost. This decision makes most invasive improvements much more obtainable and desirable to the occupants.

Even though this program is not long lasting, it plays a more important role in rising awareness among the planners and the investors in the importance of energy refurbishment. At the end, the target is to encourage a comprehensive and long-term effect on the society to live in a way that is less damaging to the environment.

5.2 Further research

Though there is a lot of research regarding energy refurbishment measures, there is a need for establishing general models for certain type of dwellings that can be applicable at the end. Due to the scope of this research, only most popular and promoted solutions were investigated for a certain building type. The next step would be investigating in green building solutions that could not only incorporate energy reductions but could also promote more environment friendly technologies in colder climates.

It would also be advisable to add an environmental footprint study to future research. Moreover, such a study could be broadened with a comparison of the environmental impact of one retrofit versus a new built construction of the same size.

Performing such convenient researches could potentially stimulate professionals in the field to start implementing more ecological measures.

LIST OF FIGURES

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6 REFERENCES

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