Comfort management in changing climate conditions with the use of green roofs

Adriana Lucia Kadhim-Abid
Technical University "Gheorghe Asachi" of Iași, Iași, Romania

Abstract: Climate changes are determined by anthropogenic activities and have a harmful effect on the environment. Through building design we can obtain mitigation and adaptation strategies in order to face climate changes and bring into being comfort management policies. The solution presented here consists of green roof implementation during the renovation or rehabilitation stage of buildings. This can solve problems regarding indoor air quality, thermal comfort and environmental issues. The analysis presented hereby supports the validity of green surfaces integration and their effectiveness in changing the indoor climate in comparison to conventional roof systems. The analysis is based on computer simulated models of the heat transfer phenomena under viable conditions, with respect to real external climatic conditions registered in the city of Iași during the summer of 2013. Studying the performance of green roof can guide authorities, urban and building design specialists to comfort management policies in order to lessen the effects of climate changes and achieve optimal indoor comfort conditions without excessively using energy consuming systems.

Keywords: comfort management, comfort conditions, climate change, energy consumption, green roofs.

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Introduction

Comfort management refers to coordinating efficiently and effectively resources at hand in order to reach indoor comfort conditions related to physiological and natural conditions (protection from harmful factors, hygiene, etc.), psychosocial demands (microclimate of the building, aesthetics, etc.) and efficiency (energy related costs for operation and maintenance). A comfortable indoor environment is achieved when comfort demands such as optimal thermal comfort, acoustic and visual performance, appliances, furniture and user control are ensured. In the past decades, Building Management Systems (BMS) have been developed allowing new technologies to be integrated and managed for building owners or inhabitants. These systems by means of constantly renewed technology enable the process of optimizing buildings in terms of energy savings and cost reduction. BMS are based on computer controlled systems installed in buildings, programmed to deal with HVAC

Correspondence:
Adriana Lucia Kadhim-Abid
E-mail: kadhim.adriana@tuiasi.ro

(heating, ventilation and air conditioning) systems, access control or fire systems. These automated systems ensure an optimal indoor environment and are designed to adapt a building to user needs. In terms of climate change, mitigation and adaptation measures must also target solutions where buildings respond to climate change and have the potential to diminish the human imprint on the environment at urban level. Concerning this aspect, green surface integration, hence green roof systems, represent sustainable solutions acting at both building and urban level. Green roof systems help achieve optimal indoor conditions and lower energy related costs (Xu et al., 2011), and reduce the negative impacts of the Urban Heat Island phenomena at the urban level (Scherba et al., 2011).

Climate changes determined by the massive presence in the atmosphere of greenhouse gases, deforestation, changing water courses and other anthropogenic activities with detrimental impact on the environment have become a certainty, as has the fact that the process cannot be stopped on the short or medium term. The harmful effects are felt not only by the natural and human systems, but by the socio-economic system too and as consequence, the associated risks require a wide range of policies and strategies at local, regional and global level. UNFCCC (United Nations Framework Convention on Climate Change) draws the main directions that include fundamental strategies in response to climate changes: mitigation and adaptation. While *mitigation* aims to limit and diminish the causes of climate change through radicalization and diversification measures to reduce emissions of greenhouse gases, *adaptation* means to lessen the aggressive impact of climate change through a series of actions and specific measures (Fussel and Klein, 2002).

In regards to the relationship between buildings and climate change it can be stated that it is complex, with a pronounced synergistic nature if we consider the following aspects: (a) according to the European Commission, buildings represent a high percentage responsible with emissions of greenhouse gases, about 40% at European level, thus contributing to the process of climate change; (b) the impact of climate changes on buildings cannot be ignored as it manifests at the structural level and is directly related to users' behaviour as much as suitable indoor environmental quality can be ensured (air quality, thermal comfort, visual comfort, etc.); (c) the impact of climate change on the behaviour of buildings manifests in particular by increased air temperature during summer, therefore the difficulty in achieving comfort conditions without additional energy consumptions which leads to mitigation measures for energy conservation and emission reduction of greenhouse gases; (d) in most cases, measures to reduce energy consumption, properly managed, contribute positively to the response of buildings to climate change.

In this context, the attitude towards climate change of the actors responsible for building design as those in the construction industry is most important and concerns regarding the mitigation-adaptation ratio become a priority. Relevant to this matter is the project "Establishing research direction in sustainable building design" by Tyndall Center for Climate Research from 2001 until 2002

(Steemers, 2002a) lead by Dr. Koen Steemers from La Martin Center for Architectural and Urban Studies, University of Cambridge. The project was responsible with developing the agenda for ongoing research. Members of this project include acknowledged research centers and universities from Europe and America, as well as industry representatives and users. The conclusions formulated during the workshop session and discussions underline that the most appropriate response to climate change is the development of the adaptive capacity of buildings and urban form, in close correlation with measures aimed at mitigating climate change architecture.

In order to support this we present the results of a series of ongoing studies performed under the supervision of Professor Steemers from Tyndall Centre. These results highlight that developing strategies that combine mitigation measures with causes of global warming to climate change adaptation at the urban unit, building and individual level, is the main direction that integrates research efforts in the construction sector and that should lead to important modifications when approaching the problem of designing sustainable buildings (Steemers, 2001; Steemers, 2002b; Steemers 2005).

The main changes with direct effects on indoor air quality and environmental welfare of the occupants are increasing air temperature (especially during hot season), the disappearance of transition periods and pronounced variability of air temperature values for short periods of time. As a result, the adaptation mechanisms of the human body are overburdened and achieving a healthy and comfortable environment throughout the year demands additional energy consumption for air conditioning and mechanical ventilation.

In this context, it is imperative to continue identifying passive solutions in order to ensure comfort both during winter and during warm periods. Integrating green surfaces at roof and facade level meets this goal and presents benefits for urban climate as well. This paper aims to highlight the opportunity and the need to integrate green surfaces in the architecture of both new and existing buildings based on arguments supported by literature review as well as novel investigations. The main objective of this study is to highlight the potential of green roof systems to lower energy consumption costs and diminish the negative effects of the Urban Heat Island phenomena. The final remarks of the present paper support this hypothesis and point out to stakeholders the feasibility of green roof systems.

Green roofs, mitigating the effects of climate change on indoor comfort management

Traditionally, the roof represents a structural element of a building, responsible for the protection against the weather and solar radiation. To maintain optimal indoor environment conditions, the roof should be insulated as to have a low thermal capacity and high capacity of solar radiation reflection. Albedo and thermal properties of the surfaces within an urban area (roofs, facades, pavement, etc.) are related to reflection and thermal properties of the component materials. Heat storage capacity and thermal inertia of the building materials of urban areas are higher than those of the natural materials used in rural areas. A large heat storage capacity means that the urban fabric absorbs and retains a greater amount of solar radiation. Urban albedo is smaller, on average, by 5-10% than in rural areas. This contributes to a higher absorption of incoming shortwave solar radiation within the urban environments.

A study conducted by Weston Design Consultants (2000) showed that during the hot season in Chicago, a reduction in energy consumption by 6357 kWh/m^2 can be achieved when using a green roof. Other studies related to modeling the effects of green roofs on urban environments have demonstrated a reduction in urban air temperature of 1-2°C if a green roof solution is adopted (Oberndorfer et al., 2002). Germany, a pioneer of green technologies, has 29 cities that offer financial support from state funds for converting conventional roofs into green ones. In 2005, Germany already registered an area of 13 million m^2 of green roof retrofit roofing. This example was followed by Switzerland with 20% of the roofs of residential buildings and 25% of commercial premises transformed into green roofs and France with 150.000 m^2 of green roof until 2002. Tokyo and Singapore are two cities that struggle with high temperatures in recent years, the effect of the Urban Heat Island phenomenon. This prompted authorities to take specific measures regarding the refurbishment of roofs and building facades by adopting green surface solutions. England provides an example of using green roofs and facades: BedZed (Beddington Zero Energy Development) is a sustainable project that has successfully implemented green roof technologies in order to reduce water and energy consumption. The system includes green roofs and solar panels forming tiered gardens that serve as an apartment complex and green solutions have been also adopted for their maintenance and renovation (Alexandri et al., 2005).

The thermal inertia of the vegetative layer helps avoid overheating and ensure comfort conditions during warm seasons. The thickness of the vegetative layer and that of the growth medium determine a classification of the green roof systems as follows: intensive green roof, extensive green roof and semi-intensive green roof (Table 1). Depending on design requirements, these structures can be realized on both new and old buildings during the renovation phase, regardless if the terrace allows foot traffic or not.

Table 1. *Classification of green roof structures depending on plant type and growth medium*

Characteristics	Extensive	Semi-intensive	Intensive
Depth of growing medium	6... 15 cm	12... 50 cm	35... 150 cm
Accessibility	Inaccessible	Semi- accessible	Accessible
Weight	under 300daN/m^2	around 300daN/m^2	above 300daN/m^2
Vegetation type	Small- grass, small flowers	Medium- flowers, shrubs	Large- trees

Green roofs provide aesthetic and psychological benefits for urban dwellers and bring a contribution of relaxation and restoration that improves health. Other uses of green roofs include urban agriculture, absorbing sound waves from the exterior environment and preventing their transmission to the interior. These systems are usually inhabited by insects and birds, which contribute to local habitats (Oberndorfer et al., 2007).

Green roofs are characterized by the presence of vegetation in the upper layer, directly exposed to solar radiation. Green roofs can have a slope or a terrace roof that integrate layers with specific functions (Baran and Bliuc, 2011). Regarding the financial aspects, Oberndorfer (2007) estimated the cost of extensive green roofs between $10 up to $30 per ft^2 ($100- $300 for 1 m^2) and the cost of an intensive green roof with $20 more per ft^2 ($200 for 1 m^2). Green roof systems involve greater costs than conventional roofing systems, but have a number of advantages that justify the investment: storm water control, extension of system maintenance, improved air quality, protection of the envelope, urban biodiversity, noise reduction and increased investment value (Gaffin et al., 2006). An estimation regarding the energy consumption was achieved by Hillel (1998) which shows the annual cost calculations for air ventilation systems in the metropolitan region of New York City. The calculation includes estimation for both conventional and green roof systems, each calculated for 85.000.000 m^2, the total roof top area of New York: conventional roofs with an albedo of 0.1 present an estimation of 500 kWh/m^2 ($8.5 billion) and green roof systems with an albedo of 0.3 present an estimation of 140kWh/m^2 ($2.43 billion).

Comfort management analysis using green roofs in Romania

The analysis presented below aims to demonstrate that green roof solutions represent a viable solution for the rehabilitation and renovation stages of buildings in order to access optimal indoor comfort conditions. Results support mitigation and adaptation measures regarding green roof solutions towards comfort management policies. The analysis follows a study for energy savings assessment used for heating and cooling as well as identifying problems that may occur in real operating conditions. For this study local meteorological condition for the city of Iași, Romania were monitored and recorded by the author and further used in the numerical simulations. The main steps of the study were the following: (a) analysis of the existing situation through systematic measurements of the values of air temperature during warm and cold seasons; (b) designing rehabilitation solutions that integrate the green roof system; (c) efficiency analysis of the proposed solutions through numeric simulation of phenomena of heat and mass transfer; (d) evaluating the effects of a green roof solution on energy consumption and thermal comfort.

In order to effect the numerical simulation, meteorological data from the city in question were needed. Information for both indoor and outdoor air temperature and humidity values was gathered using two sensors (LogTag Haxo8), mounted one on the roof terrace of the Faculty of Civil Engineering and Building Services, Iași and one inside the building, an office room situated at the top level. The measurements were recorded continuously for the entire month of August 2013. Data registered by the sensors (Table 2) reveal higher values for indoor air temperature than values for exterior air temperature, values greater than 26°C, the comfort limit recommended for summer. Table 2 depicts the influence of the green roof that transfers an inward heat flux with significant values due to its reduced albedo.

Table 2. *Temperature values registered on August 9th 2013 at the Faculty of Civil Engineering and Building Services from Iași, Romania*

Environment	Temperature		
	Maximum	Average	Minimum
Exterior	36.8°C	28.2°C	18.8°C
Interior (upper level)	34.8°C	32.3°C	31.4°C

An equation for the energy balance at roof level for a roof structure with vegetative cover was used (Equation 1) for the numerical simulation results presented in this study. The size and direction of heat flow that appear at roof level influence decisively the interior comfort conditions. Recent studies (Niall, 2010) have identified and evaluated the heat fluxes using supplemented analytical models, validated through experimental data from in-situ measurements or laboratory. The energetic balance for the green roof including the vegetative cover comprises specific heat fluxes obtained through biological processes, evapotranspiration phenomena, heat storage by the growing medium at a specific humidity level. Thus, the energy balance model at intensive green roof level, considered for green roof energy performance with WUFI software can be expressed as follows:

$$q_{rs}+ q_{lu}+ q_{conv}+ q_{em}+ q_{tr}+ q_{ev}+ q_{sp}+ q_{ss}+ q_{ti}+ q_{fs}+ q_{r}= 0 \quad \text{(Equation 1)}$$

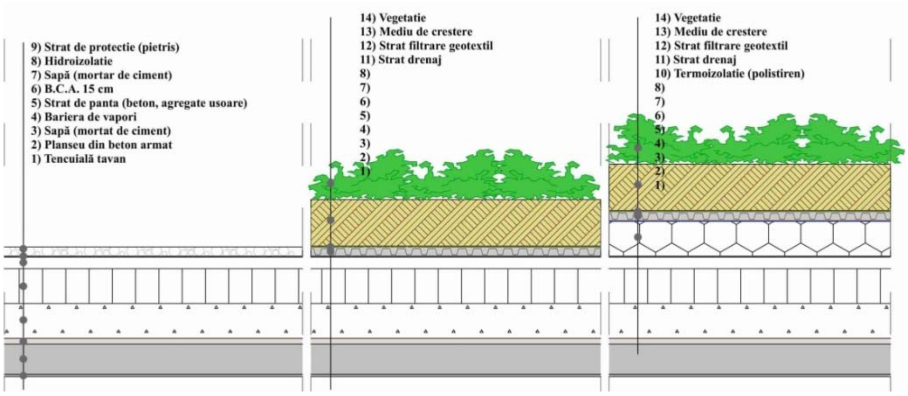
where:

q_{rs} is the heat gained from solar radiation, [W/m²];
q_{lu} is the heat gained from the long wave radiation [W/m²];
q_{conv} is the heat transferred through convection [W/m²];
q_{em} is the heat lost through emission, [W/m²];
q_{tr} is the heat lost through transpiration, [W/m²];
q_{ev} is the heat lost through evaporation, [W/m²];
q_{sp} is the heat stored by the plants, [W/m²];
q_{ss} is the heat stored by the soil, [W/m²];
q_{ti} is the heat transferred to the inside, [W/m²];
q_{fs} is the solar energy converted by the process of photosynthesis, [W/m²];
q_{r} is the heat generated by respiration, [W/m²].

The scientific literature presents different models for most terms in the balance equation. Values for some parameters such as incident solar radiation, heat transferred to the interior, outside air temperature, dew point value, plant and soil temperature, wind speed above vegetation layer and evapotranspiration rate cannot be obtained except for experimental measurements. Other parameters are considered to be constant, specified according to real operating conditions.

In order to evaluate the efficiency of green roofs through numerical simulation model two rehabilitation solutions are suggested: one, applying a green surface to the terrace and second, applying a green surface provided with an additional insulation layer (Figure 1). In order to diminish the inward heat flux during the hot season the final simulations included three cases as follows: case A represented by a conventional roof terrace, case B represented by an applied green surface to the conventional terrace from case A and finally case C, which implies a green surface provided with additional insulation mounted over the conventional roof.

Figure 1. *Rehabilitation solutions for a conventional roof (left)* [1]*, green roof without additional insulation (centre)* [2]*, and green roof with additional insulation (right)* [3] *(Kadhim-Abid et al., 2013)*



The efficiency evaluation was conducted using WUFI software, version 2.1.1.73 (WUFI Software, 2012). In regards to the mathematical model, when calculating the heat transport, the software takes into account the thermal conduction and enthalpy flows through moisture movement with phase change, as well as short-wave solar radiation (Kunzel, 1995). WUFI analysis consists of numerical simulation for three distinctive solutions (Figure 1) with high probability of occurrence in real operating conditions when using a green roof. Outdoor climate conditions such as air temperature values, direct and diffuse solar radiation indices were obtained for the month of August 2013, from Mădârjac meteorological station, data provided courtesy of the Geography Department, Faculty of Geography and Geology. The interior air temperature value was considered 26°C as recommended for indoor comfort during the hot season. The results from the numerical simulations provided data regarding temperature and humidity values registered on the analyzed domain boundaries, respectively the exterior surface of the green roof and ceiling surface as well as along the thickness of the systems layers. Final results show information related to the diurnal temperature regime on the exterior and interior surfaces of the terrace. The simulations also took into account solutions with or without vegetation present, with or without additional insulation and different stages for the saturation level of the growing medium resulting in a total of nine cases (Table 3).

Processing the experimental data led to an evaluation process of values that later became a criteria analysis of the measure in which different parameters such as the presence of vegetation, thermal insulation degree and humidity of the soil layer, influence the thermal-energy behavior of the green roof. Therefore, (a) the difference between maximum and minimum values of the temperature registered on the exterior surface, $\Delta\theta_{se}$ allows us to reveal the absorption/reflection capacity of the green surface compared to the initial conventional terrace; (b) the difference between maximum and minimum temperature values registered on the interior surface, $\Delta\theta_{si}$ allows us to evaluate the measure in which the comfort conditions are complied with; (c) the value of the average heat flow density, q that enters the interior environment from the outside needs to be compensated by the air conditioning in order to maintain a constant temperature of 26°C. Parameter q also provides a measure for the energy efficiency of the proposed solution.

Table 3. *Criteria values characterizing the situation analyzed by numerical simulation results for the nine solutions considered*

No.	Description				
	Roof system considered	$\Delta\theta_e$ [°C]	$\Delta\theta_{se}$ [°C]	$\Delta\theta_{si}$ [°C]	q [W/m²]
1	Conventional roof	25.33	44.56	1.325	6.134
2	Green roof, dry soil, no vegetation		45.62	0.183	1.062
3	Green roof, saturated soil, no vegetation, additional insulation		40.88	0.190	0.066
4	Green roof, dry soil, no vegetation, no additional insulation		45.087	0.851	4.61
5	Green roof, saturated soil, no vegetation, no additional insulation		40.15	1.046	6.62
6	Green roof, dry soil, vegetation, additional insulation		33.57	0.173	1.06
7	Green roof, saturated soil, vegetation, additional insulation		26.22	0.18	1.13
8	Green roof, dry soil, vegetation, no additional insulation		32.74	0.74	3.83
9	Green roof, saturated soil, vegetation, no additional insulation		26.17	0.86	4.688

The final results of the simulations highlight the influence of three main factors. Firstly, the *presence of vegetation* influences the difference between the maximum and minimum values of the exterior surface through the modification of the albedo value. Implicitly, the presence of vegetation leads to diminished values of the inward heat flux up to 68% in the case of a dry soil and 76% in the case of a saturated soil, even in the absence of additional insulation layer. Secondly, the *additional insulation* layer is the factor that significantly interferes with the heat flux value determining overheating and over usage of the air conditioning system. Thereby, regardless of the presence of the vegetative layer, the heat flux diminishes with 15% in case 3, 4 and 6 respectively. And thirdly, *soil moisture status* influences the inward heat flux value by raising the thermal conductivity of the soil, implicitly reducing the thermal resistance. This is more obvious for those solutions in which the vegetation is present but not the additional insulation layer, as it can be depicted from cases 8 and 9.

Regarding the temperature of the interior surface it is clear that it shows small differences between maximum and minimum values, exceeding 1°C only in the case of the conventional terrace (1.325°C) and case number five, green roof without additional insulation and a saturated soil (1.046°C). This fact is explained through the thermal inertia that characterizes the green roof systems.

Conclusions and future research

The analysis presented in this paper outlines the following conclusions: (a) the high temperature values registered in the city of Iași require comfort management policies such as green roof integration on the buildings envelope; (b) due to urbanization, the roof surfaces within the city register high temperature values, 30°C, that leads to a thermal discomfort in the buildings, especially in those rooms adjacent to the roof terrace. Consequently, for ensuring optimal comfort conditions in the building, energy demanding systems such as air conditioning are needed.

Green roof integration can be stated as a comfort management policy since the present study showed that they can diminish the inward heat flux. Changing the conventional roof with a green roof when renovating or rehabilitating a building can lead, as simulation show, to a decrease of the inward heat flux of 67% when vegetation is present and the soil is dry and 76% respectively, when the soil is saturated. Regarding comfort management policies, local authorities are advised to reconsider current measures related to building sector and take measures with respect to both the built environment and energy performance at building level. Towards achieving this goal, as results of the present study point out, local authorities should emphasize more the energy performance issue, as well as the harmful effects of the Urban Heat Island phenomena. One measure could be lower income taxes and fees from local authorities for those who would implement green roof systems or even supplement the installation costs for collective dwellings.

Future research of this ongoing study aims to evaluate the performance of green roof systems during winter in order to provide comfort management policies for cold periods through *adaptive* solutions.

Notes

[1] Conventional roof layers, as depicted in the picture: 1) ceiling-plaster; 2) concrete slab; 3) cement blanket; 4) vapor barrier; 5) slope layer (concrete, lightweight aggregate); 6) autoclaved aerated concrete 15 cm; 7) cement blanket; 8) water-proofing; 9) protective layer (gravel).

[2] Green roof without additional insulation layer, as depicted in the picture: 1) ceiling-plaster; 2) concrete slab; 3) cement blanket; 4) vapors barrier; 5) slope layer (concrete, lightweight aggregate); 6) autoclaved aerated concrete 15 cm; 7) cement blanket; 8) waterproofing; 11) drainage layer; 12) geotextile filter layer; 13) growth medium; 14) vegetation.

[3] Green roof with additional insulation layer, as depicted in the picture: 1) ceiling-plaster; 2) concrete slab; 3) cement blanket; 4) vapor barrier; 5) slope layer (concrete, lightweight aggregate); 6) autoclaved aerated concrete 15 cm; 7) cement blanket; 8) waterproofing; 10) insulation; 11) drainage layer; 12) geotextile filter layer; 13) growth medium; 14) vegetation.

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