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Green Roof Systems as an Option for Residential Buildings in Novi Sad (Serbia)

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ZUSAMMENFASSUNG

Die Senkung des Energiebedarfs von Wohngebäuden ist häufig Gegenstand von Forschungarbeiten. Die Gebäudehülle - Wände und Dach – haben einen wesentlichen Einfluss auf der Berechnung der Energieeffizienz eines Gebäudes. In dieser Diplomarbeit wurde die Problematik von Flachdächern in Novi Sad, Serbien untersucht. Typische Wohngebäude, in zwei unterschiedlichen vorgefertigten Bauweisen, wurden ausgewählt und mittels thermischer Simulation analysiert. Die Leistung der Gebäudemodelle wurden im aktuellen Bauzustand und mit unterschiedlichen Sanierungsszenarien simuliert, die gewonnenen Ergebnisse im Anschluss beurteilt und verglichen. Ziel der Arbeit war, die Annahme zu überprüfen, dass ein Gründach-System bessere Ergebnisse im Vergleich zu herkömmlichen Lösungen bei der Sanierung von Flachdächern erzielt. Um die Leistung von Gründächern zu evaluieren wurden zwei weitere Dachtypen untersucht: In einem Szenario wurde die Annahme getroffen, dass das Dach mit konventionellen Materialien gedämmt und saniert wurde. Zusätzlich wurden Kühllast und Überhitzung auch am Beispiel eines „Cool Roofs“ untersucht. Die Ergebnisse zeigen, dass Gründächer das Potenzial haben, die thermische Leistungsfähigkeit eines Gebäudes zu verbessern, obwohl es keine wesentliche Unterschiede zwischen den erhaltenen Ergebnissen mit Gründach und konventionell saniertem Dach gab. Trotzdem sollte hierbei berücksichtigt werden, dass Gründächer noch andere positive Einflüsse und Synergieeffekte für die Bewohner, das Gebäude und den urbanen Raum bewirken können.

Schlagwörter:

Gründach, EnergyPlus, Simulation, Novi Sad, Sanierung, Thermische Behaglichkeit

ABSTRACT

Reduction of energy demand in residential buildings is an issue of permanent research interest. Every building component has a role in the energy performance of a whole building, especially the building envelope - walls and roof. The problem related to flat roofs in Novi Sad, Serbia is recognized and will be addressed in this thesis. Typical residential buildings built in two prefabricated systems were selected and analyzed using a simulation tool - EnergyPlus. Models were simulated in the original and post refurbishment state, followed by an evaluation and comparison of obtained results. The aim of the thesis was to verify the assumption that the green roof system can be a better measure for the refurbishment of flat roofs in Novi Sad in terms of energy efficiency, as well as in the sense of architecture, than currently offered options. In the interest of obtaining unbiased, applicable and comparable results of green roof performance, another two roof types were additionally simulated. These are a refurbished roof with new thermal insulation, that was analyzed for both heating and cooling performance, and a white roof without insulation, that was analyzed only for its cooling performance. Furthermore, the performance of a green roof depending on the building type was analyzed. Final results showed that green roofs have the potential for improving a building's thermal performance, although there was no substantial difference between results obtained in a case of green and refurbished roof. However, other advantages of a green roof, that were outlined in the thesis, can outweigh in its favour when choosing the option for retrofit.

Keywords:

green roof, refurbishment, simulation, EnergyPlus, sustainability, thermal comfort, Novi Sad, prefabrication

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ABBREVATIONS

ACH	Air changes per hour
ECS	Energy Community Secretariat
EP	Energy Plus
EPS	Expanded polystyrene
ER	Existing roof
GR	Green roof
LAI	Leaf area index
PUC	Public utility company
RR	Refurbished roof
WR	White roof
XPS	Extruded polystyrene

NOMENCLATURE

c	Specific heat capacity [J.kg^{-1}.K^{-1}]
d	Thickness [m]
l	Length [m]
U	Thermal transmittance value [W.m^{-2}.K^{-1}]
T	Temperature [°C]
λ	Thermal conductivity [W.m^{-1}.K^{-1}]
ρ	Density [kg.m^{-3}]

1 INTRODUCTION

1.1 Objectives

Energy costs have been increasing constantly in previous years as well as awareness of the importance of sustainable and green architecture. New buildings are being built according to the new regulations for the energy performance of buildings, but a vast number of existing buildings, especially in developing countries, needs to be refurbished in order to be able to comply with the current local requirements. In these countries, a major amount of energy in built environment is mostly used for heating and cooling purposes, especially in residential buildings. According to the data acquired from International Energy Agency (IEA 2013), 33% of total final consumption of energy in Serbia is in the residential sector. While in Austria, this sector consumes 23% of energy. Therefore, proper thermal insulation of the envelope is the most important measure for reduction of the energy demand.

1.2 Motivation

The majority of the residential buildings in current building stock in Serbia were constructed more than 30 years ago, and during this time most of the objects have become dilapidated and refurbishment has become necessary (Laban 2012). Flat roofs are part of the buildings that are particularly in poor condition (Figure 1). This causes lack of indoor thermal comfort, which is most prevalent on the top floor. Extra energy is spent on heating in winter months and on cooling during the summer. Besides the poor thermal insulation, there are problems concerning the waterproofing, especially in the time when snow is melting. Energy Community has done a report on energy efficiency in buildings in contracting parties of the energy community where they have evaluated the cost effective energy savings potentials for various building typology. As it can be seen in the Table 1 insulation of the roof is one of the most important measures for residential buildings in Serbia (ECS 2012).

Table 1 - Cost effective energy savings potential apartment buildings (Serbia), according to Energy Community

Apartment buildings			**Savings**		**Investment**
Rank	**Measures**		*kWh/m²a*	*€/m²a*	*€/m²*
1	Energy efficient lighting		23.5	1.4	13.95
2	Insulation of roof				
3	Insulation of external walls				
4	Solar heaters for DHW				
Building stock area	**69 000 000**	*m²*	*MWh/a*	*€*	*€*
Total savings	**21**	%	**1 622 850**	**95 332 000**	**962 559 200**

Deterioration due to poor maintenance over a long period of time is visible on many roofs (Figure 1). Public Utility Company ''Stan'' (Novi Sad) has offered three solutions to these problems: construction of lightweight roofing, building rooftop extensions or setting up of new insulation and waterproofing (Ravic *Vecernje Novosti* 2012). Rooftop extension (Figure 2) appears to be the most popular measure among architects, though this approach tends to transform the whole structure of a building and the neighbouring area in the sense of architecture, function and construction (Kuzmanov 2009).

Figure 1 - Natural "green roof" due to poor maintenance

Figure 2 - Rooftop extension

The aim of this thesis is to add one more solution for the flat roof problematic in Novi Sad - green roofs. Even though benefits of green roofs are widely known and are being used throughout the world, in Serbia they are still very rare. Green roofs are providing insulation, absorbing the rainwater, but also have a positive impact on the urban surrounding. Vegetation on the roof through daily dew and evaporation cycle helps lowering urban air temperature and reducing the urban heat island effect (Gartland 2009). Through shading and evaporation, green roof surfaces are cooler than conventional rooftops during summer and thus contribute to cooler indoor environment. Soil that is necessary for the growth of vegetation is a thermal mass and, therefore, has insulating characteristics. As heat loss through the roof is lower, this reduces the energy heating demand. Nichaou et al. (2001) did a study on thermal properties of the green roof. Their results showed that annual savings for heating and cooling are substantial for poorly insulated building with a green roof, while for a well insulated building annual saving is very small.

2 BACKGROUND

During the period of intensive construction in 1960-s, 70-s and 80-s residential buildings were being built throughout former Yugoslavia. These buildings were designed in the style of socialist modernism. Simple cubic shapes and prefabricated construction elements mostly made of pre-stressed concrete are distinguishing features of this architecture (Perovic 2008). Flat roofs, that are one of the characteristics of international style and modern movement, were the most common type of roof for those buildings even though they are not the most suitable option for a temperate continental climate with cold, snowy winters and hot summers. Buildings from the early period were built according to the regulations that did not consider energy-saving measures and, therefore, have no or poor thermal insulation. After the maximum U-values were defined in the building regulation, thermal performance of facade elements was always in accordance with the current codes applied at the time of the construction of the building (Laban, Folic 2014).

Issues concerning flat roofs exist in a lot of places in Serbia, but this thesis will focus on Novi Sad (Figure 3) where more than 450 buildings have this type of roof and numerous problems related to leaking and thermal comfort were recorded (PUC "Stan").

Figure 3 - Flat roofs of Novi Sad

Studies on prefabricated residential buildings in Serbia have mostly dealt with the condition of facade elements. Thermal properties of facades and their influence on the energy efficiency of the building were the topic of few studies done by Laban and Folic (2011, 2012, 2014). Retrofit of the industrially built residential buildings or the whole urban blocks built this way is a common topic of many student projects or papers. Kuzmanov (2009) analyzed the reasons for constructing rooftop extensions and their impact on the building and neighbouring area in an architectural and structural sense. However, no studies on roof conditions and their influence on thermal performances of the building have been encountered.

Green roofs and their benefits are the topic of numerous studies. Columbia University researched and quantified the environmental effect, economic benefits and costs of green roof adoption in New York City (Rosenzweig et al. 2006). Another study was an experimental study of different vegetation types and growth media and their impact on energy savings (Celik et al. 2011). Green roofs were proposed as a tool for solving the problem of rainwater runoff in the paper that analyzed measurements reported in 18 publications (Mentens et al. 2005).

2.1 Green Roofs

Green roof is a roof that is partially or completely covered with vegetation. Different terms are being used to describe this type of roof. *Bioroof* or *living roof* suggests that the roof creates a living environment, not just for plants, but also for some species of birds and insects. The term *ecoroof* is being used to refer to economic and ecological benefits of green roofs, such as energy savings, pollution reductions or increasing the lifespan of a roof. Green roofs with a high percentage of recycled products are often called *brown roofs* (e.g., Cantor 2008, Dunnet, Kingsbury 2008, Sekulic 2013, The green Roof Portal 2016)

2.1.1 History of Green Roofs

From the Hanging Gardens of Babylon to *Bosco Verticale* (Vertical Forest) in Milan (Figure 4 and Figure 5), green roofs existed in one or another form throughout human history. They were developing independently in different parts of the world and they have been a feature of the vernacular architecture for centuries. The climate had great influence on shape and composition of these grass roofs. The concept of roof greening originated in Mesopotamia. In this region flat roofs were the most common type of roof and roof gardens were planted in order to cool hot landscape. Other ancient cultures - Persians, Greeks, Romans, that lived in similar climatic conditions, also used green roofs for local structures. The most famous of the green roofs from this time are Hanging Gardens of Babylon that were one of the 7 Wonders of the ancient world.

Figure 4 - Hanging Gardens of Babylon

Figure 5 - Bosco Verticale in Milan, Italy (photo: Wikimedia)

At the other climatic extreme, in Scandinavia, sod roofs provided thermal insulation in cold climates (Figure 6). They were constructed on pitched roofs and besides protection from the cold, they were built to manage rainwater runoff. Applied materials were turf grass for covering and layers of birch bark and straw or twigs placed over closely fitting wooden boards. Construction of these roofs in some way has similarities with the modern extensive roof. Traditional sod roofs still exist and are being used in Scandinavian countries, but mainly for aesthetic reasons.

Vegetated pitched roofs, sod, peat or thatch, have been part of traditional architecture in other European countries as well. They were used because of good insulation characteristics. Thatch roofs, for instance, are common vernacular materials in Ireland, Germany, The Netherlands and other countries. Traditional houses in Serbia, the country that is a subject of this research, have always had a double-pitched roof or hipped roof. In the northern region, where Novi Sad is located, houses were mostly built of rammed earth. The roof was double-pitched and covered with straw or reed. Some of the houses with thatch roof still exist in Novi Sad (Figure 7) and other places in northern Serbia.

Figure 6 - Sod roof houses in Norway (Photo by: Bård Larsen)

Figure 7- House with thatch roof in Novi Sad

History of modern green roofs dates back to Germany of the 19th century. Samuel Häusler invented new material for roof insulation in 1839 - few layers of cardboard soaked in tar covered with a layer of gravel, sand and soil. Häusler named this material *Holzzement* (wooden cement). The soil was used on flat roofs to protect roof membrane from exposure to fires. In the second half of 19th century, modern concept of green roofs appeared thanks to the development of reinforced concrete and new architectural styles. Planted concrete "natural roof" was a part of the World Exhibition in Paris in 1868. The beginning of the 20th century brought several similar experimental projects. Auguste Perret placed a roof garden at the top of the Rue Franklin apartments in Paris in 1903, in 1914 Frank Lloyd Wright designed a restaurant with a roof garden in Chicago. Similar project was done in Cologne by

Walter Gropius. One of the Le Corbusier's "Five Points of a New Architecture" was dedicated to roof gardens. For him, roof gardens could become a most favoured place in the building. Flat roofs would be used for domestic purposes, while soil and vegetation would protect reinforced concrete from changing temperatures.

The first modern green roof systems were developed in Germany in the 1960s and 1970s. For the first time technology that provided advanced irrigation system and root barriers was offered. In Germany and Switzerland, experiments were carried out concerning the new ways of integrating plants with houses that were built on a steep gradient. These houses where the roof of the lower building is the garden of the upper are called *Terrasenhäuser*. Similar technology was used for covering and greening of underground garages. The designs of Friedensreich Hundertwasser emphasised the importance of nature, and roof gardens were an essential part of his buildings. Like Le Corbusier, he believed that by planting the green roof we are giving back to nature what we took from it for the construction of a building. One of his most famous works is Hundertwasserhaus in Vienna, constructed between 1983 and 1985, with 900 tons of soil and 250 trees and shrubs (Dunnet, Kingsbury 2008).

The greening of walls and roofs was, in the beginning, the idea of environmentalist movement and the counter-culture, but soon it was taken up by the mainstream society. Green roofs became the subject of numerous scientific researches and economic evaluation. Green roof study group within the FLL (*Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau* - The Landscape Research, Development & Construction Society) was founded in 1977 and it was an important step in the development of green roofs. In the mid-1970s, the distinction between the extensive and intensive green roof was formulated and extensive roof greening has been the focus of most research since then. Development of the extensive green roofs started in the late eighties with the idea of creation of green roof system that can be applied to larger flat roofs. Together with research works on the topic of green roofs benefits, companies began to offer specialist roof-greening services and concept of greening roofs became more and more accepted.

Green roofs are now being planted in many parts of the world. By 2001 in Germany approximately 14% of all flat roofs, or more than 13.5 million square meters had been greened. Switzerland requires that 25% of new commercial development must be greened (Snodgrass 2006). Green roofs are implemented for different reasons in different countries, from solving environmental problems and economic reasons to the tradition and feeling of national heritage. No matter what are the reasons for its construction, any green roof has a net positive impact on its surroundings.

2.1.2 Types of Green Roofs

According to the type of greening and level of maintenance, green roofs can be classified into two main categories: intensive and extensive green roofs.

Intensive green roofs (Figure 8) are also called roof gardens because it is expected that they would be used in the same way as a conventional garden. For this type of green roof, a thicker layer of the substrate is needed, at least 15cm deep. Vegetation on the intensive green roof requires the same amount of maintenance as in a garden at ground level. The thickness of vegetation medium and maintenance of the plants increases the total weight and cost of the roof.

Extensive green roofs (Figure 9) are not intended for regular human usage. Maintenance is minimal and growing medium is relatively thin: between 2 and 15cm. The load on the supporting structure is significantly lower than the one of the intensive roof, hence, the extensive roofs are more often an option for existing objects. Since they are not meant to be used and maintained as traditional gardens, vegetation on extensive roof differs from the one that can be seen on ground level.

Figure 8 - Intensive green roof (photo: http://www.greenroofs.com/)

Figure 9 - Extensive green roof (photo: www.sftool.gov)

Apart from the two main types of green roofs, there are also variants between those two types. Elements of both types can be combined on the same roof. Semi-extensive green roofs are lightweight and have environmental benefits as extensive green roofs, but at the same time, they have the aesthetic potential of intensive green roofs and enable a wider range of vegetation to be grown. They are intended for human use, but paths and gathering spaces are incorporated only where underlying building structure allows. Dunnett and

Kingsbury claim that the future of green roofs lays within the concept of a hybrid roof model, where the best elements of all traditions are combined to create sustainable rooftop environments in all contexts (Dunnett, Kingsbury 2008).

2.1.3 Green Roof Layers

The main layers of a roof are: vegetation, growing medium, filter layer, drainage layer, waterproofing and roof slab. Depending on a type of a green roof and a building, additional layers - thermal insulation, root barrier, erosion control blanket, stabilization mat and others can be included.

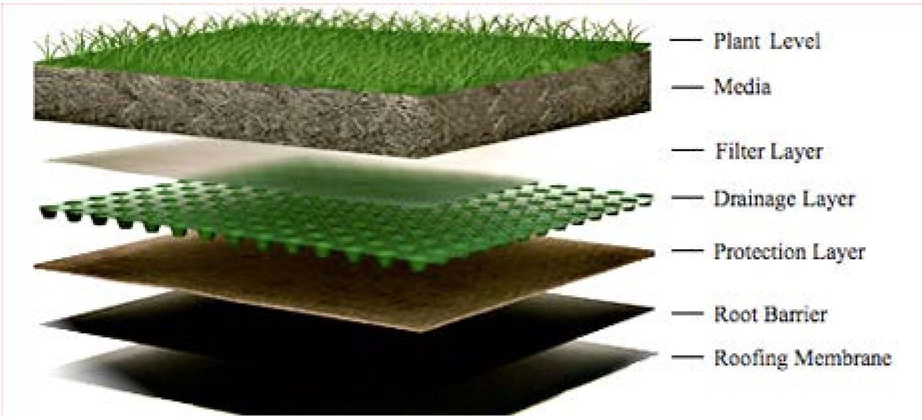

Figure 10 - Green roof layers (photo: www.godfreyroofing.com)

Vegetation Layer

Rooftop garden and traditional garden have very little in common. Weather elements have more impact on the roofs; the soil is lightweight, inorganic medium; green roofs, especially extensive ones, are in most cases non-irrigated - because of these reasons, choice of plant species is very important. By necessity, green roof plants must be more resilient than plants found in most gardens. Only some species can grow on a rooftop because of the harsh conditions, and selected plants need to be capable of growing in local climate. They should be long-living, less nutrient-reliant and have minimal maintenance requirements. Vegetation on the roof is not uniform, it is a mixture of different species. In this mixture vegetation that can grow fast, form new plants from the root and spread easily should be present. In general terms, the most successful green roof plants are low-growing, shallow-rooted perennial plants that are heat, cold, sun, wind, drought, salt, insect and disease tolerant

(Snodgrass 2006). Evergreen plants should be part of the mixture, in order to have a green roof that will be functional throughout the whole year. There is always a possibility that some of the selected species will not survive, hence a variety of plants will ensure diversity on the green roof. The diversity of species will also give protection against infestations and diseases. Low-growing plants that can form a groundcover, in temperate regions those are usually sedum mixtures, need to be predominant while other types of plants should be used as accents. Selection of plants for the green roof depends on various factors such as climate, thickness and composition of a substrate, maintenance, etc. The most common plants used for green roofs are: perennial plants, grasses, herbs, succulent plants, geophytes, shrubs, clambering plants.

Perennial plants are the plants that live more than two years. During the autumn and winter they die, but in spring they can regenerate from their root-stock. Perennials need minimum 10 cm of growing medium and irrigation. When choosing perennials for a green roof, it needs to be taken into account that while they expand in biomass, they also increase roof load by 10 to 25 kilograms per square meter (Snodgrass 2006). There are a lot of species of different colours, heights and shapes, so it is possible to achieve wider palette of plant material with the requisite accommodations. Some of the species that can be used are from the genera: *Petrorhagia, Dianthus, Phlox, Campanula, Teucreum, Allium, Potentilla, Achillea, Prunella, Viola, Origanum* and other low-growing, shallow-rooted perennials.

Succulent plants are the type of plants that are most common on green roofs. They have thick leaves and can survive longer dry periods. Another reason for being a popular type of green roof plant is the thickness of growing medium. Succulents can grow in a medium that is less than 10cm thick. Sometimes they are the only choice if a green roof is non-irrigated and with the thin substrate. Most commonly used species are from the genera *Sedum, Sempervivum* and *Jovibarba.*

Besides their minimal requirements, *Sedums* are favourable for green roofs because of visual effect (Figure 11). They have a wide variety of bloom and leaf colour and textures. Sedums are generally perennials, but under extreme stress, they can act as annuals. They would use all of their energy to produce viable seed for survival. These plants are non-invasive, and can create habitat for insects and birds.

Sempervivum and *Jovibarba* are characterized by dense basal rosettes and are usually used as accents as they are relatively slow growing. They are an excellent choice for roofs where conditions are harsh since they are extremely drought tolerant and nutrient tolerant. Plants from both of these genera are commonly called houseleek, hen and chick, or live forever

(Figure 12). In Serbian, they are called *čuvarkuća* (house guardian) and there is a folk belief that they keep home safe from thunderstruck, illness and other misfortunes. This can be one more advantage for choosing a green roof when retrofitting flat roofs in Novi Sad.

Figure 11 - Sedums on extensive green roof (photo: www.green-roofing.co.uk)

Figure 12 - Sempervivum tectorum or houseleek (photo: Charles Brun www.gobotany.newenglandwild.org)

<u>Geophytes</u> are not widely used on green roofs. This type of plants has underground storage organ (tuberous root, stem tuber, rhizome, corm) specifically modified for storage of energy or water. Storage organs can act as perennating organs and enable plants to survive adverse conditions. These plants need deep growing medium and plenty of water in spring. Because of these reasons, only limited number of geophytes can be used on green roofs, but just in areas with wet and cold spring seasons.

<u>Grasses</u> are still new to green roofs, they require mowing and deeper medium to accommodate their root systems. When calculating the load of the roof, it needs to be considered that grasses can attain larger biomass, that can also pose a fire hazard during winter dormancy or dry summer months. Even though grasses are not colourful bloomers, they add to aesthetics of the roof by motion and texture. They can create habitat for birds and insects. Some of the species that can be used on green roofs belong to genera: *Andropogon, Bouteloua, Carex, Sesleria, Sporobulus.*

<u>Herbs</u> (culinary and medical) are important for private, hospital or restaurant roof gardens. Herbs can grow in 10cm deep growing medium and once established, many species are drought tolerant. However, until they develop, it is necessary that they are watered often.

Shrubs, small trees and clambering plants should have a root system that is not aggressive when they are used for rooftop garden.

Growing Medium (Substrate)

As previously mentioned, rooftop gardens and traditional gardens have very little in common. The same can be said for growing medium and garden soil. The first difference can be noticed in terminology. Plant growth medium should be referred to as substrate, rather than soil or topsoil. Unlike topsoil, which is rich in nutrients and organic matter that are prone to decomposing, substrate consists of primarily inorganic materials, that will not decompose over time. Growing medium or substrate has a rough texture and it is made of large particles. It usually contains 80% of lightweight mineral aggregate (crushed bricks, aircrete and fired clay pellets, expanded clay, expanded slate, expanded shale, volcanic pumice, scoria...) In order to provide initial nutrients, so that plants can develop, a small percent of organic materials can be added, but these additives will not be replenished over time. One of the reasons why green roof substrate is mainly composed of inorganic materials is because a highly organic medium adds weight to the roof structure. Another reason is decomposition of organic content over time which is why the surface level of the substrate recedes, and the vertical integrity is not maintained. Clogging of the filter fabric and the drainage layer could also be potential problems that high organic content may cause. In order to provide good drainage, and at the same time retain sufficient moisture for the plants, green roof substrate needs to be porous. Lightweight and porous medium holds water and oxygen and also absorbs and retains nutrients, and that provides some stability for the plants' root systems. Growing medium should be weed free, or some species are welcome as long as their roots do not penetrate the root barrier, or their cumulative weight does not exceed the limits of the structural design. In addition to above-mentioned characteristics, growing medium needs to have a long-term lifespan, so that the return on investment is maximized. Composition and thickness of substrate depend on many factors, such as type of plants, load carrying capacity of roof structure, maintenance, local climate.

Filter Layer and Drainage and Water Retention Layer

Filter layer is a type of synthetic fabric that separates the bottom of growing medium from a drainage layer and it keeps fine substrate particles from being washed out to the drainage layer. It is important element because it prevents clogging and water build-up that can damage the plants or stress the structure of the roof. Filter layer should be resistant to chemicals, rotting, microorganisms, pests. It is made of polypropylene and polyester fibres and weighs 200-500 gr/m^2.

Drainage layer should provide adequate flow of excess water, that is not absorbed by the plants and the growing medium, off the roof. It should also retain some of the excess water and ensure that it can be used by plants during dry periods. The drainage layer is usually made of high-density polyethylene in the form of plastic sheets with recesses or cups on the upper surface to capture and store water. Since the flat roofs are especially vulnerable to standing water, proper drainage is a necessity. Excess water that is not properly drained will not just damage roof's membrane, but it will do harm to the health of the plants as well.

Waterproofing and Root Protection Layer

Correct application of a waterproofing layer is essential to the viability of any roof. Common materials used for the waterproof membrane are polymer modified bitumen, thermoplastics, EPDM rubber, liquid applied polyurethane.

Root barrier is needed in order to prevent roots from penetrating into the waterproofing and thus causing leaks. It can be a separate layer or integrated into other layers, usually waterproofing. Some of the root protections used for this purpose are thermoplastic membranes, copper foil or root-retardant chemicals.

Insulation

Installation of an insulation layer underneath the root barrier depends on the climate. When it is installed, it needs to be lightweight but it should have great compressive strength, so it can endure the weight of materials above it. Materials that are most commonly used for insulation are extruded polystyrene and polyisocyanurate.

2.1.4 Advantages of Green Roofs

Green roofs can offer a wide range of benefits, from environmental and financial to aesthetical. Advantages provided by a green roof are not strictly attached to a building on which the green roof is installed on. This type of roof can affect the urban surroundings as well. Multiple goals that green roofs accomplish simultaneously are described in the next few pages.

Storm water management - Water cannot be absorbed on hard, impervious surfaces in urban areas and it directly runs off, through drainage systems, into rivers. In the event of a heavy storm, drainage systems may not be capable of accepting the amount of water and the flooding can occur. Significant quantities of rainfall can be absorbed by the plant materials, substrate and the drainage layer in a green roof. Apart from absorbing the water and in that way reducing the amount available for runoff, a green roof is also storing water for a period before it runs off (Figure 13). Delay in water draining from the roof evens out the peaks of heavy rainfall and, as a result, the drainage system has to deal with moderately increased flow over relatively long periods instead of extremely increased flow over short periods (Mentens et al. 2006).

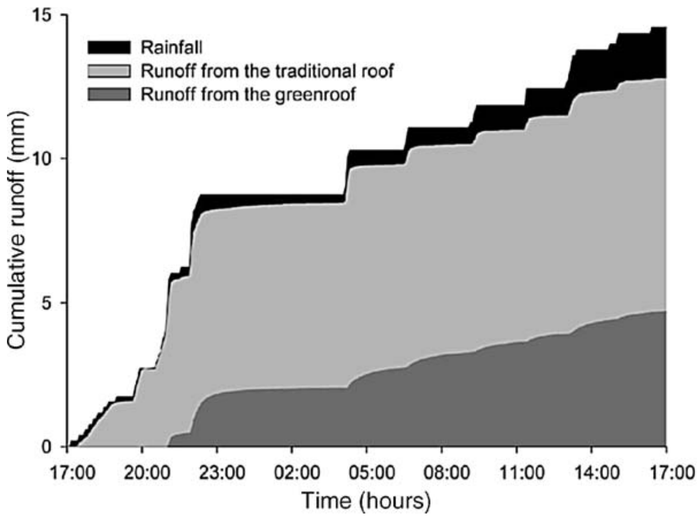

Figure 13 - Typical cumulative runoff from a non-greened roof and an extensive green roof as observed in Leuven (Belgium) during the 24 h period of a 14.6mm rain shower (April 2003, 5 p.m.–5 p.m. on the next day). Both roofs had a slope of 20◦. Mentens et al. 2006)

However, it needs to be noted that a significant effect cannot be achieved by a single green roof. The combined impact of a whole series of green roofs within the watershed of a storm drainage system would be needed to achieve a considerable effect (Cantor 2008).

Mitigation of the urban heat island - Green roofs have a beneficial effect not only on an individual building but on the whole urban environment. Air temperatures in urban areas can be several degrees higher than in surrounding suburban areas or in the countryside (Gartland 2008). The built environment, particularly dark-coloured materials absorb heat during the day and release it at night. Waste heat generated from vehicles and air conditioners and lack of vegetation add to the formation of a specific urban climate, that is characterized by polluted air, higher night-time temperatures, increased humidity. Rooftops contribute in significant percentage to non-vegetated, heat-reflective surfaces in the urban areas. Green roofs, as a collective design element, can impact the urban heat island effect. Vegetation in the city creates favourable microclimates and uses heat energy in the process of evapotranspiration, thereby achieving a general cooling effect.

Acoustical insulation - Due to the thickness of the entire installation, green roof acts as an acoustical barrier and attenuates sound inside a building. Vegetation and substrate of a green roof can absorb sound in contrast to hard surfaces of urban areas that tend to reflect it. The substrate can block lower sound frequencies and plants higher ones. Noise reduction is of a great benefit to occupants of buildings that are located near to high traffic roads, trains or industry.

Improved thermal performance - Green roof can improve the thermal performance of a building in few different ways. First of all, the thickness and insulation properties, as well as some degree of resistance in energy transmission, of the soil, help to reduce the value of thermal transmittance coefficient of the entire installation. Other properties of a green roof are also helping to obtain better thermal comfort. In summer, a combination of soil processes (evapo-transmission) and plant processes (photosynthesis and evapotranspiration) reduces the amount of solar energy absorbed by the roof membrane. While in winter, root activity of plants, air layers and the totality of the specific system create heat and in that way provide an insulation membrane.

Filtering - Urban air pollution is associated with increased respiratory disease and breathing difficulties. Vegetation on a green roof can trap particles of dust and soot from the air that would otherwise be inhaled by the people. Fine airborne particles are settling onto leaf and stem surfaces, as the air passes over the plants, and later they are being washed off into the soil. Vegetation is also able to absorb gaseous pollutants, sequestering the material in their tissues.

Reduction in carbon dioxide - It is well known that plants, during the process of photosynthesis, use carbon dioxide from the air and release oxygen as a waste product. Based on this knowledge it can be deduced that the more vegetation there is, the greater the potential to reduce the amount of carbon dioxide in the air. But, green roofs are reducing the amount of carbon dioxide in an indirect way as well. The combustion of fossil fuels, that are used for heating, generates large amounts of CO_2. Since green roofs have good thermal insulating characteristics, the heating demand, and thus the CO_2 generation, is mitigated.

Aesthetics - Green roof can add to the visual aesthetics of the city when it is visible from many vantage points. Depending on the viewing perspectives, different visual effects, from naturalistic meadows to geometric plans, can be designed. Green roofs can also add to the enjoyment of the property if they are accessible to the public or private owners.

Economic benefits - The initial cost of a green roof is higher than that of a conventional roof, but green roof can be seen as an investment and in many cases it pays off over time. A green roof covers the roofing membrane with series of layers and hence protects it from direct exposure to elements, extreme temperature fluctuations and ultraviolet radiation and in that way prolongs its life. Another major economic benefit is reduction of energy demand for heating and air conditioning. Since the developable land is becoming scarcer, green roofs will be an increasingly viable economic choice. Considering all the benefits that green roof can offer, application of a green roof on an existing building can increase its value, which is yet another economic benefit.

Habitat restoration - Rooftop meadows, as green roofs are sometimes referred to, are creating new habitats for plants, insects, and birds. They recover the area taken for construction of a building, establishing the connection to nature. Green roofs, especially extensive, and traditional gardens are quite different, plants that are usually not grown on a ground level are developing on green roofs. Extensive green roofs are good undisturbed habitat since they are isolated from people and vegetation encounters less interference than an equivalent area at the ground level. Vegetation on the green roof is mostly a mixture of different species and that is increasing biodiversity. Indigenous species, that are highly resistant to damage from climate, local disease, insects and animals can be part of the mixture if they are able to adapt to unique green roof environment and medium type and depth. Sometimes roofs are encouraged to colonize with spontaneous plant communities.

2.1.5 Disadvantages of Green Roofs

Green roofs offer a wide range of benefits, some of which were described in the previous chapter. However, there are a number of disadvantages that also need to be considered.

Increased maintenance - Green roofs can be designed for minimal maintenance, but not for no maintenance. The maintenance of a roof is crucial in the first few years when the vegetation layer is developing. Intensive green roofs require the same amount of maintenance as a garden on a ground level. Feeding, irrigation, weeding needs to be done regularly. Extensive roofs require less maintenance after the vegetation is developed. Similar to traditional flat roofs, inspections are needed at least once a year. Aside from the plants, other layers of a roof also need to be maintained. Proper drainage needs to be provided since flat roofs are especially vulnerable to standing water

High initial cost - The construction of a green roof is more expensive than the construction of a traditional flat roof. The cost of an intensive green roof for is higher, due to its complexity. The weight of the roof material can cause higher costs for the roof structure. The long-term lifespan of a green roof is essential in order to maximize the return on investment.

Structural limitations - When constructing a green roof, especially in a case of an existing building, structural limitations need to be taken into account. Green roof substrate and vegetation are increasing roof load and additional structural support may be needed. If a green roof is installed on a sloped roof, extra erosion control techniques should be used. The structural limitations are more related to intensive green roofs.

Limited choice of plants - Harsh conditions on the rooftop are not acceptable for many plant species. The soil is lightweight, inorganic medium and weather elements have more impact on the roofs. Extensive green roofs can only accommodate drought-tolerant plants that are less nutrient-reliant and have minimal maintenance requirements. It is also important that plants have a shallow root system that cannot penetrate into the waterproofing and cause leaks.

Aesthetics - Aesthetic values of a green roof can sometimes be negative. If the green roof is not designed and planned correctly, the final visual effect can be of a low aesthetic value. Improper maintenance can result in overgrown and wild look.

2.2 White Roofs

Roofs that have higher solar reflectivity in comparison to conventional roof materials are commonly referred to as white roofs or cool roofs. Material that is used as a top layer of a white roof reflects the solar radiation and at the same time releases the absorbed heat (European Cool Roof Council 2016). The top layer of a white roof can be a lighter colour roof tile (Figure 14) or a white roof coating (Figure 15) that can be added over an existing roof. Main benefits of white roofs are mostly connected to the cooling load reduction. White roof can keep the internal temperature of the building lower due to a cooler roof surface, thus reducing the cooling load during the summer. Apart from the beneficial effect for the building they are installed on, white roofs can moderate the air temperature surrounding a building and as a result mitigate the urban heat island effect (Hosseini, Akbari 2016).

Figure 14 - White roof tiles (photo: http://www.tettogresusa.com/)

Figure 15 - White roof coating (photo: http://www.nationalcoatings.com/)

2.3 Prefabricated Building Types in Novi Sad

2.3.1 History of Novi Sad

Novi Sad is located in northern part of Serbia, on the 1255th kilometre of the Danube river. Its coordinates are 45° 15’ N and 19° 50’ E. This area was populated since the prehistoric times, many archaeological sites from different eras are witnesses of it. Evidence of the first human settlements trace back to the Neolithic era (about 4500 BC). Throughout the history, this region was conquered and inhabited by Celts, Romans, Huns, Byzantines, Ostrogoths, Avars, Ottomans... The modern history of Novi Sad begins in 1692 when the construction of fortress was started on the Petrovaradin rock. Because of the construction of the fortress (Figure 16), a significant number of soldiers and civilians (mostly craftsmen and merchants) are inhabiting this territory. Part of them are settling on the left bank of Danube and they are the first people that are founding present-day Novi Sad. The names used for the settlement in that time were Racko Selo (ger: *Ratzen Stadt*) that can be translated as *Serbian Village* and Petrovaradinski Šanac (ger: *Peterwardein Schantz*, eng: *Petrovaradin Trench*). In the year 1748 citizens acquired the status of a Free royal city from the empress Maria Theresa, after paying a buy-off amount of 80000 Forint. With the edict that made Novi Sad a free royal city, it got its name in official languages of Austro-Hungarian monarchy: in Latin *Neoplantae*, in German *Ney-Satz* (later *Neusatz*) and in Hungarian *Uj-vidégh* (later *Újvidék*). On the day of the declaration, the town had 4620 residents (Srbulovic 2000).

Figure 16 - Petrovaradin fortress

Figure 17 - Central square of Novi Sad

In the early period of Novi Sad the core of the city was formed, the city centre and the surrounding streets that continued to exist until today (Figure 17). This part of the city was fully formed until 1748 when Novi Sad becomes Free royal city. During the next period, the city is growing and the new districts - Rotkvarija, Salajka, Grbavica are appearing. At the end of XIX century new district named Telep originated. New districts after the World War I are growing (old Detelinara, Little Liman, Banatic, Sajmiste etc.). After the World War II new city blocks are growing rapidly - Big Liman, New Detelinara, Bistrica, the block next to the train station...

Today, Novi Sad is the biggest city and administrative centre of Autonomous Province Vojvodina, the northern province of Serbia. Through history, it was the centre of the cultural, political and social life of the Serbian nation and thus it was called "Serbian Athens". According to 2011 census, city of Novi Sad has 341 625 residents.

2.3.2 Novi Sad Climate

Novi Sad has a temperate continental climate, all four seasons are clearly present. Winter is cold, but not too severe. On average there are 25 days of snowfall and an average of 22 days of complete sub-zero temperatures. The coldest month is January with an average temperature of -1,9°C. The coldest temperature ever recorded was -30.7°C on January 24th 1963. Summer in Novi Sad is usually hot and dry, the hottest temperature ever recorded was 41.6°C on July 24th 2007. The cold eastern-southeastern wind, named Košava, is characteristic of the local climate. It blows from the Carpathians with the average speed of 25 to 43 km/h with strokes that can reach up to 130 km/h, usually lasts three to seven days and brings clear and dry weather. The average annual rainfall is 576.8mm.

Weather data for Novi Sad, needed for EnergyPlus (NREL 2013) simulation, was acquired using Meteonorm (Meteotest 2012) software which offers access to accurate data of weather parameters for any location on the Earth. The data acquired from 8325 meteorological stations is supplemented by surface data from five geostationary satellites. The stations submit monthly values from which hourly values are calculated using a stochastic model. Meteonorm used time period 2000-2009 for temperature, humidity, precipitation and wind speed while for the solar radiation the period 1991-2010 was used. Temperature and radiation data were obtained with the standard model and the Perez model was used for tilt radiation.

Temperature - In temperature period that Meteonorm used, the average yearly temperature in Novi Sad is 12°C. The coldest month is January with an average air temperature of 0.4°C and warmest is July when the average temperature is 22.4°C. Figure

18 illustrates minimum, maximum and mean monthly temperatures according to Meteonorm.

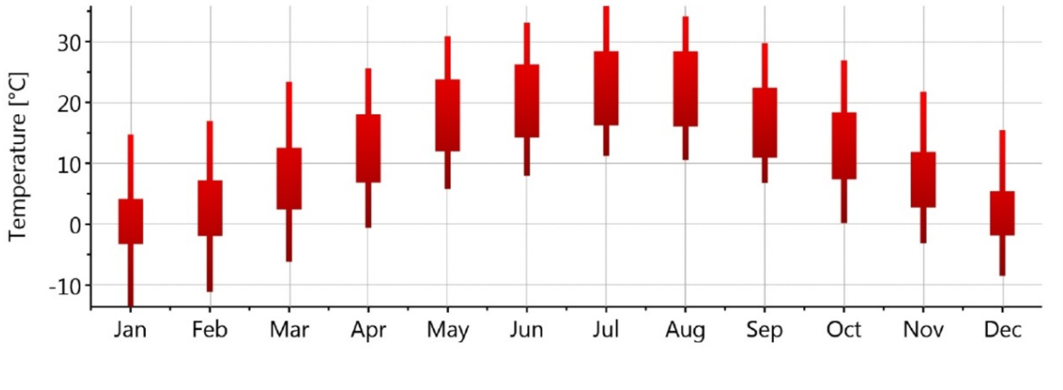

Figure 18 - Monthly temperatures in Novi Sad (Meteonorm)

Relative humidity - Average monthly relative humidity in Novi Sad is in the range from 62% in April to 83% in December.

Precipitation - Annual precipitation in Novi Sad is 576.8mm. Since the summer showers are common in continental climate it is not unexpected that June is by far the wettest month with 91.4mm of precipitation, while the driest months are January and February with 39.1 and 31.4mm. There are more days with precipitation in the spring, but the amount of the precipitation is higher in the autumn.

Solar radiation - Meteonorm calculates monthly diffuse and global radiation. Solar radiation is highest in summer months. Diffuse radiation has similar values for May, June and July while the global radiation is highest in the month of July. Lowest values of radiation are in December when the day is the shortest. In Figure 19, average monthly values for diffuse and global radiation in k.W.h.m^{-2} are showed. In the next figure duration of sunshine can be observed. As it can be expected, the sunshine duration is the longest during the summer months with the peak in July.

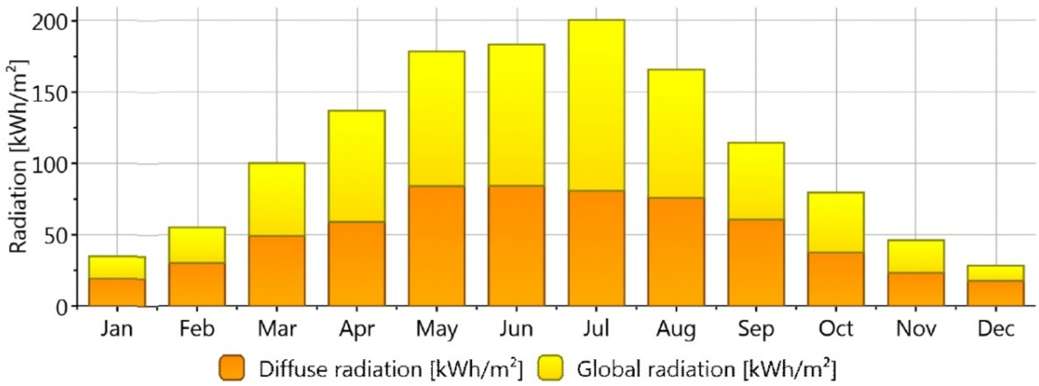

Figure 19 - Monthly radiation (Meteonorm)

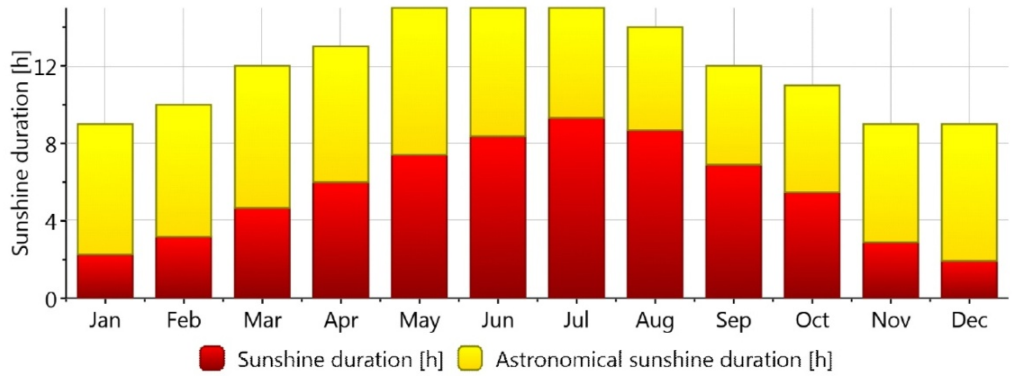

Figure 20 - Monthly sunshine duration (Meteonorm)

Wind direction and speed - The most common wind in the area of Novi Sad is eastern-southeastern wind - Košava (Figure 21). As it is mentioned before, it brings clear and dry weather and usually lasts three to seven days. Meteonorm calculates average monthly wind speed and direction. The highest monthly wind speed is in March 3.1m.s^{-1}, whereas the least windy month is August with average wind speed of 1.9m.s^{-1}. When the wind direction is analyzed on a monthly basis, it can be observed that the wind from the west and northwest blows in January, June, July and December, while Košava occurs in all of the other months.

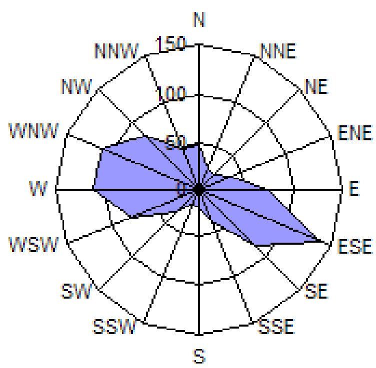

Figure 21 - Wind-rose (Republic Hydrometeorological Service of Serbia)

2.3.3 Prefabricated Residential Buildings

Most of the apartment buildings that exist in Novi Sad were built in a prefabricated system. Three systems were used: IMS, NS 71 and Montastan. Buildings constructed using first two systems had both flat and sloped roofs while Montastan only used sloped roof. Since this thesis deals with implementation of green roofs, only IMS and NS-71 prefabricated systems will be analyzed. Pre-stressed system IMS was used since the 1960s until 1990 and during this period approximately 16000 apartments were built. Semi-prefabricated system NS71 was used for a short period of time between 1974 and 1980 and there are around 3000 apartments built in this way (Laban 2012).

IMS System

The pre-stressed framed industrial prefabricated IMS system is the system that has been used the most in the industrial production of residential buildings in Novi Sad. Parapet elements with a row of windows are a distinctive trademark of the system (Figure 22 and Figure 23). Windows usually have lightweight posts between them. During the period of thirty years that it was utilized, properties of the building elements, design and materials were improved, but the way the building was constructed stayed the same.

Figure 22 - Residential building built in the IMS system in the 1960s

Figure 23 - Residential building built in the IMS system in the 1970s

Basic load bearing elements are columns, panelled slabs, cantilever slabs and beams (Figure 24). The facade is closed with wall and parapet panels. Load-bearing elements of reinforced concrete are pre-stressed during the construction in order to produce the strong connection. Panelled slabs (Figure 25) have high load carrying capacity, in experimental studies the breaking load of a slab was five to ten times bigger than the designed load (Dimitrijevic 1988), therefore, the construction of green roof is possible.

Thermal properties of buildings built in the IMS system are different depending on the time when the building was constructed. Thermal performance of facade elements was always in accordance with the current codes applied at the time of the construction of the building. In the first years of the IMS prefabricated system utilization, thermal transmittance coefficient for outside walls was not defined, the energy necessary for heating was calculated based on designed facade elements. Facade panels of buildings from this time have U-values that are approximately 1.5 $W.m^{-2}.K^{-1}$. Maximum thermal transmittance coefficient for outside walls was first defined in 1967 and it was 1.18 $W.m^{-2}.K^{-1}$. With new codes, maximum U-values were decreasing. In the period between 1980 and 1990, it was 0.83 $W.m^{-2}.K^{-1}$. Some of the panels from this last period of utilization of IMS prefabricated system have U-values that are in accordance with today's standards for existing buildings that are used in Serbia (0.4 $W.m^{-2}.K^{-1}$ for outside walls of existing buildings) (Building Regulations on Energy Efficiency 2011).

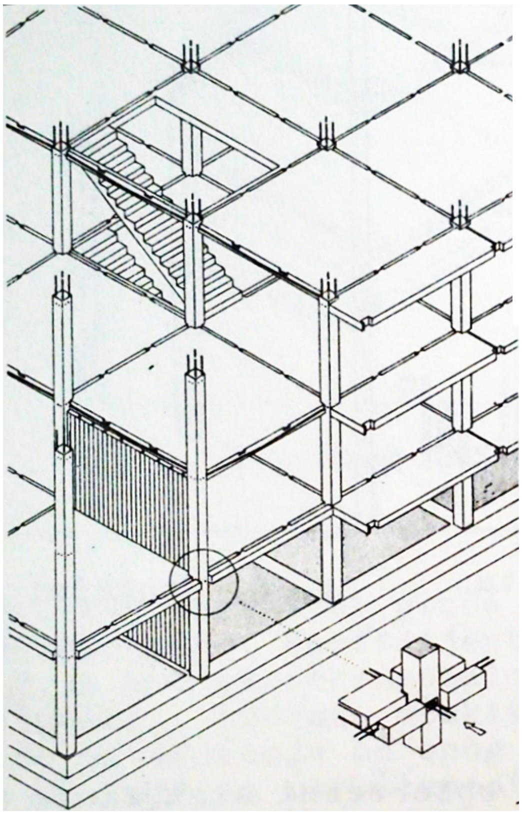

Figure 24 - Elements of IMS System (Dimitrijevic, 1988)

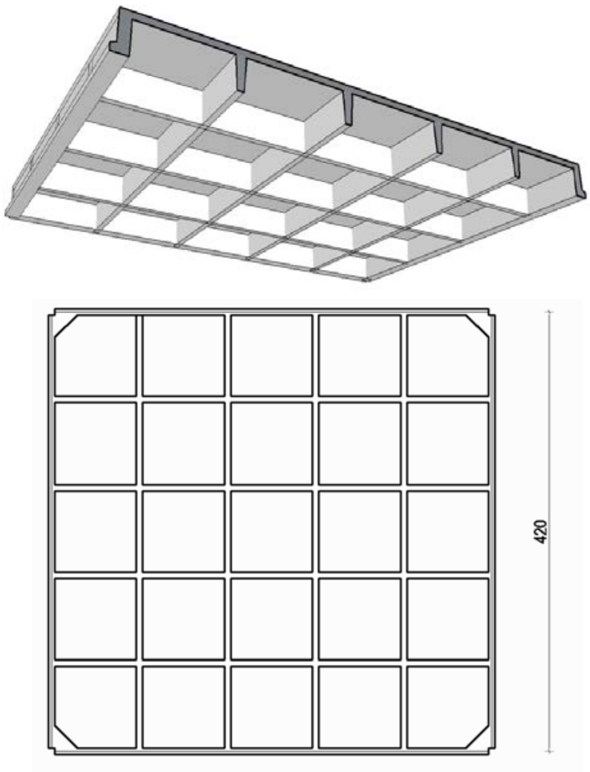

Figure 25 - IMS system floor slab

In this thesis, two objects built in the IMS system will be analyzed. The first building was built at the time when no maximum U-values were regulated and it has low thermal performances. The second one is from the later phase of IMS system utilization and has better thermal performances of the envelope.

NS-71 System

A system for industrial production of apartments NS-71 (Figure 26) was designed as a semi-prefabricated system, for urban development competition in Novi Sad that required that buildings were designed in appropriate and modern architectural skeleton construction for industrial production (Cagic 1976). This system was used only in Novi Sad and for a short period of time, hence never reaching the full level of prefabrication. Approximately 3000 apartments were built in the system (Laban 2012). The visual appearance of the facade elements with exposed aggregate concrete makes this system easily recognizable (Figure 27).

Figure 26 - Residential buildings built in NS-71 system

Figure 27 - Facade detail of NS-71 system

Main structural elements of NS-71 system (Figure 28), that are forming the basic frame of a building are:

- hollow columns 60*60*260 cm (the diameter of the hole inside the column was adjusted depending on the floor level and the loading while the outside dimensions of the column stay the same)
- floor slabs made of reinforced concrete with hollow clay blocks (Figure 29)
- beams
- cantilever slabs
- stairways

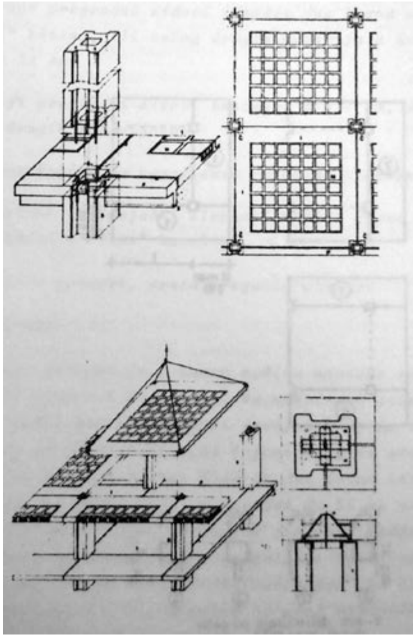

Figure 28- Elements of NS-71 System (Cagic, 1976)

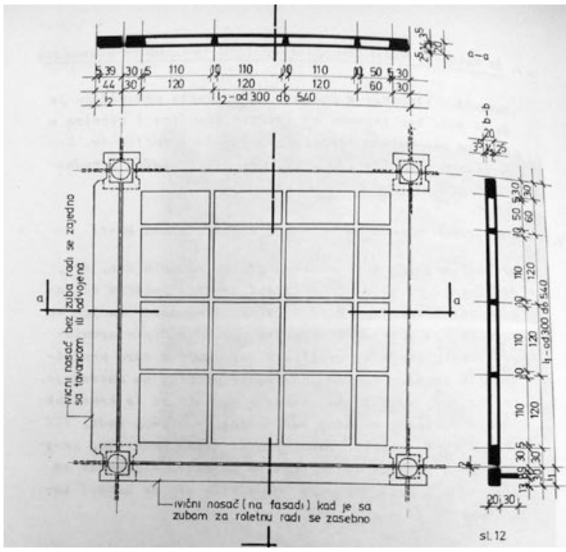

Figure 29 - NS-71 system floor slab (Cagic, 1976)

Other prefabricated elements are facade walls, inner walls and sanitary cabins. There are three types of facade walls: full-height wall panels made of haydite concrete with exposed aggregate concrete as the outside layer, parapet panels and brick parapets. Parts of a building that were built in traditional method are foundation, staircase walls and roof terrace.

Thermal characteristics of the envelope are not in accordance with today's standards for existing buildings (Building Regulations on Energy Efficiency 2011). Laban and Folic (2014) analyzed thermal properties of facade elements used in the NS-71 system (Figure 30). Some of the articles about this system include the information that 6cm of thermal insulation (EPS) was used between concrete layers in wall panels (A* in Figure 30), but, according to Laban and Folic, this is not listed in the original design documentation. Haydite concrete that was used for panels has good thermal properties, but without insulation it cannot fulfil requirements of building regulations on energy efficiency. Other elements that they have analyzed are parapet panels, brick parapets and columns. All of which have high heat transfer coefficient values.

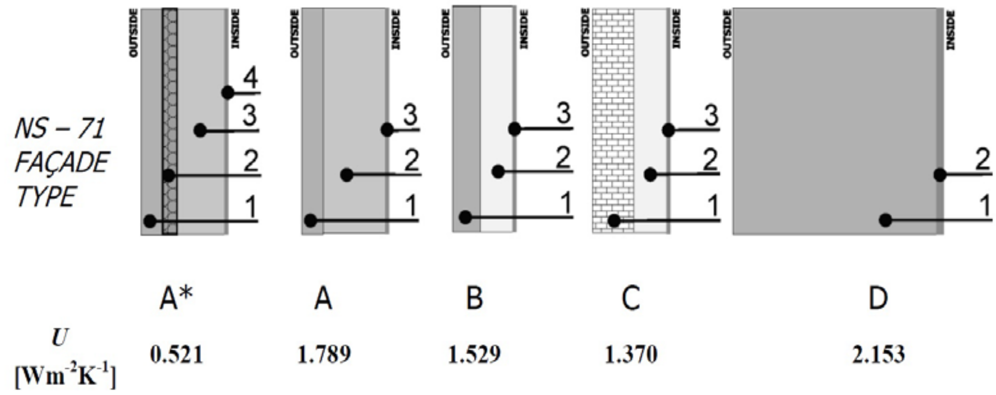

Figure 30 - Thermal properties of NS-71 facade types (Laban, Folic 2014)

Residential buildings built in the NS-71 semi-prefabricated system had both flat and sloped roofs. According to the available documentation, flat roofs were insulated with wood chip boards. Flat roofs are designed to be used as roof terraces (Figure 31), with the exception of the roof over the corridor that is covered with gravel and is not intended to be used on a regular basis (Figure 32). Roof terraces are paved with concrete tiles over sand and hollow brick.

Figure 31 - Roof terrace

Figure 32 - Roof over corridor

3 METHODOLOGY

The thermal performance of IMS buildings, as previously mentioned, varies according to the year of construction. Therefore, two objects were analyzed. The first building (IMS NS1) was constructed at the time when no maximum heat transfer coefficients of building components were regulated. Consequently, it is characterized by poor thermal performance. The second building (IMS N), was constructed in the later phase of the IMS system utilization and, therefore, has better thermal performances of the envelope. In addition to these two IMS buildings, one object built in the NS71 system was analyzed.

Three selected buildings were analyzed using identical simulation procedure. Two different series of simulations were run for each building and for each roof type. Four roof scenarios were analyzed in the free running model simulation and in the controlled model simulation. These are: existing roof (ER), refurbished roof (RR), green roof (GR) and white roof (WR).

In the first place, current thermal performances of examined buildings were obtained. The data from original project documentation, scientific publications about prefabricated systems and scientific studies, was used as input data for simulation of the existing state of the building (ER). As the next step, the flat roof was improved and three more scenarios were simulated. One scenario included only replacement of top layers of the flat roof with the addition of thermal insulation (RR) and the second scenario was extensive or semi-extensive green roof (GR). In the last scenario, a high solar reflectivity layer was added over the existing roof in order to evaluate the impact of reflectivity on the cooling performance of the roof (WR). For each roof type, a free running model was simulated at first. This simulation, with no assumed mechanical heating or cooling, was carried out in order to attain the values of inside temperatures and to compare different scenarios in that aspect. In the second simulation run, the set-point temperature for winter and summer months was determined. The heating and cooling loads, necessary to provide and keep thermal comfort, were obtained in this stage. In Figure 33 a graphical representation of the simulation scenarios is presented.

The obtained results were at first individually analyzed and evaluated and later the results of different scenarios were compared.

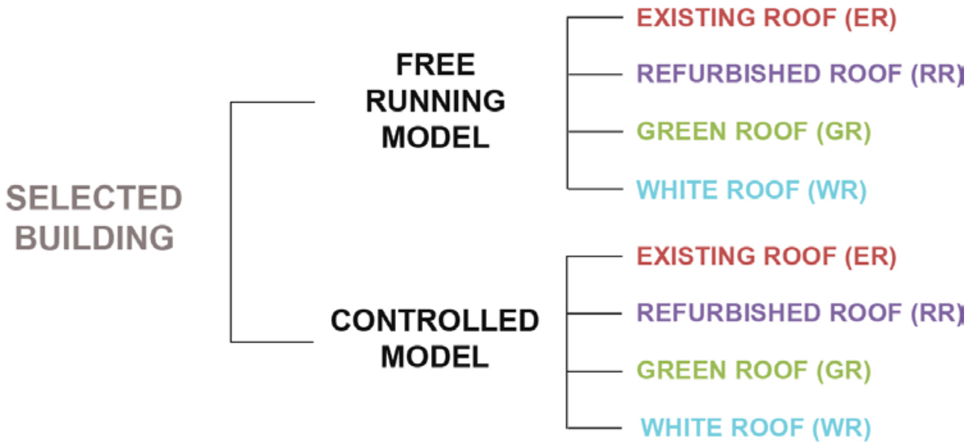

Figure 33 - Simulation scenarios

The simulation of the free running model provided the values for indoor temperatures on the hourly and monthly basis. Values for indoor temperatures in the thermal zones of the top floor were used for further analyses. Monthly temperatures were compared for the period of one year. The thermal performance of different roof types was analyzed via comparison of hourly temperature values during the coldest (12th of January, -13.3°C) and the hottest (21st of July, 35.7°C) day in the used weather file. Cooling efficiency of different roof types was additionally analyzed via the comparison of amount of overheating degree hours during the summer months. The time period between 1st of June and 31st of August was selected and the comfort threshold temperature is set at 27°C. Each 1°C above the threshold temperature during 1 hour equals 1 degree hour (e.g. Temperature of 30°C for 1 hour is equal to 4 degree hours). Overheating degree hours were calculated for thermal zones of the top floor.

The controlled model simulation provided the values for heating and cooling demand. These values were analyzed for the whole building, as well as for the thermal zones of the top floor. The reduction rates achieved by each examined roof type were compared.

3.1 Simulation

The EnergyPlus (NREL 2013) simulation software was chosen, after study of past research and all relevant parameters, as the most suitable for this thesis. The geometrical models of analyzed buildings were first created in Open Studio (NREL 2012) plug-in for SketchUp (Trimble 2012) and later imported to EnergyPlus.

3.1.1 Input Parameters

As the first step, inputs that were applied for all three models will be discussed. Those include internal gains (people, lights, electric equipment), shading, infiltration and ventilation rate. Along with these inputs as well as construction data for each building separately interior temperature values were obtained. As the next step of the analysis, heating and cooling systems were added. The data for these inputs were entered according to building standards and regulations, where that was possible, otherwise, assumptions had to be made.

Internal gains

When a building is occupied, internal heat gains from people, household appliances and lighting contribute to space heating.

People - Number of people in living areas of analyzed buildings was determined using area/person calculation method. According to the data acquired from Statistical Office of the Republic of Serbia (2013), an average of 31m^2 of living area is available per person in Novi Sad and average household size is 2.57. Since this data is an overall number for all types of dwellings (family houses, apartments in residential buildings), it is assumed that available living area in residential buildings is less than total average. For the simulation, 25m^2 of zone floor area per person was used. Schedules were created for activity level, work efficiency and clothing insulation calculation. Assumptions on the level of activity were made depending on the time of the day and based on the data from EnergyPlus Input Output Reference (2013, p.345). The work efficiency schedule determines will the energy produced by the human body be converted to heat or mechanical energy. For this calculation, it is assumed that all of the body energy will be converted to heat. The clothing insulation schedule was created for two seasons, 0.5 clo for Summer and 0.9 clo for Winter months.

Lights - Internal gains produced by lights were calculated using Watts/Area method, assuming heat gain as 10 W.m^{-2}. The schedule that controls the use of lights depends on the time of the day and year.

Electric equipment - Internal gains produced by electric equipment were calculated using Watts/Area method. It is assumed that their output as a heat gain is 11 Watts per square meter of zone floor area. The schedule according to which electric equipment was utilized depends on the building occupancy and time of the day.

Shading

Windows of all analyzed buildings are equipped with manually operable external roller blinds. The operation of blinds was defined in schedules (Table 2). Period of the year, time of the day and orientation of a thermal zone were taken into account when creating schedules. Two schedules were created, one for the south zones and another for north oriented zones. It is assumed that in the wintertime, regardless of orientation, blinds are open during the day and closed during the night. In the summer period, it is presumed that blinds are open during the night in order to allow increased natural ventilation rate. In south oriented zones, blinds are closed in the early afternoon and partially closed in the late afternoon and evening, while in north oriented zones, blinds are partially closed during the day to avoid overheating.

Table 2 - Shading schedule

		North oriented zones	South oriented zones
SUMMER 1.5. - 1.11.	DAY 08:00 - 16:00 16:00 - 20:00	partially closed partially closed	closed partially closed
	NIGHT 20:00 - 08:00	open	open
WINTER 1.11 - 1.5.	DAY 08:00 - 20:00	open	open
	NIGHT 20:00 - 08:00	closed	closed

Infiltration

Infiltration, or air leakage, is an unintentional or accidental flow of outside air into a building, usually through cracks around windows, roller blind boxes, opening and closing of exterior doors or through building elements. Air leaks in analyzed buildings are mostly present in the area of windows and roller blind boxes. AirChanges/Hour calculation method was used with a constant infiltration rate of 0.35 ach for all zones.

Ventilation

The quality of indoor air is of great importance for human health, especially considering the fact that people spend almost 90% of the time indoors. Air contains different chemical and biological pollutants that may influence the risk of developing some respiratory diseases, a high concentration of CO_2 can cause headaches, poor concentration, increased heart rate and other symptoms. The content of CO_2 in the air can be a significant indication of air quality. Typical CO_2 concentration for indoor air lays between 350 and 1000 ppm, while values between 1000 and 2000 ppm can cause a feeling of drowsiness and poor air (ASHRAE 2013). For simplification purposes, it was presumed that solely air infiltration is sufficient to provide good air quality. This assumption was tested using CO_2 concentration calculation in EP. Obtained results showed that concentration of Carbon Dioxide does not exceed 1120 ppm and in 93% of hours stays under than 1000 ppm. These results showed that there is no necessity for ventilation during the whole year. Natural ventilation is not only an effective way to dilute contaminants in the indoor air, but it can also make a positive impact on the thermal comfort. Hence, the night ventilation was scheduled during the summer months (from mid-May until the middle of September). It was assumed that windows are open (9 ach) during one hour in the evening, and tilted (3 ach) throughout the rest of the night. During the summer period, the green roof contributes to the preservation of low air temperature during the day and high air temperature during the night. Thus, night ventilation favours the conservation of air temperature at lower levels not only during the night but also during the day (Nichaou 2001).

Heating system

Heating for residential buildings in Novi Sad is provided by the community heating centre - PUC "Novosadska Toplana". Heating season starts on 15th of October and lasts until 15th of April and the main energy source is natural gas (PUC "Novosadska toplana" 2016). The heating cost is calculated for a whole building and cost for each dwelling depends on the corresponding floor area. There are plans for changing this payment method in the future so that each apartment pays according to the energy that is used for its heating. For the simulation, the heating schedule was created based on duration of the heating season with the temperature setpoint of 21°C.

Cooling

Split air conditioning units have become a part of necessary home appliances in apartments in recent years. They are mostly used for cooling, but sometimes when it is required, they are used for additional heating. In this simulation, it is assumed that they are used only for cooling in the summer period, during the daytime when natural ventilation is off. Cooling is set to start when the indoor temperature increases over 26°C.

3.1.2 Green Roof Model

Flat roofs of analyzed buildings are in most parts not accessible to residents. The roof of the first building is completely inaccessible while roofs of other two examples have parts that were designed to be used by residents. Access to a flat roof is an asset that contributes to the quality of living and it would be an adequate option to keep that possibility. The extensive green roof would be applied where the flat roof was not accessible, while on the flat roofs that were accessible, a semi-extensive green roof would be installed. The semi-extensive roof, as it was discussed earlier, combines both basic green roof types on the same roof. However, EnergyPlus doesn't enable the user to model intensive roof over some segment of structure and an extensive roof elsewhere. Because of this, the same model of the extensive green roof was used for all analyzed examples.

EnergyPlus allows a user to specify green roof as the outer layer of a rooftop construction and its characteristics using the class that defines input parameters for vegetation and substrate while other layers of the green roof are defined separately and later added to the green roof construction.

Green roof vegetation in EnergyPlus is defined by the following parameters: height of plants, leaf area index (LAI), leaf reflectivity, leaf emissivity and minimum stomatal resistance. Since a wide range of plant species can be grown on a green roof, values for these parameters can differ substantially. The fact that the vegetation on a green roof is usually not uniform and represents a mixture of different species is additionally making input parameter value selection more complex. Sailor (2008) analyzed a range of different green roof models for energy simulation with LAI values between 1.0 and 5.0 while in baseline simulation it was set to 2.0. The results of this research showed that the higher LAI increased gas consumption in the winter and reduced electricity consumption in the summer. The increase in LAI influenced cooling effect increase in the research carried out by Takakura (2000). The impact of broad leaf plants on cooling of the roof surface was studied in the research conducted by Blanusa (2012). Plant species that were studied had similar LAI, but the characteristic that was important for the regulation of temperature and lower temperature of the roof surface, as it was concluded, was the presence of leaf hairs. Differences in plant structure and function, as well as variations in plant phenotype and physiological adaptations, can influence cooling effects on a leaf which will further influence substrate and air temperatures.

Above mentioned research works illustrate the diversity of vegetation characteristics and its influence on built environment. Considering both the vegetation characteristics analyzed in the research works and EnergyPlus default values for parameters that describe those characteristics, following input parameters for green roof vegetation were selected and used in the simulations (Table 3).

Table 3- EnergyPlus input parameters for green roof vegetation

Field	Units	Definition*	Value
Height of Plants	m	This field defines the height of plants in units of meters. Values are in the range of 0.005 to 1.00 m.	0.4
Leaf Area Index	-	Projected leaf area per unit of soil surface. It is limited to values in the range of 0.001 to 5.0.	4
Leaf Reflectivity	-	The fraction of incident solar radiation that is reflected by the individual leaf surfaces (albedo). Values must be between 0.05 and 0.5.	0.25
Leaf Emissivity	-	The ratio of thermal radiation emitted from leaf surfaces to that emitted by ideal black body at the same temperature. Values must be between 0.8 and 1.0.	0.95
Minimum Stomatal Resistance	$s.m^{-1}$	The resistance of the plants to moisture transport. Values are in range of 50.0 to 300.0	180
*EP Input-Output Reference			

Input parameters that define growing medium include: roughness, thickness, conductivity, density and specific heat of dry soil. Given that the green roof substrate differs from a typical soil, it is composed primarily of lightweight aggregate making it more porous and with less organic matter, values that are describing its physical characteristics will also be different than those for natural soils.

Sailor (2008) argues that values found in literature are for natural occurring soils and that they should not be used for green roof simulation. In his research, he analyzed eight types of substrate that consist of three components in different proportions. These eight types were tested at four moisture levels. EnergyPlus requires inputs for dry soil, therefore, parameters for this moisture level were studied. Sailor finds that thermal conductivity of dry soil is between 0.14 and 0.21 $W.m^{-1}.K^{-1}$ and suggests that these values should be used. Since EnergyPlus allows only values higher than 0.2 $W.m^{-1}.K^{-1}$, it was decided that soil type with this value of thermal conductivity will be used and that corresponds to soil type DH05 from Sailor's research. Input parameters are presented in Table 4.

Table 4 - EnergyPlus input parameters for green roof soil

Field	Units	Definition*	Value
Roughness	-	The relative roughness of a particular material layer. Options between "VeryRough" to "VerySmooth" are possible.	Medium Smooth
Thickness	m	The dimension of the layer in the direction perpendicular to the main path of heat conduction. Maximum value is 0.7	0.2
Conductivity of Dry Soil	$W.m^{-1}.K^{-1}$	The thermal conductivity of the material layer. Values must be between 0.2 and 1.5.	0.2
Density of Dry Soil	$kg.m^{-3}$	The density of the material layer, must be a positive quantity. Values are in range of 300 to 2000.	1360
Specific Heat of Dry Soil	$J.kg^{-1}.K^{-1}$	The specific heat of the material layer. Only positive values of specific heat are allowed.	887
*EP Input-Output Reference			

Layers that are positioned below the substrate are crucial for proper functioning of the green roof system. These additional layers (Table 5), above all, are filter fabric, drainage layer and waterproofing. In EnergyPlus, their physical characteristics were added in class Materials, and together with roof vegetation, which describes characteristics of both vegetation and soil, they create green roof structure in EP class Construction. Heat transfer coefficient of a green roof composed of previously described layers is 0.115 $W.m^{-2}.K^{-1}$.

Table 5 - Additional green roof layers

	Thickness [m]	Conductivity [$W.m^{-1}.K^{-1}$]	Density [$kg.m^{-3}$]	Specific Heat [$J.kg^{-1}.K^{-1}$]
filter fabric	0.005	0.06	160	1900
drainage layer	0.06	0.1	400	1250
waterproofing	0.01			
thermal insulation XPS	0.2	0.033	32	1210
vapourseal	0.01			
cement screed	0.04	1.4	2200	1050
pre-stressed concrete	0.04	2.5	2400	1110
air	0.18			
gypsum board	0.019	0.16	800	1090

3.1.3 Refurbished Roof Model

Refurbishment of the roof suggests new waterproofing and better thermal insulation while the top layer remains unchanged. Model of a refurbished roof represents the existing roof with the addition or replacement of a thermal insulation layer (20cm of XPS). Added insulation layer improves the thermal performance of the roof, the thermal transmittance value of the refurbished roof is 0.142 $W.m^{-2}.K^{-1}$. Properties of the materials used for the model of the refurbished roof are presented in Table 6.

Table 6 - Refurbished roof materials

Building Element	Thickness [m]	Conductivity [$W.m^{-1}.K^{-1}$]	Density [$kg.m^{-3}$]	Specific Heat [$J.kg^{-1}.K^{-1}$]	U-value [$W.m^{-2}.K^{-1}$]
Refurbished Roof					0.142
gravel	0.03	0.81	840	1700	
waterproofing	0.01				
thermal insulation XPS	0.2	0.033	32	1210	
vapourseal	0.005				
cement screed	0.04	1.4	2200	1050	
pre-stressed concrete	0.04	2.5	2400	1110	
air	0.18				
gypsum board	0.019	0.16	800	1090	

3.1.4 White Roof Model

The white roof model that was used in the simulation replaces the top layer of an existing roof with the high solar reflectivity layer. The U-values of a white roof and existing roof are equal, but the values for solar reflectance and infrared emittance of a white roof are higher. As a top layer of the white roof, two different materials (off-white gravel and modified bitumen white coating) were used depending upon the type of the existing roof. Solar reflectance value that was used for both materials in the simulations is 0.75 (European Cool Roof Council 2016).

3.1.5 Residential Building Type IMS NS-1 Model

The first object that was examined is one of the first residential buildings built in the IMS system in Novi Sad (Figure 34 and Figure 35). There are seven identical 5-storey objects that were constructed between 1962 and 1965. In the following years, taller buildings - up to 22 storeys, were built based on this typology.

Figure 34 - Residential building IMS NS-1 (photo: M. Laban, 2012)

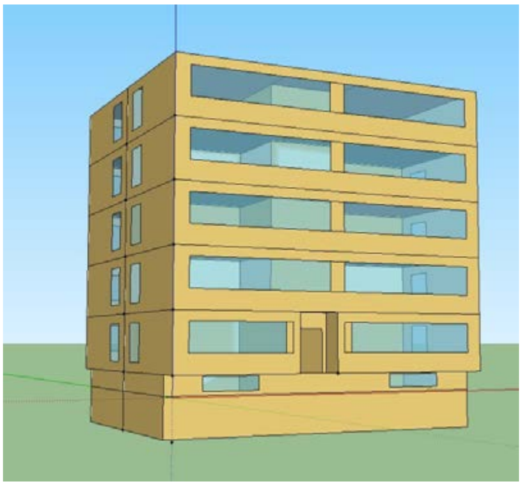

Figure 35 - Building model created in Open Studio

Typical floor comprises of four apartments positioned around corridor and staircase. Structural grid is 4.2m x 4.2m with 1.25m cantilever on the longer facade. Floor area of each apartment is approximately 55 square meters.

Different orientations of the object are possible since several identical objects were built. In this analyses object was positioned with its longer facades oriented towards north and south. Taking such orientation into account, each floor was divided into three thermal zones. Two apartments oriented towards north comprise north zone, and two south apartments are assigned to south zone. The corridor and the staircase, that are located in the centre of the building, are modelled as a shaft and they create one unheated zone through the whole building (Figure 36).

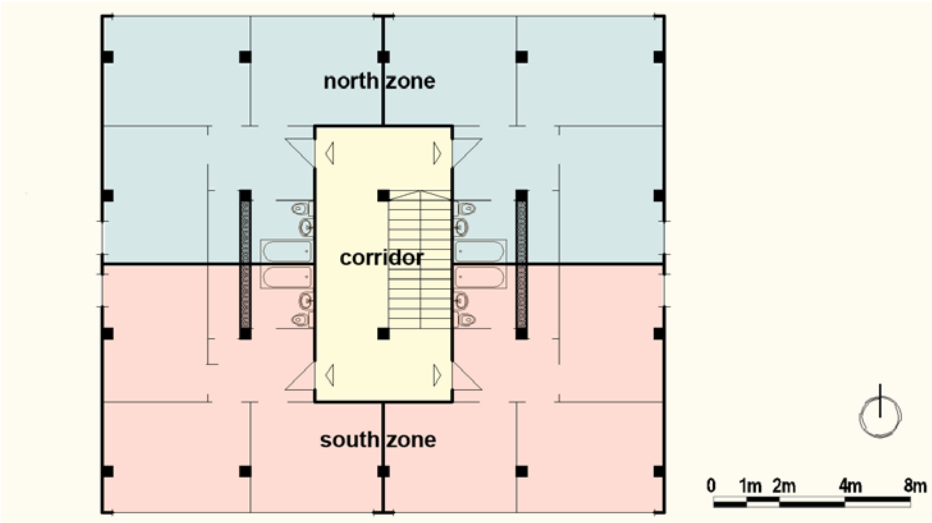

Figure 36 - Zoning of the building IMS NS-1

The longer facade consists of parapet panels and strips of windows with lightweight posts between them. Windows are double glazed with wooden frame. The shorter facade has two French windows on each floor and the rest is full-height wall panel. Inner walls of the apartments are made of gypsum boards while walls between two apartments, as well as walls between apartment and corridor consist of two gypsum boards with air between them. According to the data acquired from the original project and research by Laban (2012, 2013), full-height wall facade panels and parapet panels are composed of two concrete plates with wood chip board between them. These panels have high U-values, according to Laban they are between 1.12 $W.m^{-2}.K^{-1}$ and 2.22 $W.m^{-2}.K^{-1}$. In the simulated model, U-values of the wall and parapet panels are 1.65 and 1.67 $W.m^{-2}.K^{-1}$ respectively. Other facade elements characterized with high heat transfer coefficient are lightweight posts between windows, that are made of cement sheeting and woodchip board (1.79 $W.m^{-2}.K^{-1}$ in the simulated model).

The flat roof of the analyzed building is meant to be used only for maintenance works. Layers of hollow brick, slag concrete, waterproofing and gravel as finishing layer are placed above the pre-stressed concrete slab. The U-value of this structure is 1.14 $W.m^{-2}.K^{-1}$.

Physical properties of materials used for the construction of building elements in the analyzed building are presented in Table 7.

Table 7 - IMS NS-1 Materials

Building Element	Thickness [m]	Conductivity [W.m^{-1}.K^{-1}]	Density [kg.m^{-3}]	Specific Heat [J.kg^{-1}.K^{-1}]	U-value [W.m^{-2}.K^{-1}]
Panel					1.651
concrete	0.08	2.5	2400	1110	
wood chip board	0.06	0.15	460	1600	
concrete	0.06	2.5	2400	1110	
Parapet Panel					1.673
concrete	0.06	2.5	2400	1110	
wood chip board	0.06	0.15	460	1600	
concrete	0.06	2.5	2400	1110	
Lightweight Window Post					1.796
cement sheeting	0.01	1.4	2100	1050	
wood chip board	0.06	0.15	460	1600	
Existing Roof					1.139
gravel	0.03	0.81	840	1700	
waterproofing	0.005				
slag concrete	0.04	0.76	1600	960	
hollow brick	0.065	0.61	1400	920	
pre-stressed concrete	0.04	2.5	2400	1110	
air	0.18				
gypsum board	0.019	0.16	800	1090	
Floor/Ceiling					
parquet	0.025	0.21	700	1670	
cement screed	0.04	1.4	2200	1050	
pre-stressed concrete	0.04	2.5	2400	1110	
air	0.18				
gypsum board	0.019	0.16	800	1090	
Floor to Ground					
terazzo	0.0254	1.,8	2560	790	
cement screed	0.04	1.4	2200	1050	
waterproofing	0.005				
wood chip board	0.06	0.15	460	1600	
concrete slab	0.2	2.5	2400	1110	
waterproofing	0.005				
concrete	0.08	2.5	2400	1110	
Wall Between Apartments					
gypsum board	0.07	0.16	840	1200	
air	0.04				
gypsum board	0.07	0.16	840	1200	
Partition Wall					
gypsum board	0.07	0.16	840	1200	

3.1.6 Residential Building Type IMS N Model

The next object type considered in this work is a residential building built in IMS system with panels that have better thermal performance in comparison with the older buildings built in the IMS system. This type was being built during the 1970s, the height of the objects vary between four and ten floors. For this study a seven storey tall residential building, was modelled (Figure 37 and Figure 38). Only two sides of the simulated unit are exposed to the outside conditions, as it can be seen in the Figure 37, while on the other two sides the analyzed unit is adjacent to the neighbouring building units. One part of the building is lower and has a roof terrace, while the taller part has a flat roof that is not being used regularly.

Figure 37 - Residential building IMS N

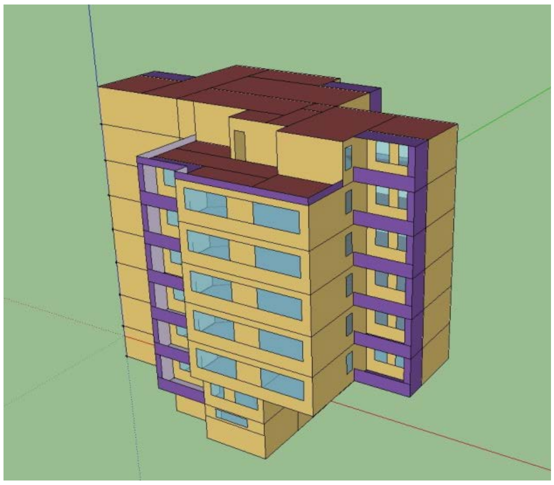

Figure 38 - Building model created in Open Studio

As it was mentioned in the previous chapter, for each building type there are several identical objects with different orientation, therefore, south-north orientation for each model was chosen. The typical floor of the IMS N building type has four apartments and core with staircase and elevator in the center (Figure 39). Two apartments in north section of the building comprise the north zone, and the south zone consists of two apartments oriented towards south. The central core is modelled as a shaft and it forms one unheated zone through the whole building. Zones that are under the flat roof will be analyzed in more detail (Figure 40). Those are the south zone of the fifth floor and both zones of the sixth floor. The south zone of the sixth-top floor consists of only one apartment and thus is smaller than the other south zones in the model. The roof of this building type have better thermal performance than a roof in the previously described building type. Above pre-stressed concrete slab, there are waterproofing layers, sand as inclination layer and 10cm thick woodchip board used as thermal insulation (Original project documentation - GP "Beton" 1975). The roof terrace is covered with concrete tiles and flat roof of the seventh floor is covered with a layer of gravel. Both roofs have U-value of 0.56 $W.m^{-2}.K^{-1}$.

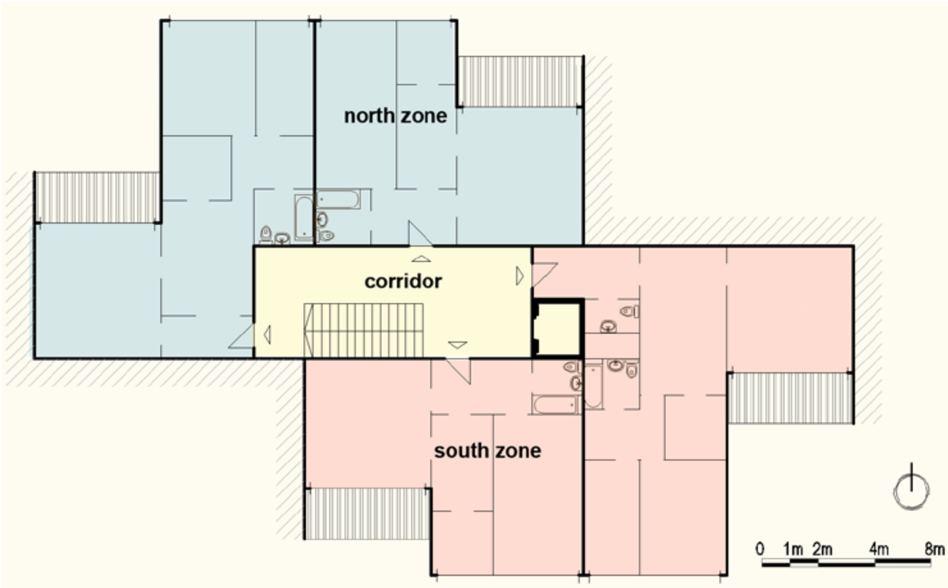

Figure 39 - Zoning of the building - typical floor IMS N

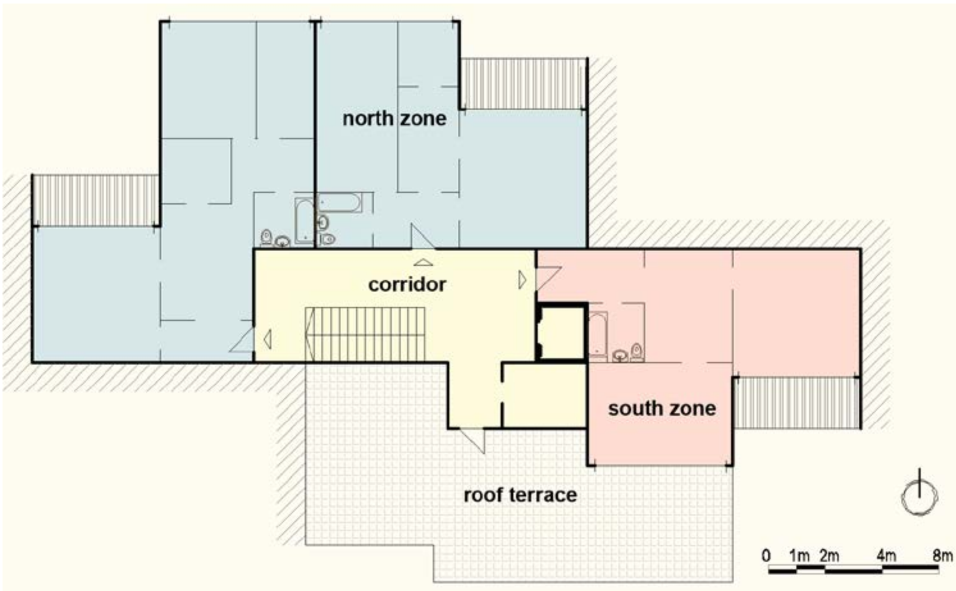

Figure 40 - Zoning of the building - top floor IMS N

The building envelope is enclosed with three types of panels. Full-height wall panels and parapet panels consist of two concrete plates with 6cm of expanded polystyrene as thermal insulation between them. U-value of these panels is 0.55 $W.m^{-2}.K^{-1}$. Windows are double glazed with wooden frame. Space between windows is closed with lightweight panels made of cement sheeting and woodchip board with high heat transfer coefficient (1.78 $W.m^{-2}.K^{-1}$).

Physical properties of the materials used for the construction of building elements in the analyzed building are presented in the Table 8 and Table 9.

Table 8 - IMS N Materials

Building Element	Thickness [m]	Conductivity [W.m^{-1}.K^{-1}]	Density [kg.m^{-3}]	Specific Heat [J.kg^{-1}.K^{-1}]	U-value [W.m^{-2}.K^{-1}]
Panel					0.554
concrete	0.06	2.5	2400	1110	
EPS	0.08	0.05	15	1450	
concrete	0.08	2.5	2400	1110	
Lightweight Panel Board					1,783
cement sheeting	0.01	1,4	2100	1050	
wood chip board	0.06	0,15	460	1600	
Existing Roof					0.559
gravel	0.04	0.81	840	1700	
waterproofing	0.005				
wood chip board	0.1	0.15	460	1600	
sand	0.1	0.58	1400	800	
vaporseal	0.005				
pre-stressed concrete	0.04	2.5	2400	1110	
air	0.18				
gypsum board	0.019	0.16	800	1090	
Existing Roof - Paved Roof					0.573
concrete tiles	0.03	2.33	2400	960	
sand	0.02	0.58	1400	800	
waterproofing	0.005				
wood chip board	0.1	0.15	460	1600	
sand	0.08	0.58	1400	800	
vaporseal	0.005				
pre-stressed concrete	0.04	2.5	2400	1110	
air	0.18				
gypsum board	0.019	0.16	800	1090	
Floor/Ceiling					
parquet	0.025	0.21	700	1670	
cement screed	0.04	1.4	2000	1080	
pre-stressed concrete	0.04	2.5	2400	1110	
air	0,18				
gypsum board	0.019	0.16	800	1090	
Floor to Ground					
terazzo	0.0254	1.8	2560	790	
cement screed	0.04	1.4	2000	1080	
waterproofing	0.005				
wood chip board	0.06	0.15	460	1600	
concrete slab	0.2	2.5	2400	1110	
waterproofing	0.005				
concrete	0.08	2.5	2400	1110	
Wall Between Apartments					
slag concrete	0.07	0.64	1600	920	
air	0.04				
slag concrete	0.07	0.64	1600	920	
Partition Wall					
slag concrete	0.07	0.64	1600	920	

Table 9 - IMS N Refurbished roof materials

Building Element	Thickness [m]	Conductivity [$W.m^{-1}.K^{-1}$]	Density [$kg.m^{-3}$]	Specific Heat [$J.kg^{-1}.K^{-1}$]	U-value [$W.m^{-2}.K^{-1}$]
Refurbished Roof					0.142
gravel	0.03	0.81	840	1700	
waterproofing	0.01				
thermal insulation XPS	0.2	0.033	32	1210	
vapourseal	0.005				
cement screed	0.04	1.4	2000	1080	
pre-stressed concrete	0.04	2.5	2400	1110	
air	0.18				
gypsum board	0.019	0.16	800	1090	
Refurbished Roof - Paved					0.115
concrete tiles	0.03	2.33	2400	960	
sand	0.02	0.58	1400	800	
waterproofing	0.01				
thermal insulation XPS	0.2	0.033	32	1210	
vapourseal	0.005				
cement screed	0.04	1.4	2000	1080	
pre-stressed concrete	0.04	2.5	2400	1110	
air	0.18				
gypsum board	0.019	0.16	800	1090	

3.1.7 Residential Building Type NS-71 Model

The semi-prefabricated building system NS-71 was used for a short time during the 1970s. Residential buildings with both flat and sloped roof were built using this system. The objects are five until 17 floors tall. Flat roofs are paved, with the exception of the highest roof - the roof over the corridor that is covered with gravel. Structural grid is 4.5m x 4.5m with massive square columns (60cm x 60cm) (Cagic 1976). Two types of panels and brick parapets were used for the facade. Some of the scientific publications about this system include the information that thermal insulation was used between concrete layers in panels, but this is not mentioned in the project documentation (Laban 2012). Without insulation, thermal performances of buildings constructed in the NS-71 system are at the low level.

The apartment building block consists of two or more buildings that are usually not placed in a straight line, so that the side walls of the two adjacent units are partly adiabatic. The typical unit layout has four apartments per floor and a corridor with staircase and elevator in the centre of the building. One unit situated in the middle of the building was modeled for the analyses (Figure 41 and Figure 42). As in the previously analyzed models, each floor was divided into three thermal zones. Two north apartments form the north zone, and south zone consists of two apartments oriented towards south (Figure 43). The corridor and staircase are modelled as a shaft and they form one unheated zone through the whole building. The top floor has two apartments oriented towards the north and the roof terrace on the south side (Figure 44).

Figure 41 - Residential building built in system NS71

Figure 42 - Building model created in Open Studio

The facade was built using two types of panels and brick wall. Finishing layer for both types of panels is exposed aggregate concrete. The full-height wall panels were made of haydite concrete while cellular concrete was used for the parapet panels. Heat transfer coefficient is high for all three facade types. The worst thermal performance has full-height wall panel with U-value of 1.92 $W.m^{-2}.K^{-1}$. Windows have wooden frames and double glazing.

The flat roof was insulated with wood chip board and it has better thermal performance. The roof terrace is paved with concrete tiles over sand and hollow brick, that also add to insulation properties, U-value is 0.69 $W.m^{-2}.K^{-1}$.

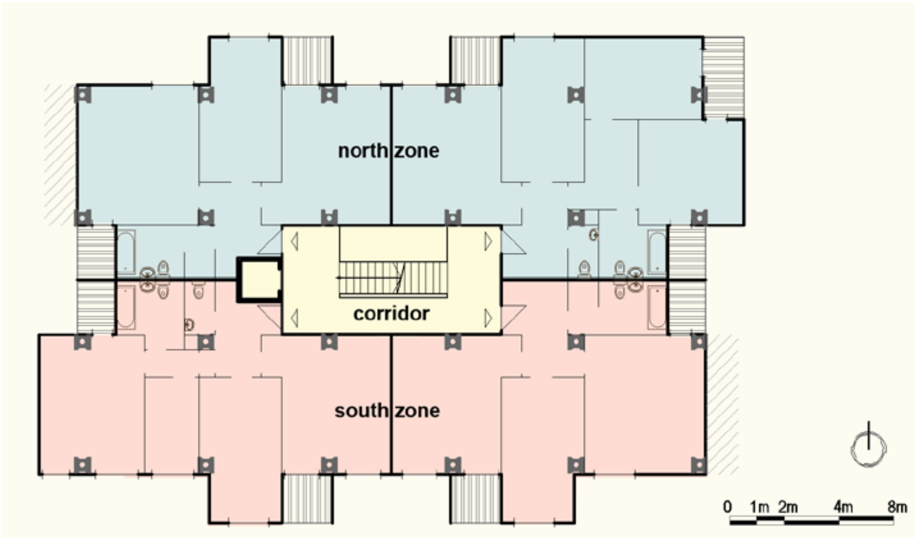

Figure 43 - Zoning of the building - typical floor NS-71

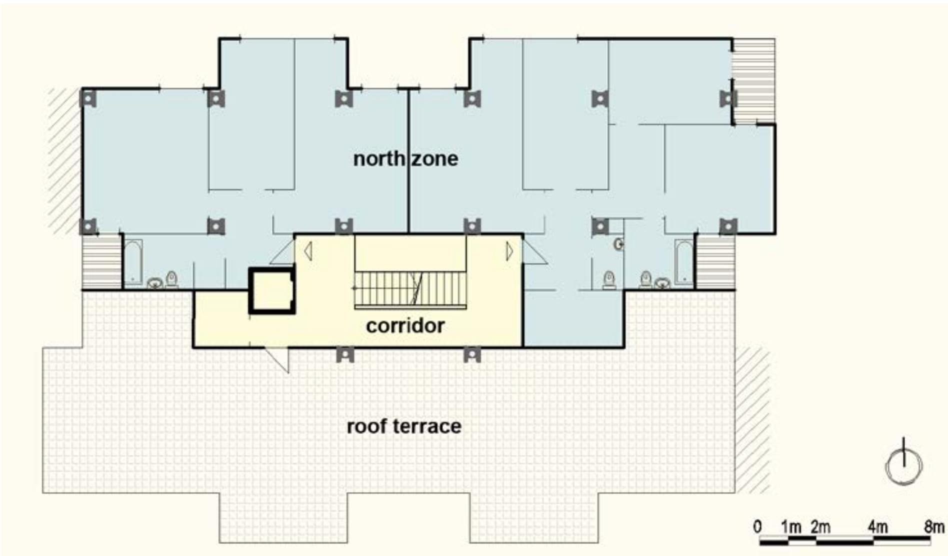

Figure 44 - Zoning of the building - top floor NS-71

Physical properties of the materials used for the construction of building elements in the analyzed building are presented in Table 10 and Table 11.

Table 10 - NS-71 Materials

Building Element	Thickness [m]	Conductivity [W.m^{-1}.K^{-1}]	Density [kg.m^{-3}]	Specific Heat [J.kg^{-1}.K^{-1}]	U-value [W.m^{-2}.K^{-1}]
Panel					1,922
exposed aggregate concrete	0,06	2,33	2500	960	
haydite concrete	0,2	0,58	1400	1000	
Parapet Panel					1,848
exposed aggregate concrete	0,08	2,33	2500	960	
cellular concrete	0,125	0,35	800	1050	
Brick Wall					1,582
hollow brick	0,12	0,61	1400	920	
cellular concrete	0,1	0,35	800	1050	
Existing Roof					0,690
gravel	0,04	0,81	840	1700	
waterproofing	0,005				
hollow brick	0,07	0,61	1400	920	
wood chip board	0,05	0,15	460	1600	
vaporseal	0,005				
cement screed	0,04	1,4	2000	1080	
reinforced concrete	0,04	2,5	2400	1100	
hollow clay block	0,16	0,52	1200	920	
cement plaster	0,02	1,4	2100	1050	
Existing Roof - Paved Roof					0,695
concrete tiles	0,03	2,33	2400	960	
sand	0,02	0,58	1400	800	
waterproofing	0,005				
hollow brick	0,07	0,61	1400	920	
wood chip board	0,05	0,15	460	1600	
vaporseal	0,005				
cement screed	0,04	1,4	2000	1080	
reinforced concrete	0,04	2,5	2400	1100	
hollow clay block	0,16	0,52	1200	920	
cement plaster	0,02	1,4	2100	1050	
Floor/Ceiling					
parquet	0,025	0,21	700	1670	
cement screed	0,04	1,4	2000	1080	
reinforced concrete	0,04	2,5	2400	1110	
hollow clay block	0,16				
cement plaster	0,02	0,16	800	1090	
Floor to Ground					
terazzo	0,0254	1,8	2560	790	
cement screed	0,04	1,4	2000	1080	
waterproofing	0,005				
wood chip board	0,05	0,15	460	1600	
concrete slab	0,2	2,5	2400	1110	
waterproofing	0,005				
concrete	0,08	2,5	2400	1110	
Wall Between Apartments					
cellular concrete	0,19	0,35	800	1050	
Partition Wall					
hollow brick	0,07	0,61	1600	920	
Wall to Corridor					
reinforced concrete	0,15	2,5	2400	110	

Table 11 - NS-71 Refurbished roof materials

Building Element	Thickness [m]	Conductivity [W.m^{-1}.K^{-1}]	Density [kg.m^{-3}]	Specific Heat [J.kg^{-1}.K^{-1}]	U-value [W.m^{-2}.K^{-1}]
Refurbished Roof					0.142
gravel	0.03	0.81	840	1700	
waterproofing	0.01				
thermal insulation XPS	0.2	0.033	32	1210	
vapourseal	0.005				
cement screed	0.04	1.4	2000	1080	
reinforced concrete	0.04	2.5	2400	1100	
hollow clay block	0.16	0.52	1200	920	
cement plaster	0.02	1.4	2100	1050	
Refurbished Roof - Paved Roof					0.115
concrete tiles	0.03	2.33	2400	960	
sand	0.02	0.58	1400	800	
waterproofing	0.01				
thermal insulation XPS	0.2	0.033	32	1210	
vapourseal	0.005				
cement screed	0.04	1.4	2000	1080	
reinforced concrete	0.04	2.5	2400	1100	
hollow clay block	0.16	0.52	1200	920	
cement plaster	0.02	1.4	2100	1050	

Table 12 - Overview of the characteristics of the analyzed buildings

analyzed building	IMS NS1 	IMS N 	NS-71 
year of the construction	1962-1965	1976	19790s
number of storeys including ground floor	5	6-7	6-7
sides exposed to outdoor conditions	4	2	3
top layer of the existing roof	gravel	gravel/ concrete tiles	gravel/ concrete tiles
U-value of facade elements [$W.m^{-2}.K^{-1}$]	1.65 - 1.67	0.55	1.58 - 1.92
U-value of lightweight window posts [$W.m^{-2}.K^{-1}$]	1.79	1.79	-
U-value of existing roof [$W.m^{-2}.K^{-1}$]	1.14	0.56 - 0.57	0.69
U-value of refurbished roof [$W.m^{-2}.K^{-1}$]	0.14	0.14	0.14
U-value of green roof [$W.m^{-2}.K^{-1}$]	0.12	0.12	0.12

4 RESULTS

The performance of the different roof types was analyzed and simulation results were evaluated. For each building model existing roof and three other roof types were simulated. Every roof scenario was simulated twice, as it was described in the previous chapter (see Figure 33). First as a free running model, without input parameters for heating and cooling, in order to obtain data for comparison of indoor temperatures. Then, it was simulated as a conditioned building for the calculation of the energy demand. Refurbishment or replacement of the roof mostly affects the top building floor, and the whole building to a smaller extent. Considering this fact, results for the top floor are described in the next chapters in a more detailed manner.

4.1 Residential Building Type IMS NS-1

The residential building type IMS NS-1 has high heat transfer coefficient for both facade elements and roof. Replacement of the roof resulted into significant reduction of energy demand. If we compare annual heating and cooling loads for the whole building, heating is reduced by 17% with the refurbished roof and by 18% with the green roof. Reduction in the cooling load is smaller, both new roofs reduce it by 4%. Besides thermal insulation, the reflectivity of the roof has an additional impact on the cooling load. Simulation results show that a white roof reduces cooling demand more than other two roof types. Annual energy cooling demand for white roof is 24.61 $kWh.m^{-2}$, that is a reduction of 10%.

This reduction is more considerable for the top floor, where the heating demand decreases to almost half of the amount. Heating energy demand equals 91.4 $kWh.m^{-2}$ per year with the existing roof. Refurbished roof reduces consumption by 46% (49.3 $kWh.m^{-2}.a^{-1}$), while green roof heating load comprises 47.3 $kWh.m^{-2}$ per year, that is a reduction of 48%. Heating load reduction in the lower floors showed insignificant differences to original construction. The green roof reduces energy consumption on the third floor by 8%, and refurbished roof by 7%.

Monthly energy consumption used for heating in south and north zone of the fourth floor is presented in Figure 45 and Figure 46. Reduction achieved with the new roof is approximately 50% for each month, regardless of the zone orientation.

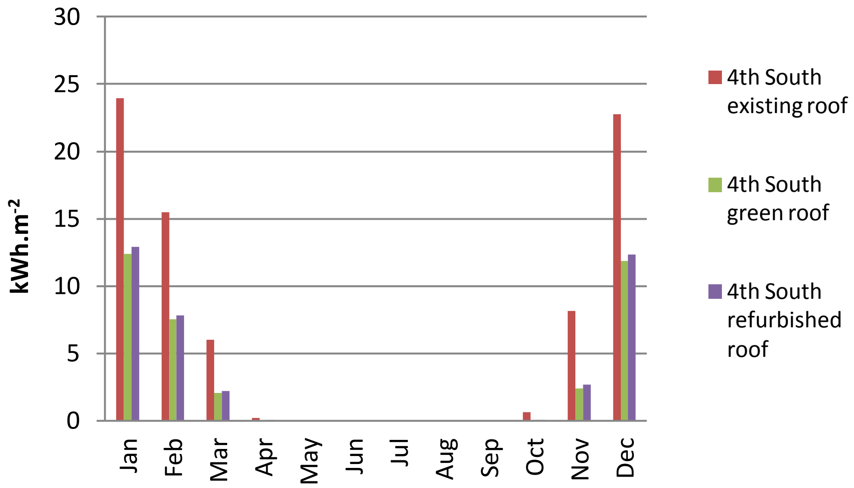

Figure 45 - Monthly heating load per m² for the top floor south zone IMS NS-1

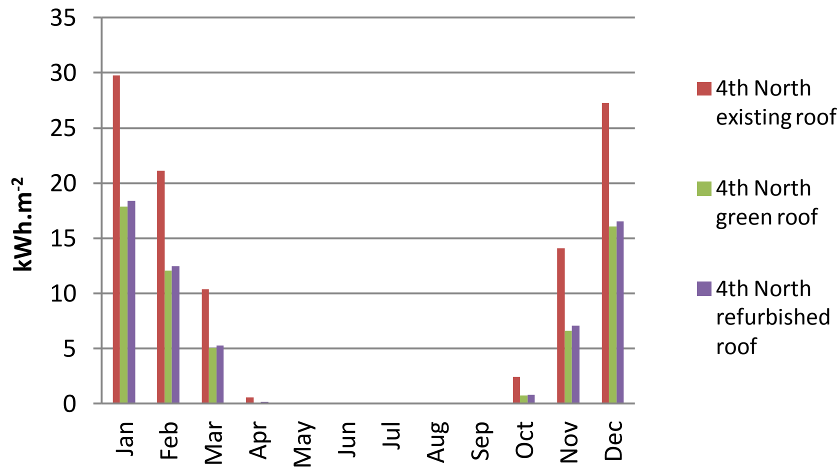

Figure 46 - Monthly heating load per m² for the top floor north zone IMS NS-1

The difference in energy consumption used for cooling in analyzed roof scenarios is smaller than the difference in the heating energy loads. Occupants of apartments situated on the last floor of simulated building would have to use 26 kWh.m^{-2} of energy per year for cooling in order to obtain comfortable indoor temperature. If the roof is replaced with a green roof, or thermal insulation is added, cooling load decreases by 15%. If the top layer of the roof has a higher reflectivity, cooling load is reduced by 37%. The results are represented in Figure 47.

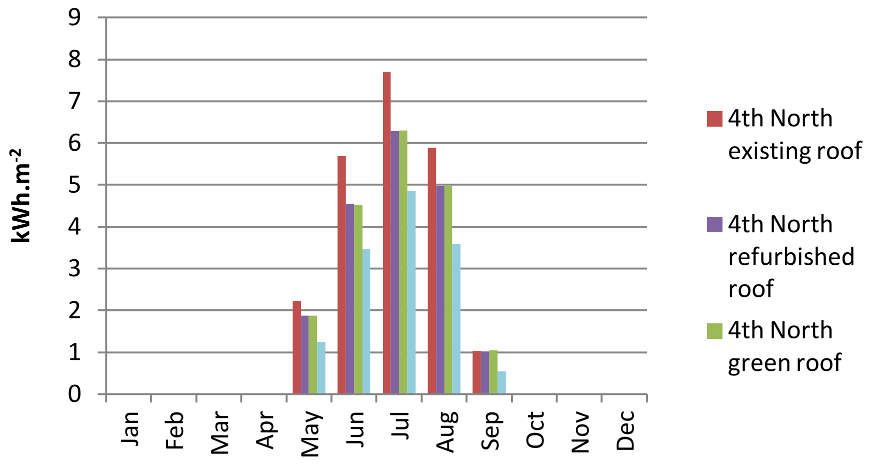

Figure 47 - Monthly cooling load per m^2 for the top floor north zone IMS NS-1

The performance of different roof types can be observed through indoor temperature values for a free running model.

When indoor temperatures of the last floor are compared, it can be easily noticed that during the Winter temperatures are higher with the green roof than with the existing roof, while in Summer they are somewhat lower (Figure 48). This difference is noticeable in both zones of the last floor, but it becomes smaller on each floor that is lower in the building.

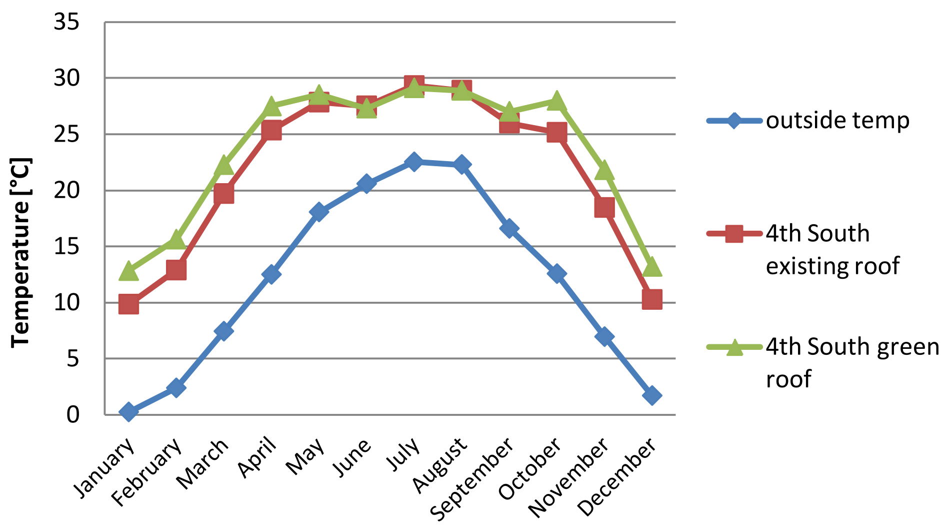

Figure 48 - Monthly temperatures for the top floor south zone IMS NS-1

Indoor temperatures with the refurbished roof are similar to the temperatures with the green roof (Figure 49 and Figure 50).

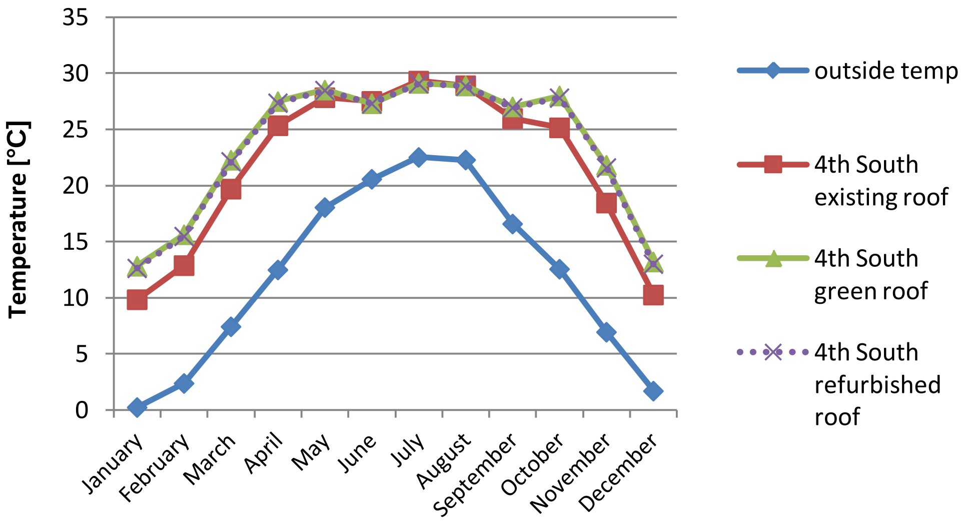

Figure 49 - Monthly temperatures for the top floor south zone IMS NS-1

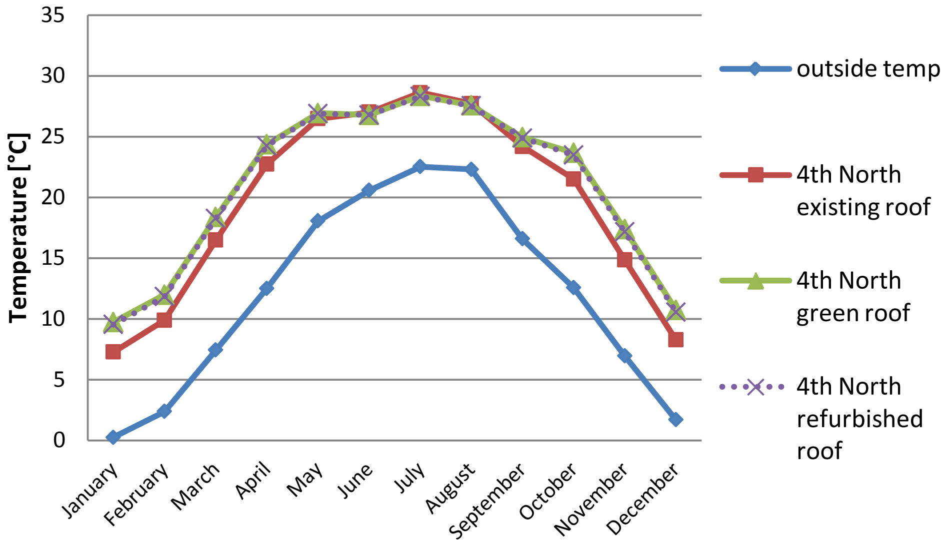

Figure 50 - Monthly temperatures for the top floor north zone IMS NS-1

Day with the lowest temperature in the used weather file was January 12th with -13.3°C. The temperature difference between existing and green or refurbished roof is approximately 3 degrees. Indoor temperature of the last floor under the green roof is slightly higher than under the refurbished roof (Figure 51).

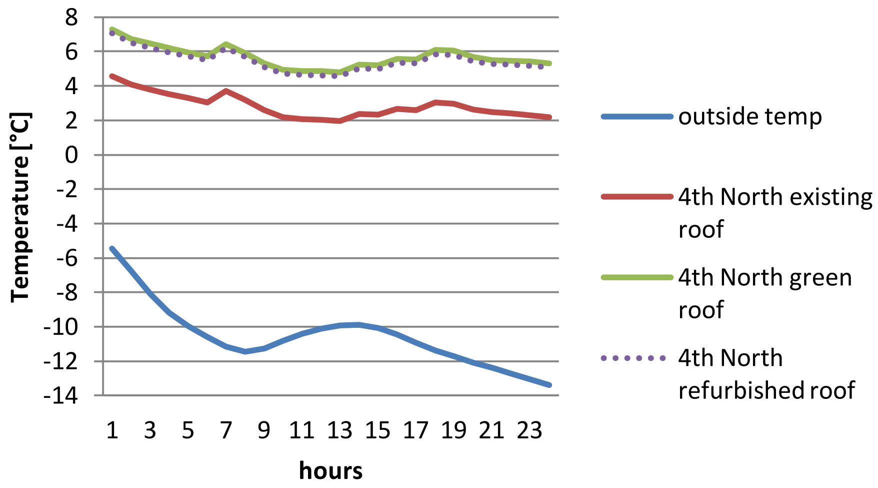

Figure 51 - Hourly temperature on January 12th IMS NS-1

The hottest day with the temperature of 35.7°C was July 21st. On this day, indoor temperatures for all three scenarios are similar from the morning until the midday. In the afternoon, the temperature under the existing roof becomes higher - reaching the point of 35°C in the evening before the natural ventilation starts, while the highest temperature for other two scenarios is 34°C. If the roof has white paint coating, temperatures are lower during the whole day with the peak temperature of 33°C (Figure 52). The difference in the performance of the analyzed roof types and their impact on the indoor temperatures is more noticeable in the chart that shows the hourly temperatures for the day after the hottest day of the year (Figure 53).

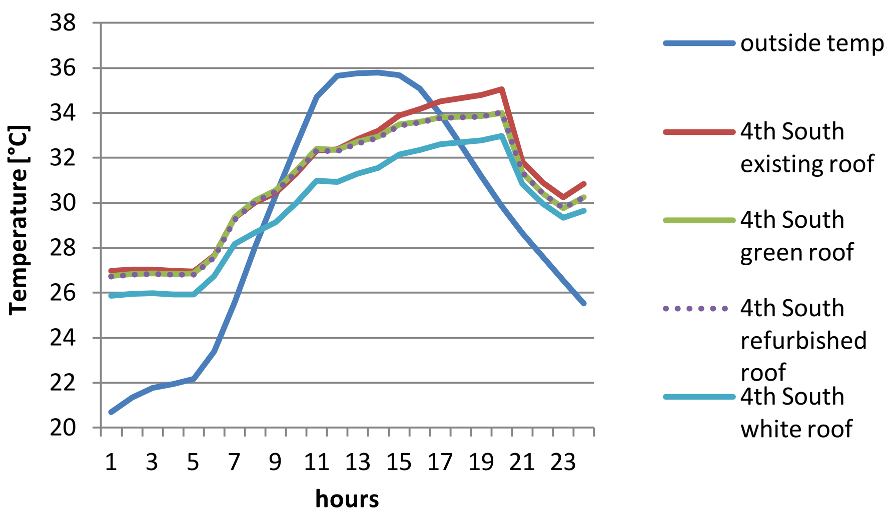

Figure 52 - Hourly temperature on July 21st for the top floor south zone IMS NS-1

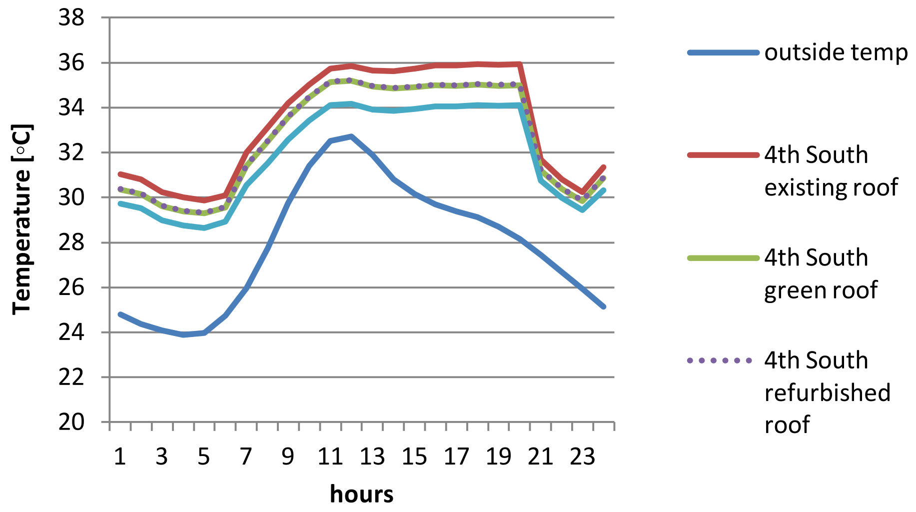

Figure 53 - Hourly temperature on July 22nd for the top floor south zone IMS NS-1

In the time period between 1st of June and 31st of August, there are 10935 degree hours above 27°C in the both thermal zones of the top floor (Figure 54). Both new roofs reduce the number of overheating hours by roughly 7% while the white roof is more efficient and it lowers the number of degree hours with temperature higher than 27°C by 38%. The reduction rate is higher in the north thermal zone than in the south zone.

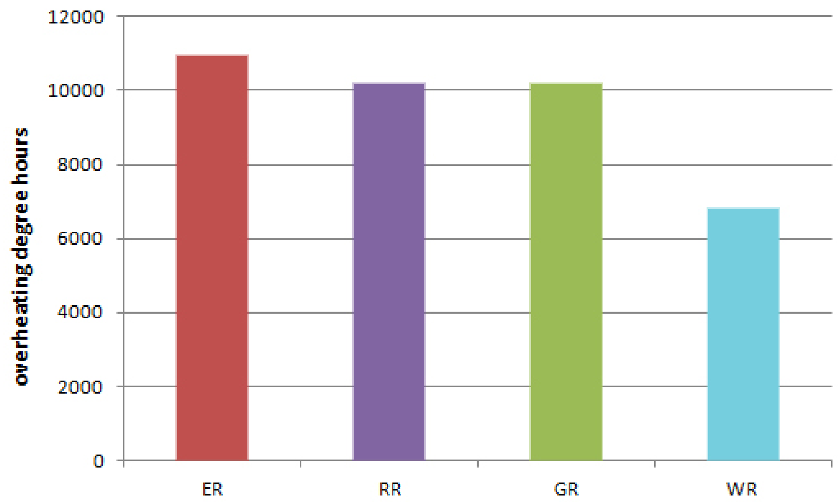

Figure 54 - Overheating degree hours in period between 1st of June and 31st of August for the top floor IMS NS-1

In Figure 55 flood plots are showing indoor temperatures in 4th floor south zone during the month of July. As it can be observed, white roof performed better than the other roof types. Green roof and refurbished roof noticeably decreased temperatures in comparison to the existing state of the building.

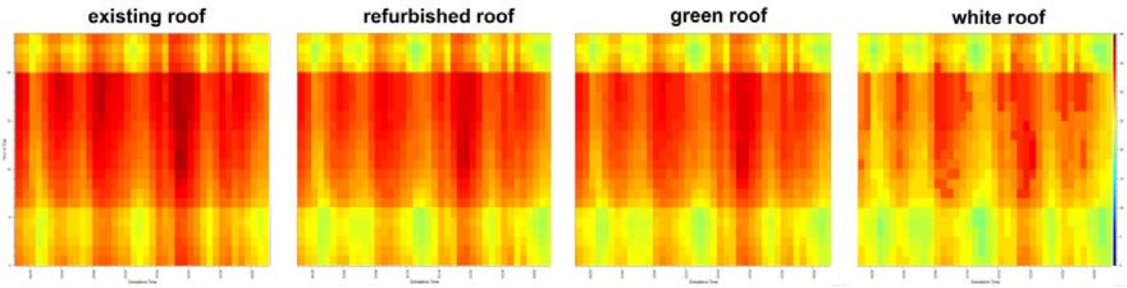

Figure 55 - Flood plots for zone air temperature in July IMS NS-1

4.2 Residential Building Type IMS N

Residential building type IMS N have better thermal performances of the envelope when compared with older buildings built in the IMS system. Heating energy demand for the simulated model with the existing roof is relatively low - 23.10 kWh.m^{-2}.a^{-1}, which can be explained with the fact that the building is a compact volume, adjacent to the neighbouring units from two sides. Walls on these two sides were simulated as adiabatic. With the replacement of the roof, energy consumption decreases by 15%. Refurbished roof decreases consumption to 19.75 kWh.m^{-2}.a^{-1}, and with green roof it is almost identical - 19.42 kWh.m^{-2}.a^{-1}. Cooling load for existing state of the building is 11.25 kWh.m^{-2}.a^{-1}, both new roofs reduce cooling demand by 5% (10.72 kWh.m^{-2}.a^{-1} with refurbished roof and 10.68 kWh.m^{-2}.a^{-1} when roof is green). White roof with high reflectance reduces it by 16% (9.25 kWh.m^{-2}.a^{-1}).

Heating load for the three thermal zones situated on the top floor (south and north zone of the 6th floor and south zone of the 5th floor) in existing state of the building is 35.74 kWh.m^{-2}.a^{-1}. Refurbished roof reduces consumption by 41% (21.22 kWh.m^{-2}.a^{-1}), while green roof is slightly more effective and has reduction of 45% (19.84 kWh.m^{-2}.a^{-1}). If each zone is analyzed separately, it can be concluded that the highest reduction is achieved in the top 6th floor south zone - refurbished roof reduces heating load by 52% and green roof by 57%. Monthly heating energy demand per square meter for three zones is presented in the following charts.

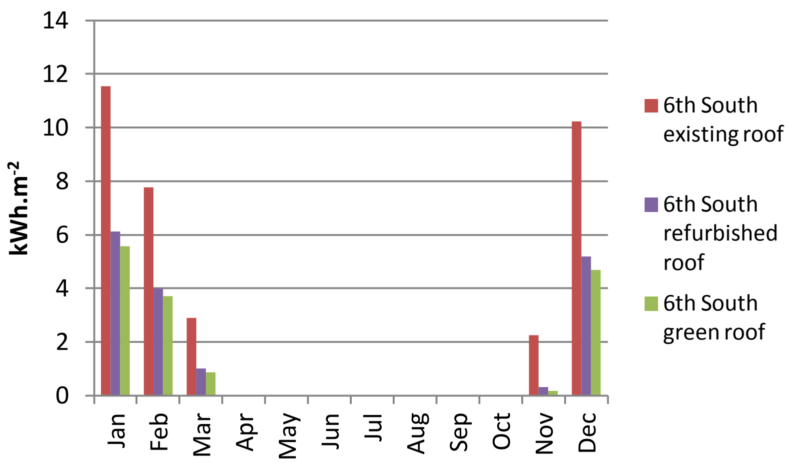

Figure 56 - Monthly heating load per m^2 for the 6th floor south zone IMS N

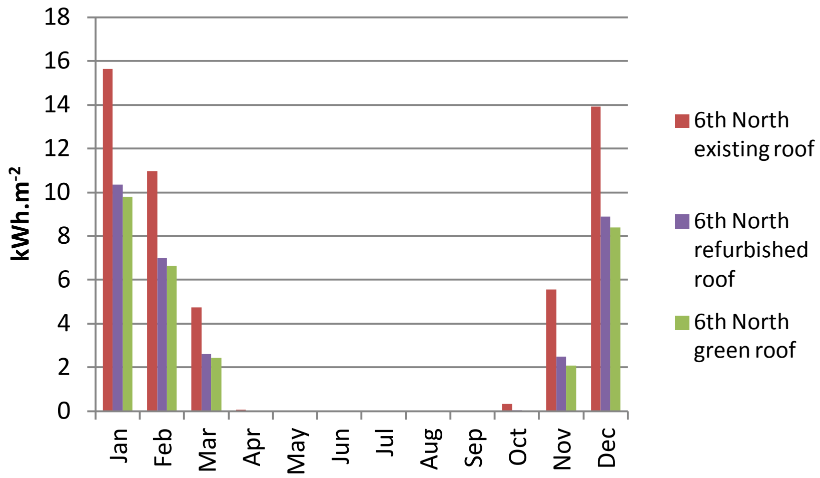

Figure 57 - Monthly heating load per m² for the 6th floor north zone IMS N

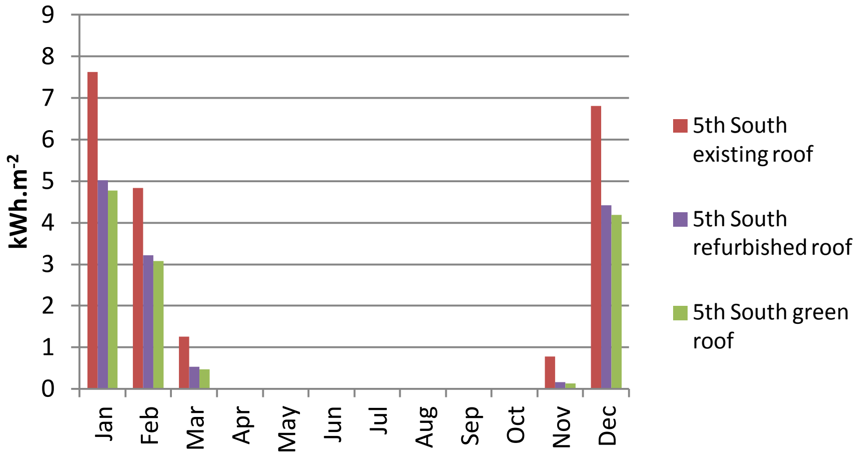

Figure 58 - Monthly heating load per m² for the 5th floor south zone IMS N

Building type IMS N, with adiabatic outside walls on two sides and with better thermal performances of the envelope, consumes less energy for cooling than the older type IMS NS1. Annual cooling consumption for the simulated unit with the existing roof is 11.25 kWh.m^{-2}. Consumption decreases by 5% when the roof is replaced, but if the roof surface has a higher reflectivity, the reduction is more considerable - 16%.

Similar to the heating load, reduction in a cooling load is the most noticeable in the thermal zones that are situated under the roof. Refurbished and green roof reduce the cooling load in three thermal zones under the roof by 16% and 18% respectively. The white roof was more effective and it reduced the cooling energy consumption by 38%. The reduction is greater in the zones on the 6th floor than in the 5th-floor zone. Monthly cooling loads for the 6th floor south zone are presented in Figure 59.

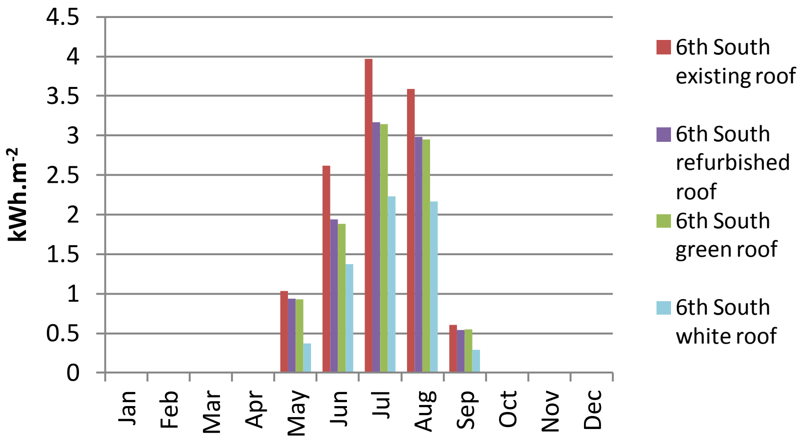

Figure 59 - Monthly cooling load per m^2 for the 6th floor south zone IMS N

Simulation of the free running model allows us to compare the performance of different roof types through indoor temperature values. The Figure 60 shows average monthly values of indoor temperatures for thermal zone oriented towards north on the top, 6th floor.

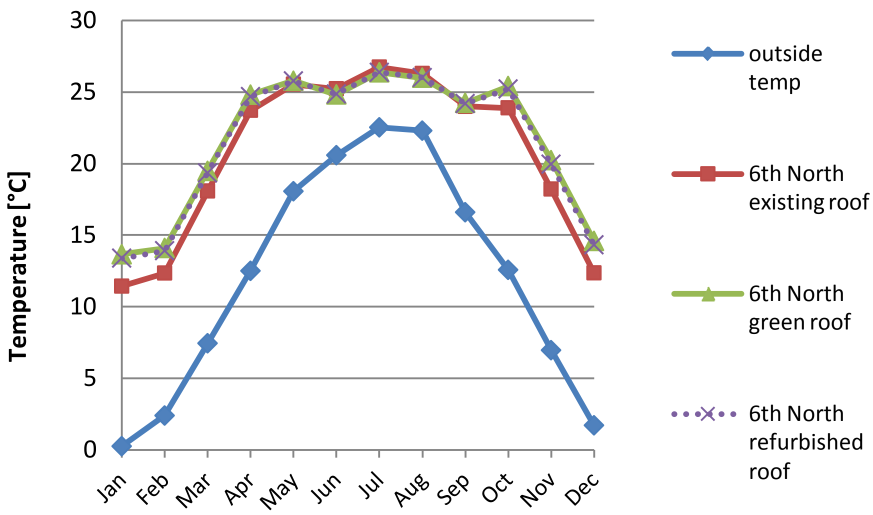

Figure 60 - Monthly temperatures for the 6th floor north zone IMS N

In comparison to the existing roof, the refurbished roof and the green roof are providing higher temperatures during the Winter and lower during the Summer. This can be better observed in charts that show hourly temperatures during the coldest and hottest day of the year. Indoor temperatures on the 12th of January are in average 3 degrees higher when the roof is replaced (Figure 61).

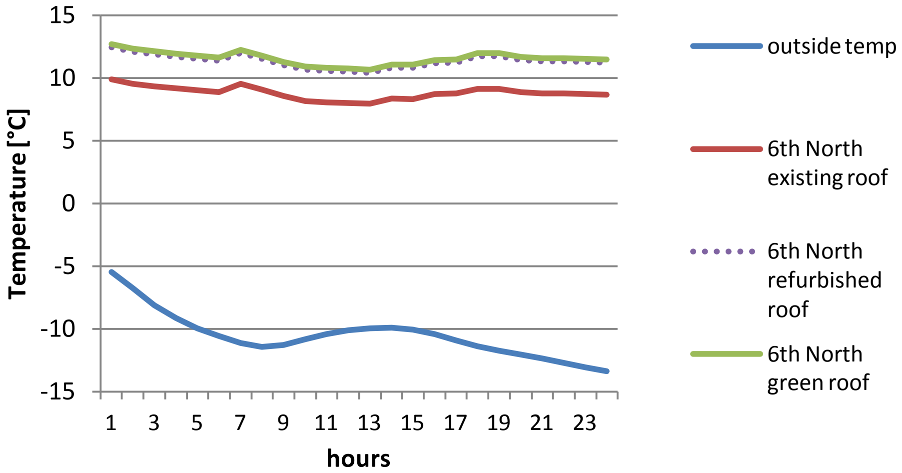

Figure 61 - Hourly temperatures on January 12th for the 6th floor north zone IMS N

The hourly temperatures for the hottest day of the year - July 21st and for the following day are presented in Figure 62 and Figure 63.

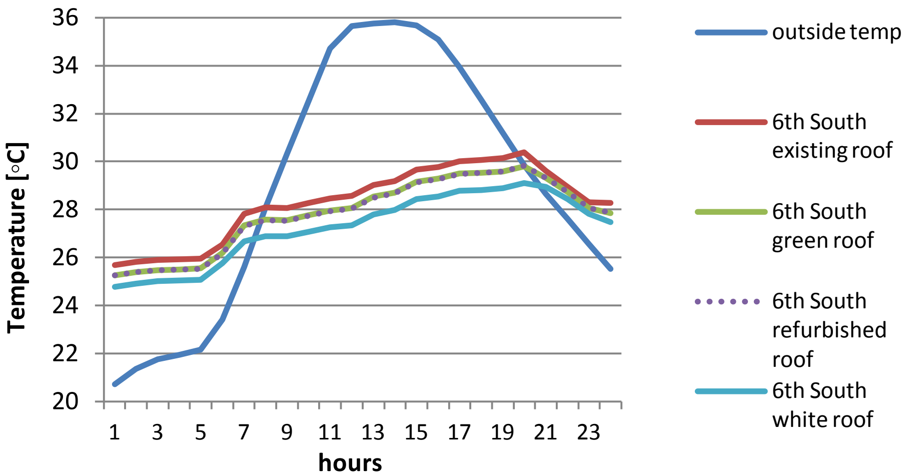

Figure 62 - Hourly temperatures on July 21st for the 6th floor south zone IMS N

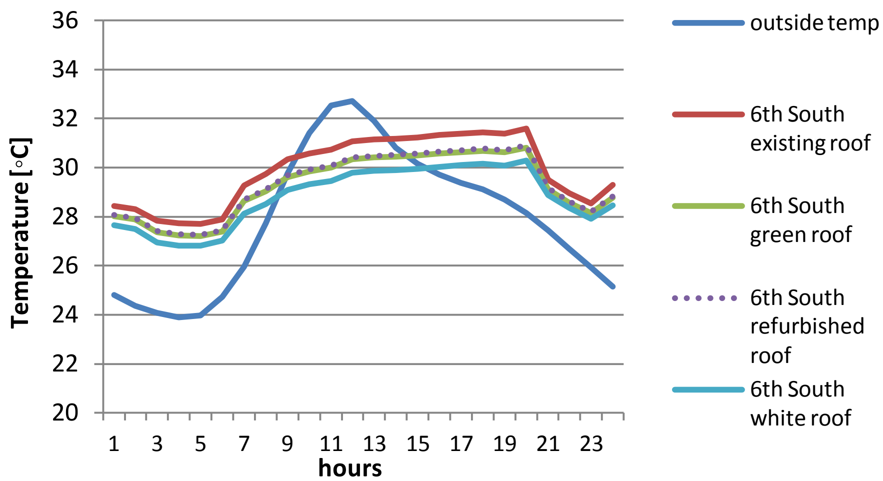

Figure 63 - Hourly temperatures on July 22nd for the 6th floor south zone IMS N

Number of overheating degree hours during the summer months can be compared for different roof types in order to evaluate their cooling efficiency (Figure 64). In all of the three top thermal zones green and refurbished roof decrease number of overheating degree hours by a similar percent. More effective is a roof with high solar reflectivity. In all three thermal zones that are situated under the roof, there are 6827 degree hours above 27°C with the existing roof. Refurbished roof reduces the number of overheating degree hours by 17% and green roof by 19%. With the white roof number of overheating degree hours drops by 40%. The reduction rate is the highest in the thermal floor of the 6th floor that is oriented towards north.

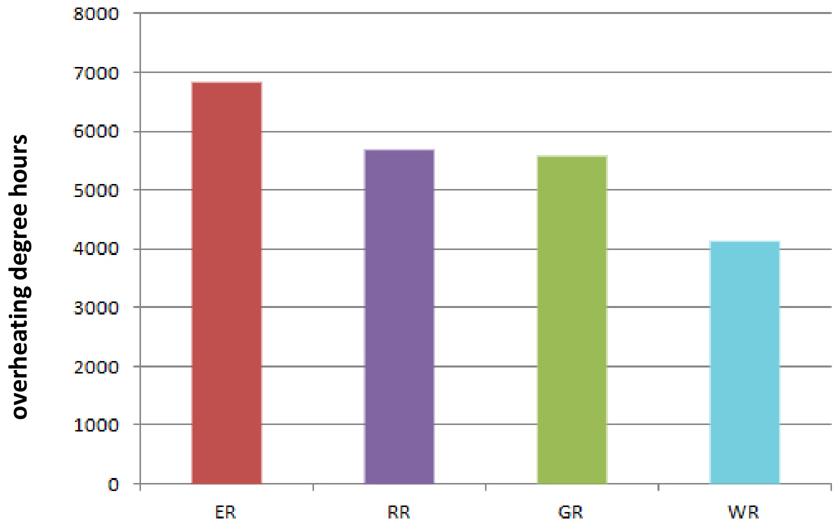

Figure 64 - Overheating degree hours in period between 1st of June and 31st of August - top floor IMS N

The cooling performance of different roof types is presented in flood plots in Figure 65. Plots are showing hourly indoor temperatures in the south zone of the 6th floor during the month of July. The range of colors is showing the performance of the each roof type.

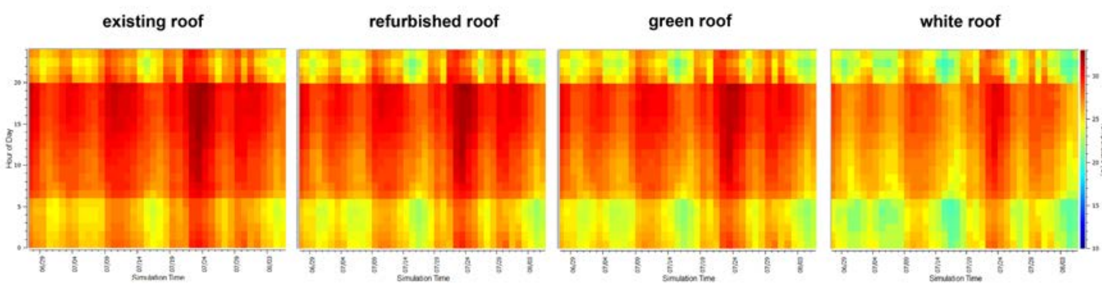

Figure 65 - Flood plots for zone air temperature in July in the south zone of the 6th floor IMS N

4.3 Residential Building Type NS-71

The semi-prefabricated system NS-71 used facade elements that have high heat transfer coefficient, but the roof has better thermal performances. Effect of the roof replacement on the building with these characteristics was examined. Annual heating load of the building is 63.05 kWh.m^{-2} before changes in the roof construction. When the model is simulated with a refurbished roof, consumption drops by 8% and by 9% in the case of a green roof. Both new roofs decrease annual cooling load by 5% while the white roof is more effective with reduction of 9%. As in previous examples, the reduction is greater in the zones that are directly under the roof. Consumption of energy used for heating for the north zone on the 6th floor and south zone on the 5th floor is 89.72 kWh.m^{-2}. Refurbished roof lowers this value by 26% and green roof by 28%. If these two zones are analyzed separately (Figure 66 and Figure 67), it is noticeable that the consumption per square meter is lower in the zone on 5th floor, that is oriented towards south, and that in the same zone the reduction is greater (31% for refurbished roof and 32% for green roof, compared to 23% and 25% in the zone on the 6th floor).

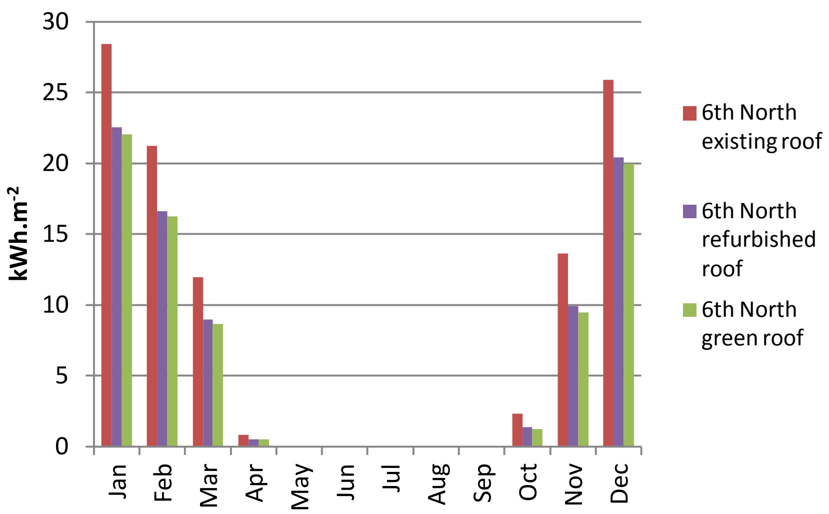

Figure 66 - Monthly heating load for the 6th floor north zone NS-71

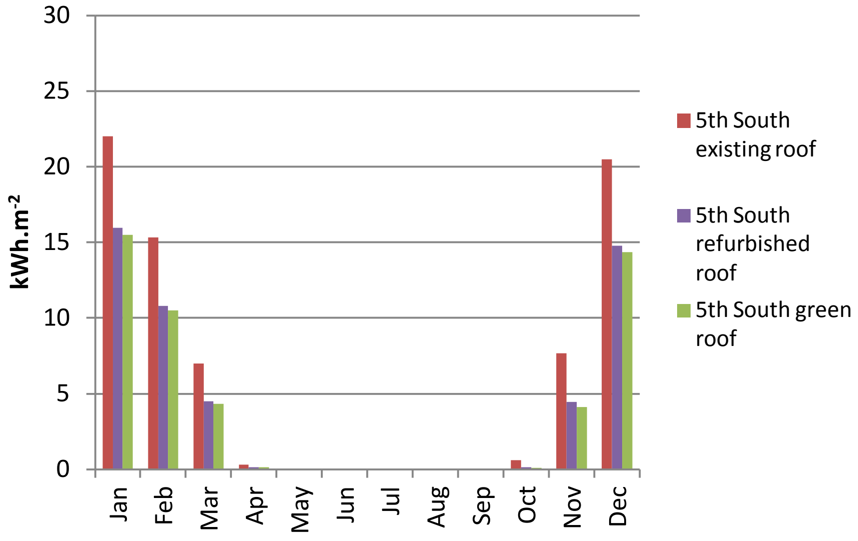

Figure 67 - Monthly heating load for the 5th floor south zone NS-71

When it comes to the consumption during summer months both new roofs have the same success rate, they reduce cooling load by 17%. The white roof is more successful with the reduction of 30%. There is no difference in reduction rate between the two top floor zones.

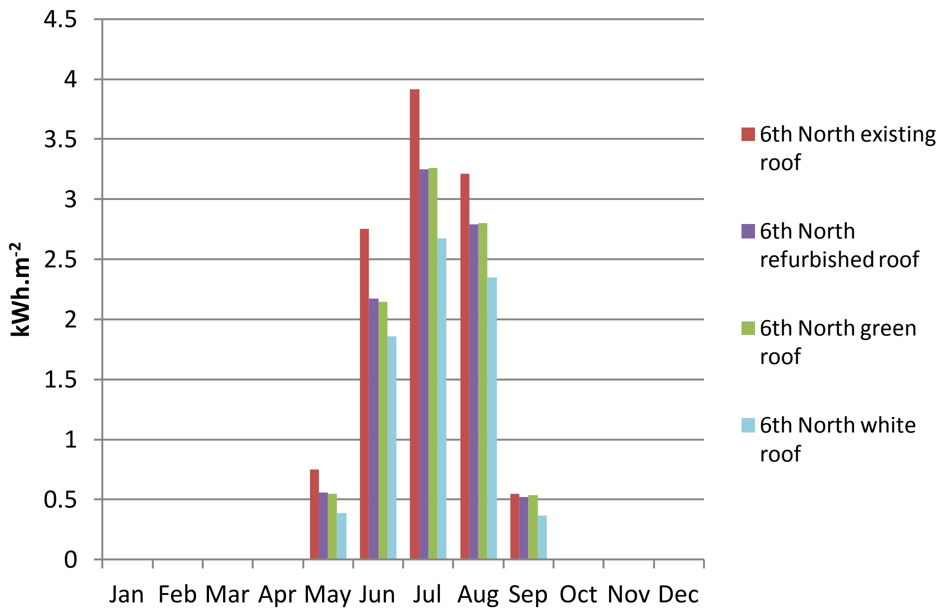

Figure 68 - Monthly cooling load for the 6th floor north zone NS-71

Indoor temperature values in the thermal zones under the roof are compared after simulation of the free running model. Average monthly values of the indoor temperatures for the north zone on the 6th floor are presented in Figure 69.

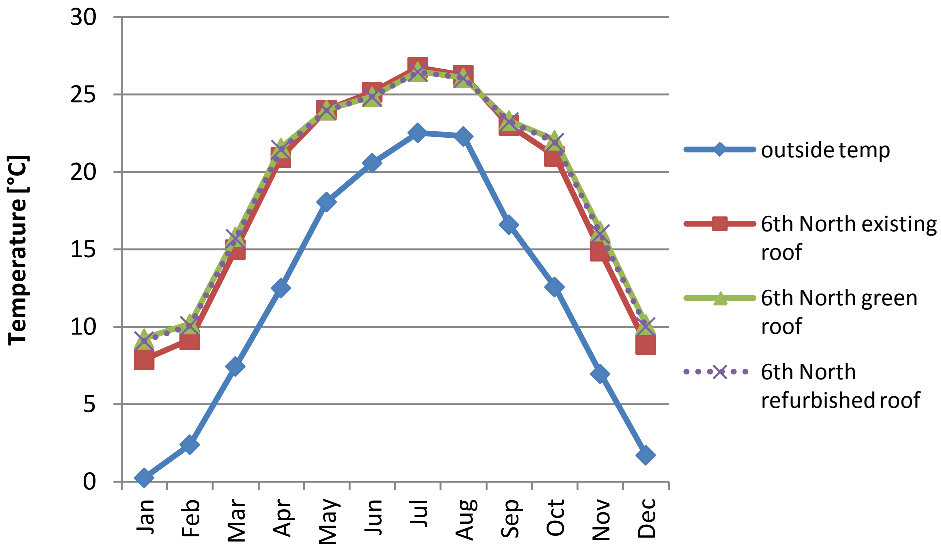

Figure 69 - Monthly temperatures for the 6th floor north zone NS-71

The difference in temperatures can be better observed in charts that show hourly temperatures during the coldest and hottest day of the year for the same thermal zone (Figure 70 and Figure 71).

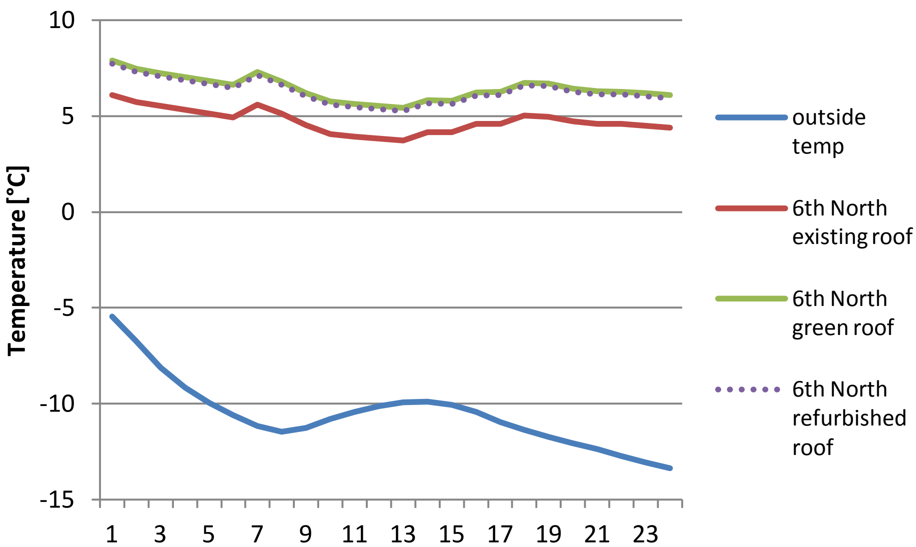

Figure 70 - Hourly temperatures on the January 12th for the 6th floor north zone NS-71

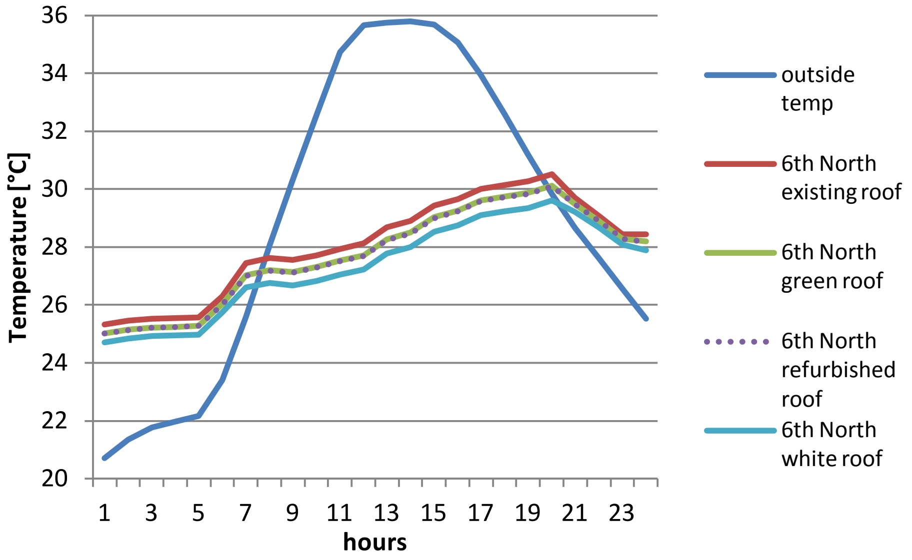

Figure 71 - Hourly temperatures on July 21st for the 6th floor north zone NS-71

The chart in Figure 72 shows the hourly temperatures during the day that follows the hottest day of the year.

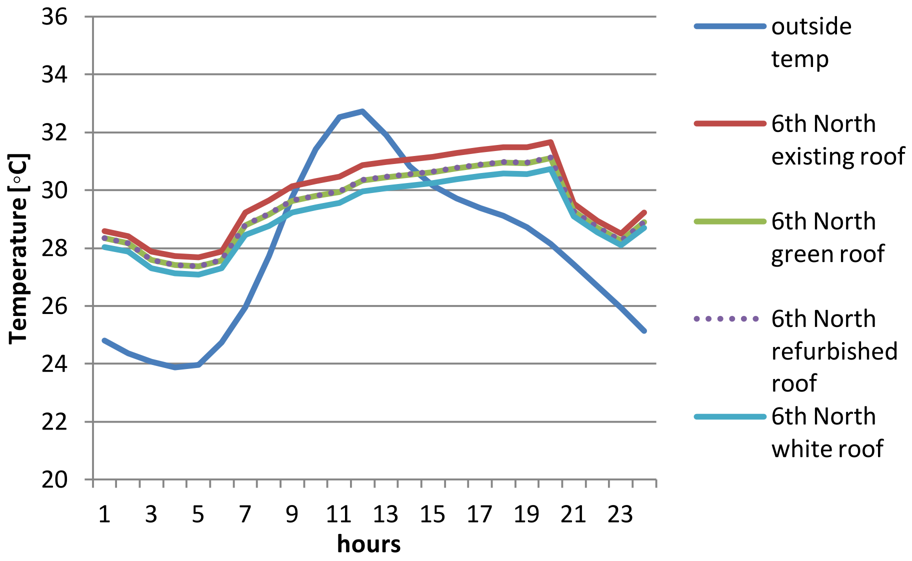

Figure 72 - Hourly temperatures on July 22nd for the 6th floor north zone NS-71

The efficiency of different roof types was analyzed through comparison of number of overheating degree hours in the period between 1st of June and 31st of August (Figure 73). In two thermal zones situated under the roof number of degree hours above 27°C is 4614 in the existing state. Refurbished roof and green roof reduce this number by 16% and 17%, respectively. Roof with high solar reflectivity is the most effective with reduction of 34%. Results are similar for each separate zone.

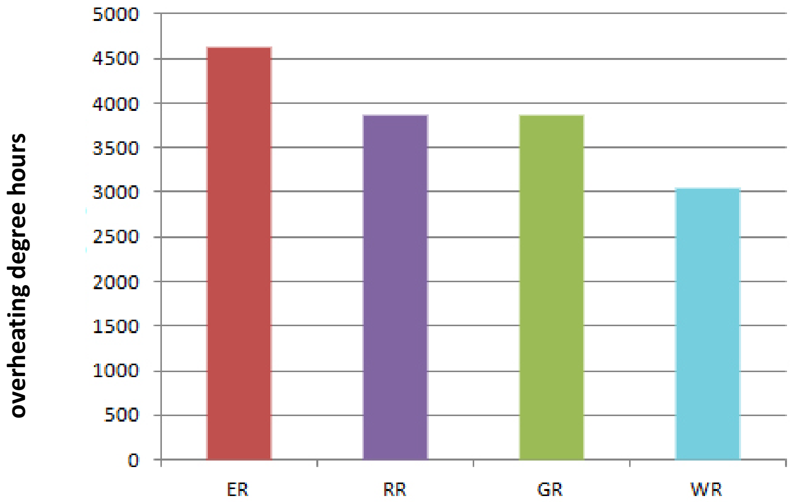

Figure 73 - Overheating degree hours in period between 1st of June and 31st of August for the top floor zones NS-71

Hourly indoor temperatures during the month of July in the south zone of the 5th floor are presented in flood plots in Figure 74.

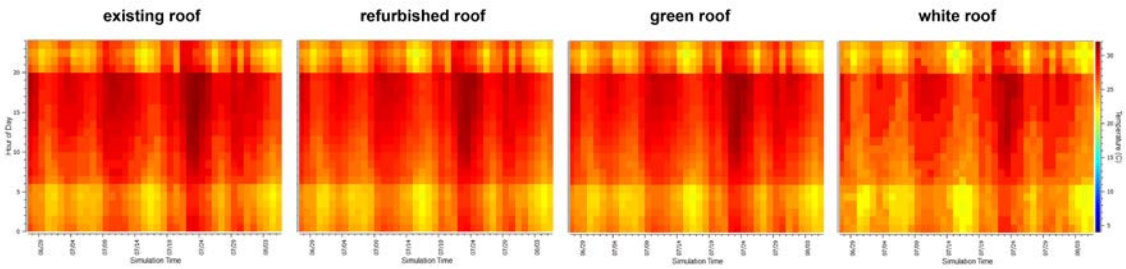

Figure 74 - Flood plots for zone air temperature in July in the south zone of the 5th floor NS-71

5 COMPARISON OF THE RESULTS AND DISCUSSION

The difference between heating and cooling loads of each building is rather significant. This is explained by different building geometry and thermal properties of the envelope. In the comparison of the annual heating consumption per square meter (Figure 75), it is noticeable that the building type IMS N showed the best performances due to the characteristics of its envelope as well as the position of the analyzed unit within the building.

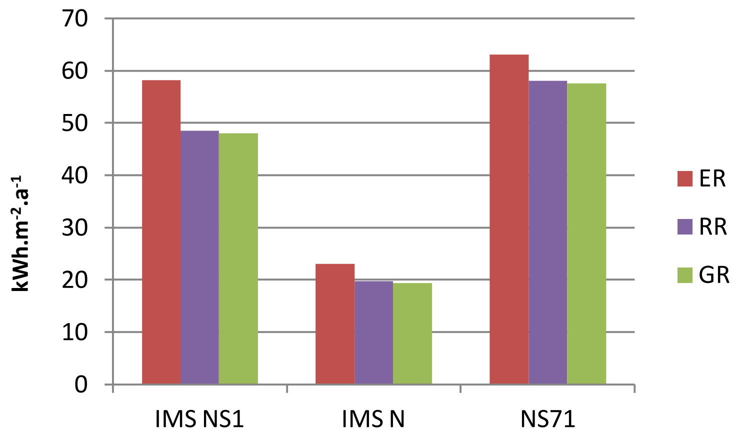

Figure 75 - Annual heating load per m² per analyzed building model

Reduction of the heating load (Figure 76) after the replacement of the roof is more significant for the two IMS building types, while the new roofs influenced heating consumption in NS-71 type to a lower extent (8% reduction with refurbished roof and 9% with green roof). This difference is due to the better thermal characteristics of the existing roof but the worse thermal performance of the facade elements of the NS-71 building, in comparison with the characteristics of the envelope of IMS buildings. Green roof is slightly more effective than refurbished roof in all three analyzed examples. The study conducted by Nichaou et al. (2001) showed that the green roof reduces heating load in greater percent when applied on not well-insulated buildings. This was confirmed in the case of the IMS NS1 building that is characterized with poor thermal characteristics of both roof and facade. In a case of a building with not well insulated facade and a roof with low U-value, replacement of the roof doesn't have a significant effect.

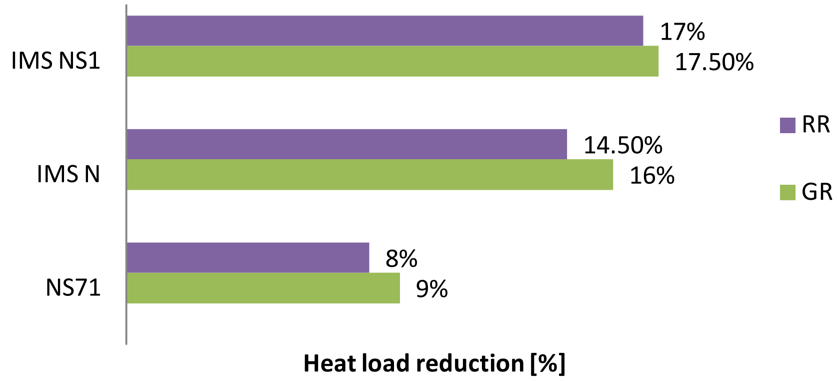

Figure 76 - Reduction in heating load per analyzed building model

As it was mentioned in separate analyses, replacement of the roof influences the most the thermal zones on the top floor. Heating load is the highest for the building IMS NS1 (Figure 77). The reduction is nearly 50% on the top floor of IMS NS1 building type, little less for the IMS N type and significantly lower for the last analyzed type. The orientation of the thermal zone is influencing the energy consumption, and in the lesser amount the reduction rate with the replacement of the roof. When the two charts in Figure 77 are analyzed, considerably lower heating energy load in the south thermal zone can be noted.

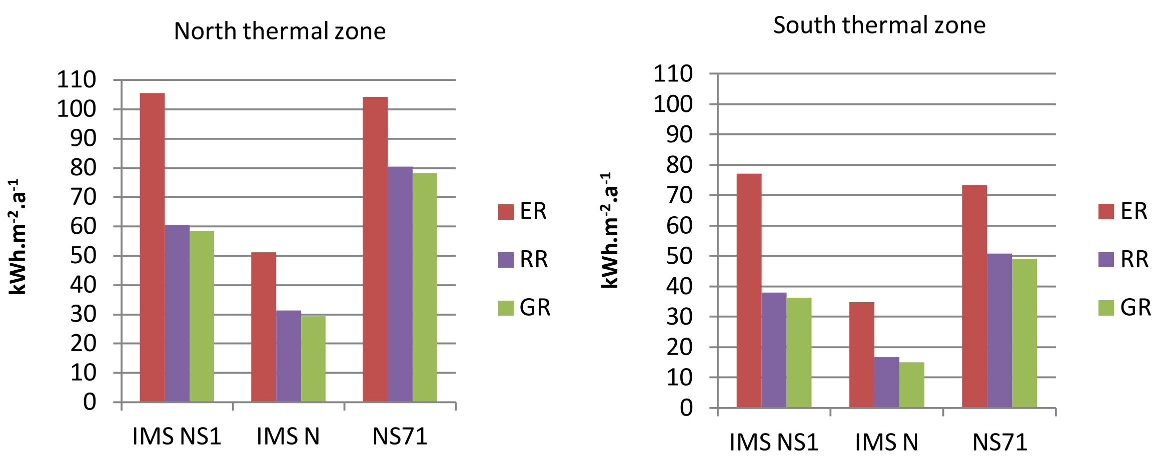

Figure 77 - Annual heating load per m^2 per thermal zone of the top floor of analyzed building models

If the obtained values are further inspected, it can be observed that the replacement of the roof has had more impact in the south zone for each analyzed model. The difference is the greatest for the IMS N building type, reduction in the north thermal zone is 39% with refurbished roof and 43% with a green roof, while in the south zone refurbished roof lowers the consumption by 52% and green roof by 57%. The green roof was more efficient in both thermal zones and for the each building type (Figure 78).

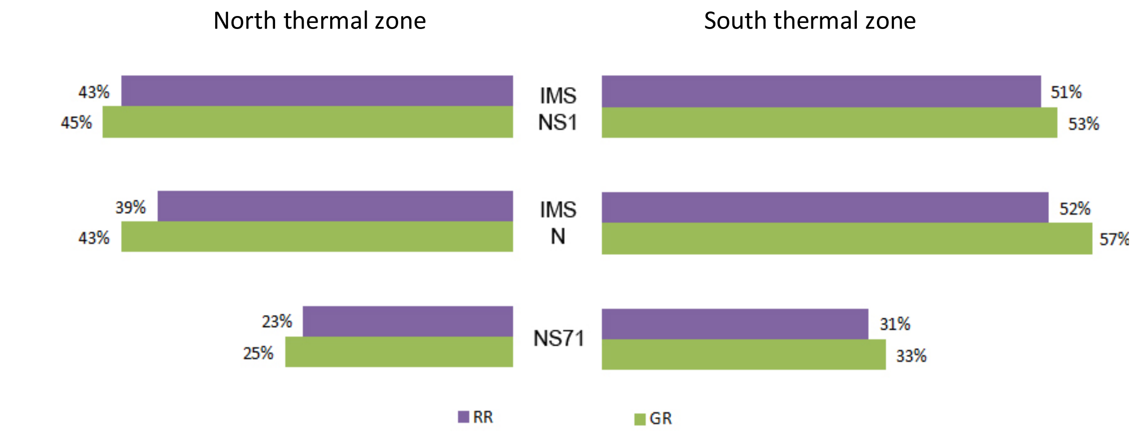

Figure 78 - Reduction in heating load per thermal zone of the top floor of analyzed building models

Less energy is needed to obtain thermal comfort during the summer in analyzed building models than it was needed during the colder months. When the chart that shows annual heating load is compared to the chart which illustrates energy demand for cooling, it is noticeable that the consumption of energy is not in correlation for different building types. Building type NS-71 that used the most energy for heating, now has cooling load similar to the IMS N type that has the best thermal performances. For cooling during the summer both IMS types need approximately half of the energy used for heating to obtain thermal comfort, while the NS-71 type needs almost five times less energy. This can be explained by the fact that IMS building types have straps of windows through most of the facade which let in the sunshine and in that way increases the temperature inside the building during the whole year, while the ratio of window to wall area in NS-71 type is smaller.

Analyzed models were simulated with the existing roof which was later replaced with the refurbished roof and the green roof. Roof with high solar reflectivity, commonly known as a white roof, was also simulated in order to compare its performance with the other roof types (Figure 79).

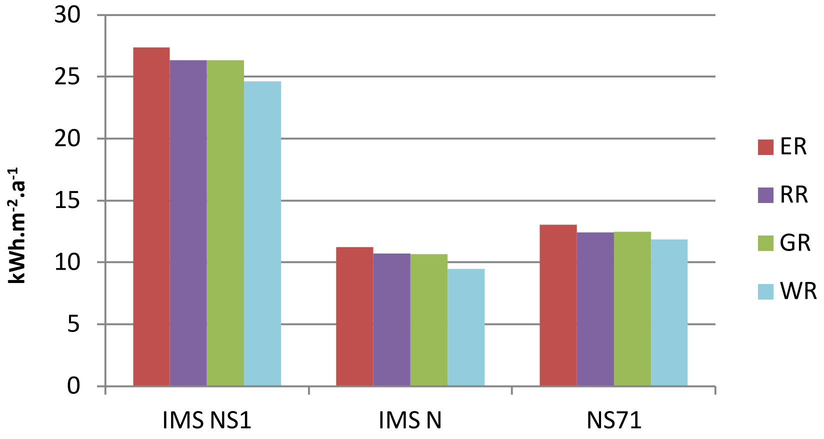

Figure 79 - Annual cooling load per m² per analyzed building model

Reduction in the annual heating demand with the replacement of the roof was more perceptible than it is a reduction in the cooling demand. What is common for three simulated models is that refurbished and green roof reduce the consumption of energy used for cooling by the same percentage (around 5% for all models), while roof with high solar reflectivity is more efficient in all three cases (Figure 80). The largest reduction is observed in IMS N building type, in which the white roof reduced the cooling load by 16%, while in other two models this value was 10% and 9%.

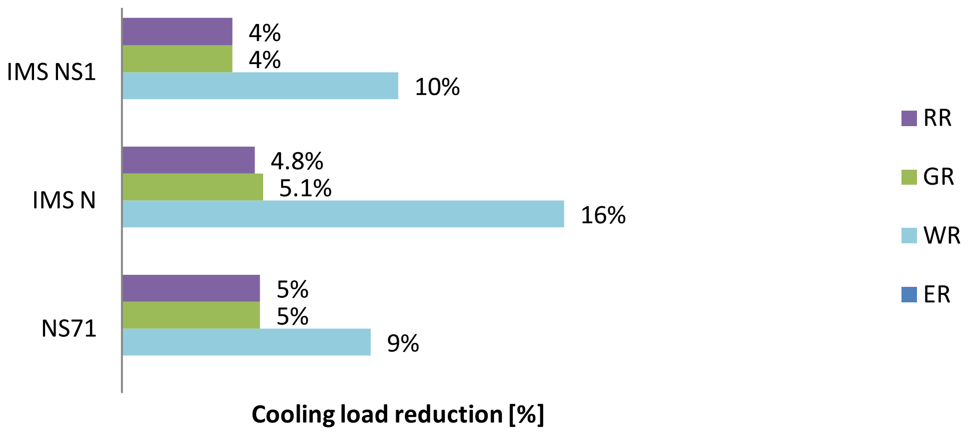

Figure 80 - Reduction in cooling load per analyzed building model

The reductions in the cooling load are greater in the thermal zones of the top floor. Consumption of energy used for cooling differs depending on the orientation of a thermal zone. As it can be expected, cooling load is lower in thermal zones oriented towards the north (Figure 81).

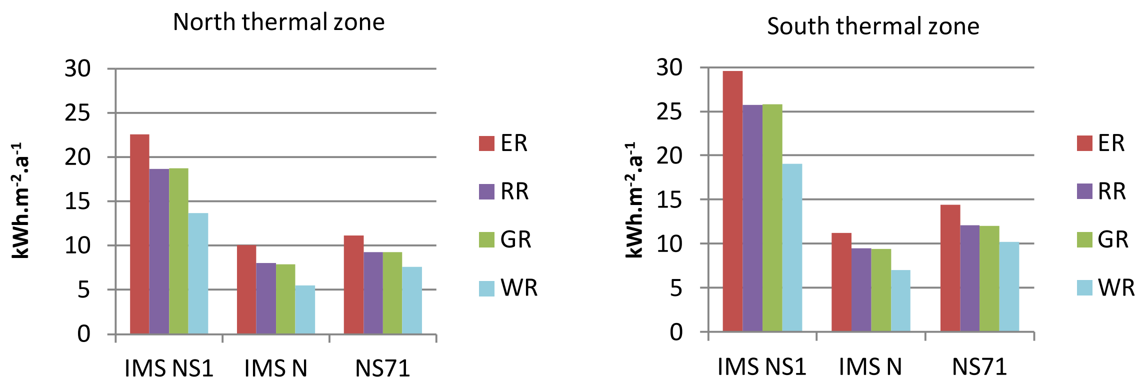

Figure 81 - Annual cooling load per m² per thermal zone of the top floor of analyzed building models

Similar to the results of the whole building, a refurbished and a green roof had the same reduction rate for the top floors of models IMS NS1 and NS-71, while on the top floor of IMS N green roof was more effective. In this building type, the refurbished roof reduced the cooling demand by 16% and the green roof by 18% (calculated for all thermal zones on the top floor). The white roof was the most efficient, but the results do not have the same tendency as those obtained for the whole building energy consumption. The white roof decreased energy consumption for the top floor by similar percent for two IMS building types, while for the third model the reduction rate was lower.

There are no substantial differences in the reduction rate achieved by different roof types based on the orientation of a thermal zone in the model NS-71, while in the types IMS NS1 and IMS N it is observed that all of the roof types are more effective in a thermal zone oriented towards the north (Figure 82).

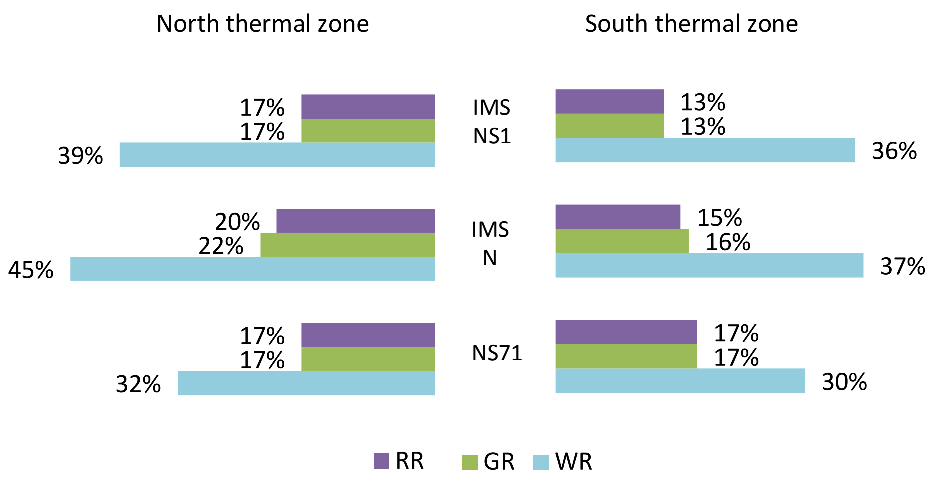

Figure 82 - Reduction in cooling load per thermal zone of the top floor of analyzed building models

The performance of different roof types on analyzed building models can be studied by comparing the number of overheating degree hours during the summer months in the free running model. Total overheating degree hours for the top floor of each model were calculated as it is explained in previous chapter. These absolute values are later divided with the floor area in order to obtain comparable values (Figure 83). First building type that was analyzed has the largest number of overheating degree hours which is in a correlation with the energy needed for cooling of this building type. Values obtained for other two types are in contrast to the results obtained for cooling load. IMS N building type that used the least energy for cooling has more overheating degree hours per square meter than the third analyzed model NS-71. This inconsistency can be explained by the fact that the cooling energy was calculated for the run period of the whole year, while the overheating degree hours were calculated only during the Summer months (June, July and September).

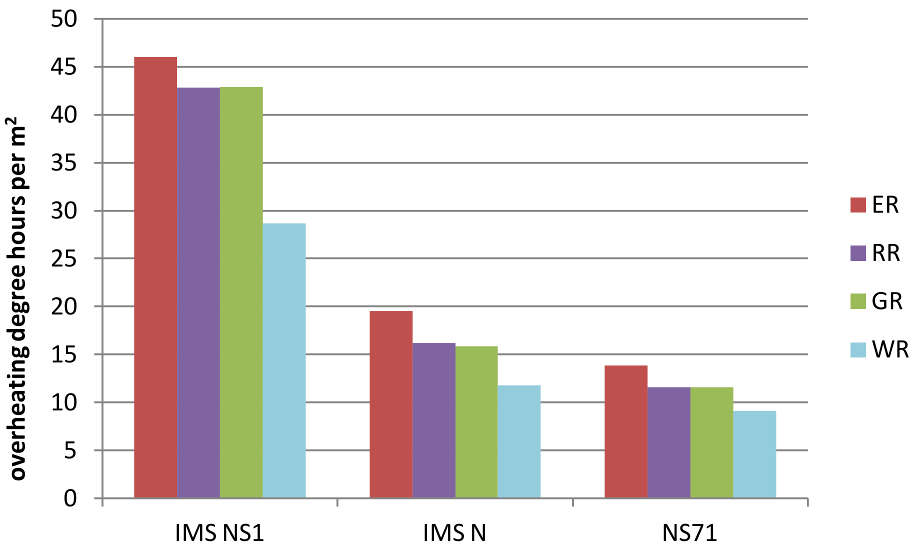

Figure 83 - Overheating degree hours per m^2 per analyzed building model

The impact of undertaken roof retrofit measures was studied in an additional analysis that assumed more realistic natural ventilation schedule with lower air exchange rate. The ventilation was scheduled during the summer months from 19pm until 8am with two air changes per hour. The performance of this ventilation schedule was analyzed by comparing its results to the results acquired by the original ventilation schedule (9ach for one hour in the evening and 3ach throughout the night). The hourly values for indoor temperatures during two summer days are compared. The results show a similar tendency for both ventilation schedules and for all analyzed buildings.

Hourly temperatures for the top floor south zone of the residential building IMS NS1 are presented in Figure 84 and Figure 85. Indoor temperature values are higher with the second ventilation scenario. In both cases, the existing roof has the worst thermal performance while the white roof is the most effective. It can be noted that the difference in the indoor temperatures between existing roof and refurbished or green roof is higher in the first ventilation scenario.

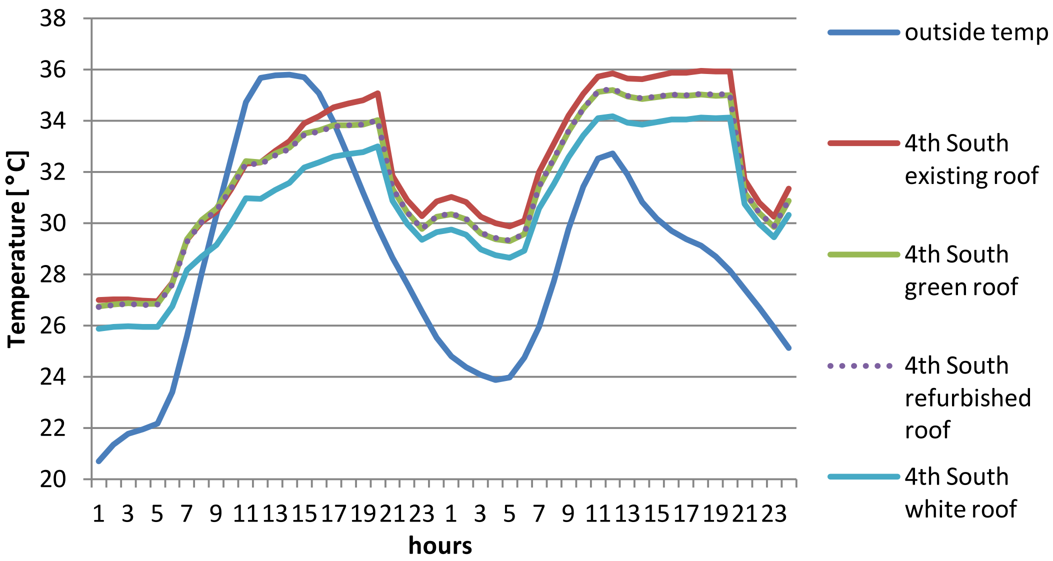

Figure 84 - Natural ventilation 9ach + 3ach: hourly temperatures on July 21st and 22nd for the 4th floor south zone IMS NS1

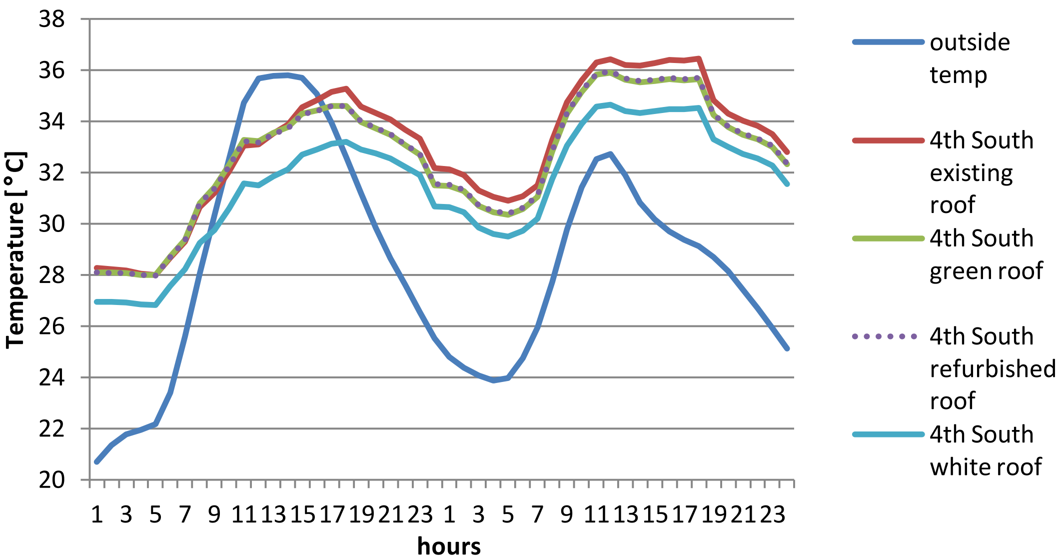

Figure 85 - Natural ventilation 2ach: hourly temperatures on July 21st and 22nd for the 4th floor south zone IMS NS1

Hourly indoor temperature values for the residential building IMS N (Figure 86 and Figure 87) are significantly lower, due to the better thermal performance of the facade and roof. Performance of different types of roofs has the same tendency as in the previous building. The indoor temperature results of the two different ventilation scenarios are to some extent different. The temperatures for the each roof type are approximately one degree higher when the ventilation is set to 2ach.

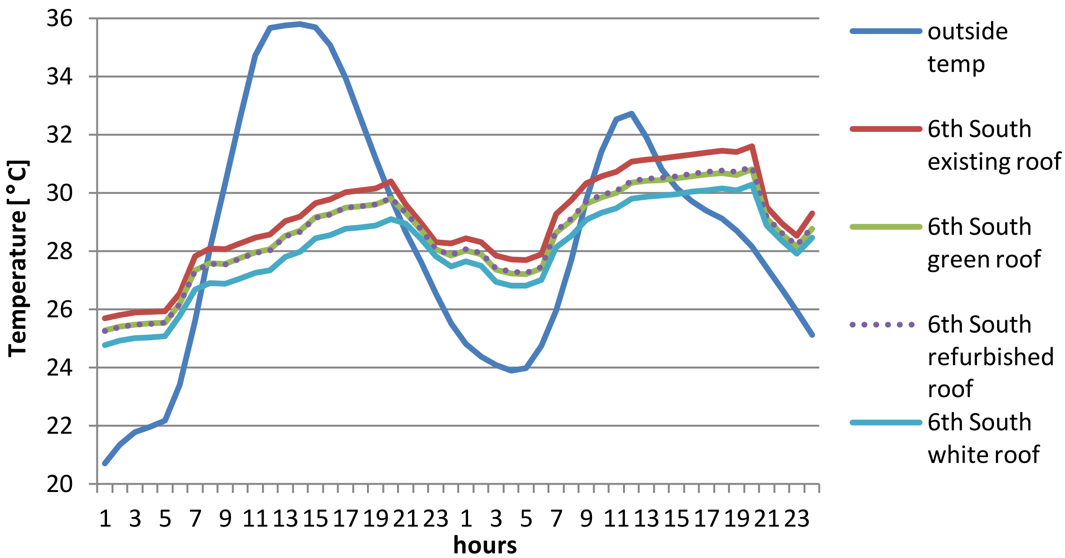

Figure 86 - Natural ventilation 9ach + 3ach: hourly temperatures on July 21st and 22nd for the 6th floor south zone IMS N

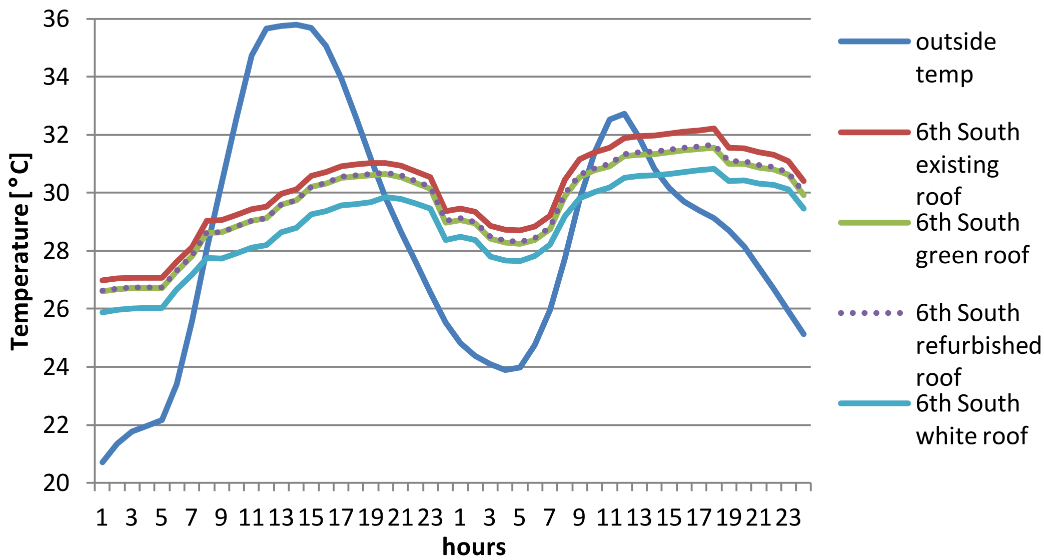

Figure 87 - Natural ventilation 2ach: hourly temperatures on July 21st and 22nd for the 6th floor south zone IMS N

The indoor temperatures for the top floor south zone of the residential building built in the NS-71 system are presented in Figure 88 and Figure 89. The performances of studied roof types have the lowest level of differentiation in this building type. The reason for this is the better thermal performance of the existing roof compared to the thermal performance of the facade elements. In the second ventilation scenario, the white roof is more effective than the other roof types. The refurbished roof, as well as the green roof, are not significantly lowering the indoor temperatures in comparison to the existing roof.

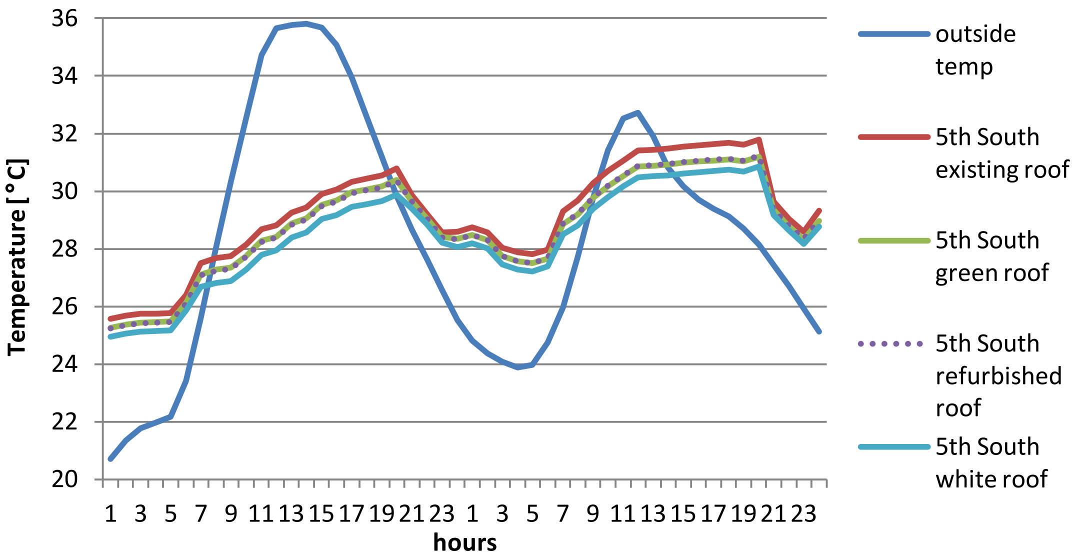

Figure 88 - Natural ventilation 9ach + 3ach: hourly temperatures on July 21st and 22nd for the 5th floor south zone NS-71

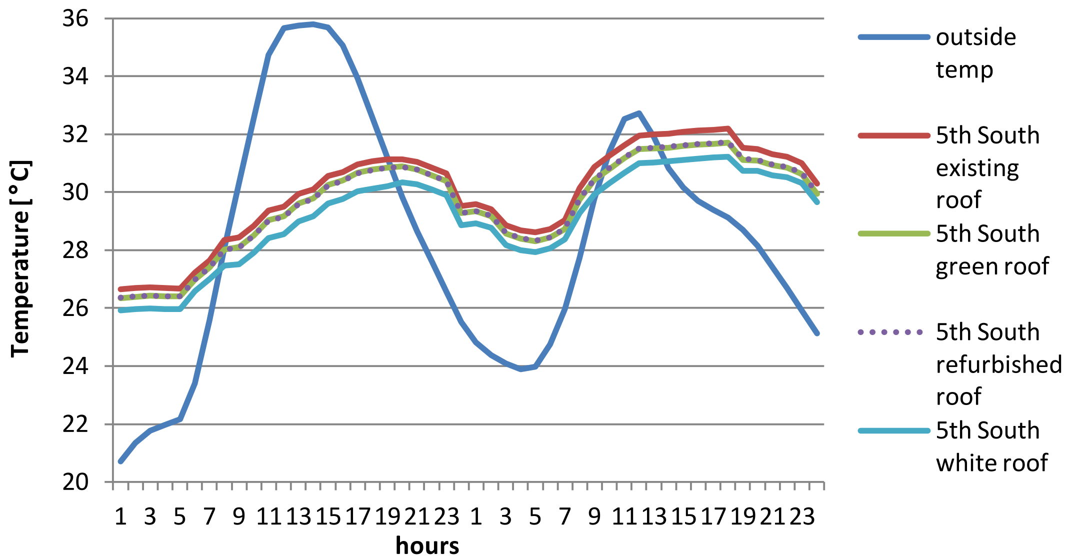

Figure 89 - Natural ventilation 2ach: hourly temperatures on July 21st and 22nd for the 5th floor south zone NS-71

6 CONCLUSION

The aim of this thesis was to present and examine the option for the refurbishment of flat roofs of prefabricated residential buildings in Novi Sad, Serbia. Green roof as a type of roof that brings many benefits was described and later simulated in EnergyPlus on three selected models. In order to obtain unbiased and applicable results of green roof performance, two other roof types were simulated: refurbished roof with new thermal insulation and a roof with high solar reflectivity, but without insulation. The results of the simulations were compared and analyzed. It can be concluded that the green roof has a positive effect on the building. EnergyPlus simulation showed that energy demand for heating and cooling of a building can be reduced with the installation of a green roof. The simulation also showed that performances of the green roof and the refurbished roof are similar. White roof was simulated in order to compare its cooling performance with other two roof types. As expected, it showed the best results which are explained by its high reflectivity. The performance of the same roof type but on different building types was also analyzed and evaluated. The green roof, as well as the refurbished roof, were the most successful on the building that has the low thermal performances of the roof and the facade elements. As it was anticipated, reduction in heating and cooling demand was the most significant on the top floor. The orientation of the thermal zones did not have a considerable effect on the reduction rate. The temperate continental climate requires that thermal comfort is achieved by heating during the winter or by cooling during the summer. The largest savings appeared to be for winter heating of the building with the poorly-insulated facade and roof. The smallest savings were identified for the building featuring a roof structure with better thermal characteristics than the facade.

The green roof has shown capability for enhancing a building's thermal performance, although there were no big differences between results obtained with a green roof and a refurbished roof. Nevertheless, other advantages of the green roof can outweigh in its favor when choosing the option for retrofit. Besides the benefits on a building level (protection of roofing membrane, reduction in cooling and heating demand, acoustical insulation) green roof also contributes to the urban surroundings (storm water management, reduction in CO_2, habitat restoration etc.), and thus creates more pleasant urban environments.

The obtained results showed that green roof is a suitable solution for problems with thermal comfort during the whole year. Other problems connected with flat roofs, such as leaking, can also be solved for a long term with the installation of a green roof, because it protects the waterproofing layer and hence extends its life cycle. However, when retrofitting an older building, it is important to improve all elements of its envelope. Only roof refurbishment can be helpful in the case where facade elements have good thermal properties, which is not the case with most of the prefabricated buildings in Novi Sad.

This research is based only on computer models simulated using average input parameters based on the assumption of residents' behaviour. More accurate results could be obtained in a study that would analyze one case study building with precisely defined parameters and inputs for simulation. Life cycle costs analysis was not a part of this study, and it can be a topic of some subsequent work. Future research works could additionally analyze the impact of a green roof on building performance in combination with thermal insulation of facade and replacement of the windows in prefabricated residential buildings. Another point of interest could be the effect of a green roof on a bigger scale. Analyzed residential buildings are situated in the multifamily housing areas, so that impact of the multiple green roofs on urban surrounding, in terms of microclimate, storm water management or biodiversity, can be examined.

Results obtained in this study can be used as suggestions and guidelines for future refurbishments of flat roofs not only in Novi Sad, but also in other places where similar problematic exist.

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8 REFERENCES

ASHRAE. 2013. *ASHRAE Standard 62.1-2013 Ventilation for Acceptable Indoor Air Quality*. American Society of Heating, Refrigerating and Air-Conditioning Engineers INC

Blanusa, T., **Vaz Monteiro**, M., **Fantozzi**, F., **Vysini**, E., **Li**, Y., **Cameron**, R.W.F., 2013. Alternatives to *Sedum* on green roofs: Can broad leaf perennial plants offer better 'cooling service'?. *Building and Environment 59* (January), pp. 99-106

Cagic, P., 1976. *Opsti prikaz sistema NS-71 (General Presentation of the NS-71 System).* Novi Sad. Indis76

Cantor, S.L., 2008. *Green Roofs in Sustainable Landscape Design*. New York - London. W.W. Norton & Company

Castleton, H.F., **Stovin**, V., **Beck**, S.B.M., **Davison**, J.B. 2010. Green roofs; building energy savings and potential for retrofit. *Energy and Buildings 42* (2010),pp. 1582-1591

Celik, S., **Morgan**, S., **Retzlaff**, W. and **Once** O. 2011. Thermal Insulation Performance of Green Roof Systems. *IGEC-VI*. Conference paper

Dickinson, R.E., **Henderson-Sellers**, A., **Kennedy**, P.J., and **Wilson**, M.F. 1986: Biosphere-atmosphere Transfer Scheme (BATS) for the NCAR Community Climate Model. NCAR Technical Note NCAR/TN-275-+STR

Dimitrijevic, R., 1988. Skeletni sistem IMS (Skeleton Construction System IMS). *Expert Seminar IMS - Technology of Designing and Building*. Belgrade

Dunnett, N., **Kingsbury**, N. 2008. *Planting Green Roofs and Living Walls*. Portland. Timber Press, Inc.

Energy Community Secretariat. 2012. Energy Efficiency in Buildings in the Contracting Parties of the Energy Community, Final Report. Internet. Available from http://www.energy-community.org/pls/portal/docs/1410177.PDF. Accessed 27.10.2013

Energy Saving Trust. Reducing overheating - a designer's guide. Internet. Available from: http://www.seai.ie/Archive1/Low_Carbon_Homes_Programme/Best_Practice_Guides/CE129_Reducing_overheating_-_a_designers_guide_Mar_2005_.pdf. Accessed 03.05. 2015

EnergyPlus. 2013. Input Output Reference

European Cool Roof Council. webpage: http://coolroofcouncil.eu/. Last acessed 02.2016

Folic, R., **Laban**, M., **Milanko**, V. 2011. Reliability and Sustainability Analysis of Large Panel Residential Buildings in Sofia, Skopje and Novi Sad. *Facta Universitatis Series: Architecture and Civil Engineering 9* (1), pp. 161-176

Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau. webpage: http://www.fll.de/. Last acessed 02.2016

Frankenstein, S., **Koenig**, G. 2004. *FASST Vegetation Models*, *Technical Report TR-04-25*. Hanover, New Hampshire: U.S. Army Engineer Research and Development Center. Cold Regions Research and Engineering Laboratory (ERDC/CRREL)

Gartland, L., 2008. *Heat Islands: Understanding and Mitigating Heat in Urban Areas*. London. Sterling VA: Earthscan

Green Roofs for Healthy Cities. webpage: http://www.greenroofs.org/. Last acessed 02.2016

Green Roof Technology. webpage: http://www.greenrooftechnology.com/, Last acessed 02.2016

G.P. "Beton" Novi Sad. 1975. Building Documentation for Dwelling Buildings Block "N2"

G.P. "Beton"Novi Sad. 1968. Building Documentation for Dwelling Buildings Block "NS-2/II"

Hosseini, M., **Akbari**, H., 2016. Effect of cool roofs on commercial buildings energy use in cold climates. *Energy and Buildings* 114 (February), pp. 143-155

International Energy Agency. Indicators for 2013. webpage: http://www.iea.org/statistics. Accessed 11.2015

Kuzmanov, L., 2009. Effect of the Process of Building Rooftop Extensions on Residential Buildings in Novi Sad. *Nauka + Praksa* 12 (February), pp. 12-15

Le Corbusier, 1999. *Towards a New Architecture.* Belgrade. Gradjevinska Knjiga

Laban, M., 2012. *The improvement of envelopes' performances of multi-storey prefabricated and semi-prefabricated residential buildings in Novi Sad.* PhD Dissertation: University of Novi Sad

Laban, M., **Folic**, R. 2014. Energy Efficiency of Industrially Made Buildings Influenced by Thermal Properties of Façades. *Thermal Science 18* (2)*, pp.* 615-630

Mentens, J., **Raes**, D. and **Hermy**, M. 2005. Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century? *Landscape and Urban Planning* 77 (May), pp. 217-226

Meteotest Genossenschaft, 2012. "Meteonorm 7", http://www.meteonorm.com/. Last acessed 02.2016

Ministry of Environment, Mining and Spatial Planning, Republic of Serbia. 2011. Building regulations on energy efficiency, Belgrade. Sluzbeni glasnik 61/2011

Nichaou, A., **Papakonstantinou**, K., **Santamouris**, M., **Tsangrassoulis**, A. and **Mihalakakou**, G. 2001. Analysis of the green roof thermal properties and investigation of its energy performance. *Energy and Building 33* (January), pp. 719-729

NREL, 2013. "EnergyPlus 8.1.0.008", webpage: https://www.energyplus.net/. Last acessed 02.2016

NREL, 2012. "OpenStudio 0.9.0.10000", webpage: https://www.openstudio.net/. Last acessed 02.2016

Papavasileiou, G. 2014. *Comparing the impact of Green and Cool roofs on a building's thermal performance.* Master Thesis: Vienna university of Technology

Perovic, M. 2008. *Iskustva proslosti (Lessons of the Past)*. Belgrade. Gradjevinska Knjiga

Public Utility Company "Stan" Novi Sad. webpage: http://www.stanns.rs/. Last acessed 02.2016

Public Utility Company "Novosadska Toplana" Novi Sad. webpage: http://www.nstoplana.rs/. Last acessed 02.2016

Ravic, M. 2012. *Novi Sad - Ravni krovovi večiti problem (Flat Roofs as an eternal problem of Novi Sad)*. Vecernje Novosti, 19 Feb. Newspaper article. Internet. Available from http://www.novosti.rs/vesti/srbija.73.html:367021-Novi-Sad-Ravni-krovovi-veciti-problem. Accessed 27.10. 2013

Rosenzweig, C., **Gaffin**, S. and **Parshall**, L. (Eds.) 2006. *Green Roofs in the New York Metropolitan Region: Research Report*. New York: Columbia University Center for Climate Systems Research and NASA Goddard Institute for Space Studies.

Sailor, D.J., **Hutchinson**, D., **Bokovoy**, L. 2008. Thermal property measurements for ecoroof soils common in the western US. *Energy and Buildings 40* (7), pp. 1246-1251

Sailor, D.J., 2008. A green roof model for building energy simulation programs. *Energy and Buildings 40* (8), pp. 1466-1478

Sekulic, M., 2013. *Evolution and Transformation of the Roof Garden from its Origins to the Present Day and its Modern Application.* PhD Dissertation: University of Novi Sad

Snodgrass, E.C., **Snodgrass**, L.L. 2006. *Green Roof Plants*. Portland. Timber Press, Inc.

Srbulovic, D., 2000. *Kratka istorija Novog Sada (Short History of Novi Sad)*. Novi Sad. Prometej

Statistical Office of the Republic of Serbia. 2013. *Book 22: Housing units according to the number of occupants and households*. 2011 Census of Population, Households and Dwellings in the Republic of Serbia. Internet. Available from: http://pod2.stat.gov.rs/ObjavljenePublikacije/Popis2011/Knjiga%2022_Broj%20i%20povrsina%20stambenih%20jedinica-Number%20and%20the%20floor%20space%20of%20housing%20units.pdf. Accessed 09.2014

Statistical Office of the Republic of Serbia. 2013. *Book 26: Number and the floor area of housing units*. 2011 Census of Population, Households and Dwellings in the Republic of Serbia. Internet. Available from: http://pod2.stat.gov.rs/ObjavljenePublikacije/Popis2011/Knjiga26.pdf. Accessed 09.2014

Takakura, T., **Kitade**, S., **Goto**, E. 2000. Cooling effect of greenery cover over a building. *Energy and Buildings 31* (1), pp. 1-6

The Green Roof & Greenwall Industry Resource Portal. webpage: http://www.greenroofs.com/. Last acessed 02.2016

Trimble, 2012. "SketchUp 8", webpage: http://www.sketchup.com/. Last acessed 02.2016

Urban, B., **Roth**, K. 2010. Guidelines for Selecting Cool Roofs. US Department of Energy. Internet. Available from: http://www1.eere.energy.gov/femp/pdfs/coolroofguide.pdf. Accessed 05.2015.

Weiler, S.K., **Scholtz-Barth**, S. 2009. *Green Roof Systems*. New Jersey. John Wiley & Sons, Inc.