Strojniški vestnik - Journal of Mechanical Engineering 52(2006)9, 568-586
UDK - UDC 551.583:699.86:620.92(497.4)
Pregledni znanstveni članek - Preview scientific paper (1.02)

# Povezava modela podnebnih sprememb z modelom toplotnega odziva stavb - primer Slovenije

## The Connection Between the Climate Change Model and a Building's Thermal Response Model: A Case of Slovenia

Boris Vidrih[1] - Mojca Dolinar[2] - Sašo Medved[3]
([1]Termo, Škofja Loka; [2]Agencija RS za okolje, Ljubljana; [3]Fakulteta za strojništvo, Ljubljana)

*Vodilni svetovni klimatologi menijo, da je celovito spreminjanje podnebja neizbežno. Temelj za tako razmišljanje je dejstvo, da se s podnebnimi spremembami že srečujemo, te spremembe pa naj bi bile v prihodnosti še bolj izrazite. Vplivi sprememb podnebja so in bodo opazni na vseh področjih človekovega delovanja, torej bodo vplivali tudi na oskrbo in rabo energije. Ker opazujemo dolgo časovno obdobje, ki je primerljivo z dobo trajanja stavb, raba energije v njih pa količinsko pomembna, je nujno, da gradnjo in obnovo stavb prilagodimo napovedanim podnebnim spremembam. Napoved toplotnega odziva stavb je osnova za celovito načrtovanje stavb in sistemov strojnih inštalacij, s katerimi v stavbah ustvarjamo primerno bivalno ugodje. Za napoved pričakovanega spreminjanja toplotnega odziva stavb v prihodnosti, je treba dandanes razpoložljive baze meteoroloških spremenljivk ustrezno popraviti. V prispevku prikazujemo različne scenarije podnebnih sprememb, ki jih pričakujemo na področju Slovenije in metode poprave izhodiščnih krajevnih meteoroloških baz. Za popravo uporabljamo poenostavljene prilagojene modele, s katerimi na podlagi metodologije oblikovanja testnih referenčnih let (TRL) izdelamo prilagojena testna referenčna leta (PTRL). Slednje nato uporabimo za napoved sprememb v rabi energije v stavbah in učinkovitosti izbranih naprav, ki uporabljajo naravne vire energije. Glede na napovedane podnebne scenarije za celinsko področje Slovenije se bo raba energije za ogrevanje stavb zmanjšala za 1,5 do 31,4 odstotkov. Bistveno bolj bodo napovedane podnebne spremembe vplivale na toplotno ugodje v stavbah poleti. Tudi v masivno grajenih stanovanjskih stavbah, ki so naravno prezračevane in v katerih je dandanes ustrezno toplotno ugodje, bodo primerne temperature poleti presežene v 20 do 33 odstotkih poletnega obdobja. Bistveno se bodo spremenile tudi učinkovitosti tehnik naravnega in aktivnega naravnega hlajenja. V hlajenih stavbah lahko pričakujemo med 2- do 40-krat večjo rabo koristne energije glede na sedanje stanje. Rezultati, predstavljeni v prispevku, potrjujejo, da je treba posledice globalnih podnebnih sprememb ocenjevati tudi z vidika rabe energije v stavbah in zasnovi stavb in sistemov strojnih inštalacij.*

**(Ključne besede: podnebne spremembe, modeliranje numerično, toplotni odzivi stavb, raba energije, Slovenija)**

*The world's leading climatologists believe that global climate changes are inevitable. The basis for this is the fact that we are already facing climate changes that will become even more significant in the future. The impact of climate changes is and will be noticeable in all fields of human activity; therefore, it will also influence the supply and demand of energy. Since we are observing a longer period of time, comparable to the lifespan of a building, and the amount of energy demanded is an important factor, it is necessary to adjust the building and the renovation of buildings to the predicted climate changes. The prediction of a building's thermal response is the basis for the integral planning of the building and building services installation with which we create suitable living conditions. In order to predict the expected changes in the building's thermal response in the future it is necessary to correct the available meteorological variable databases today. In this paper we present various climate-change scenaria expected for Slovenia and the methods for correcting the starting points of the local meteorological databases. For the correction we used simplified mathematical models with which we - by forming test reference years (TRYs) - elaborate corrected test reference years (CTRYs). The latter are used for declaring the changes in* *energy demand in buildings and the effectiveness of a chosen building services installation that uses natural energy sources. As regards the predicted climate scenaria for the continental part of Slovenia, the energy use for heating buildings will be reduced by 1.5% to 31.4%. These climate changes will have a substantial influence on the thermal comfort in buildings during the summer. In the heavyweight and naturally ventilated residential buildings that are currently thermally comfortable, suitable summer temperatures will be exceeded during 20% to 33% of the summer. The effectiveness of natural and passive cooling techniques will radically change. In cooled buildings we can expect a 2-to-40-fold increase in the use of final (end-use) cooling energy when compared to today. The results presented in this paper confirm the fact that it is necessary to evaluate the consequences of global climate changes also from the point of view of energy use in buildings, their construction and building services installations.*

**(Keywords: global climate change, numerical modelling, buildings thermal response, energy usage, Slovenia)**

## 0 UVOD

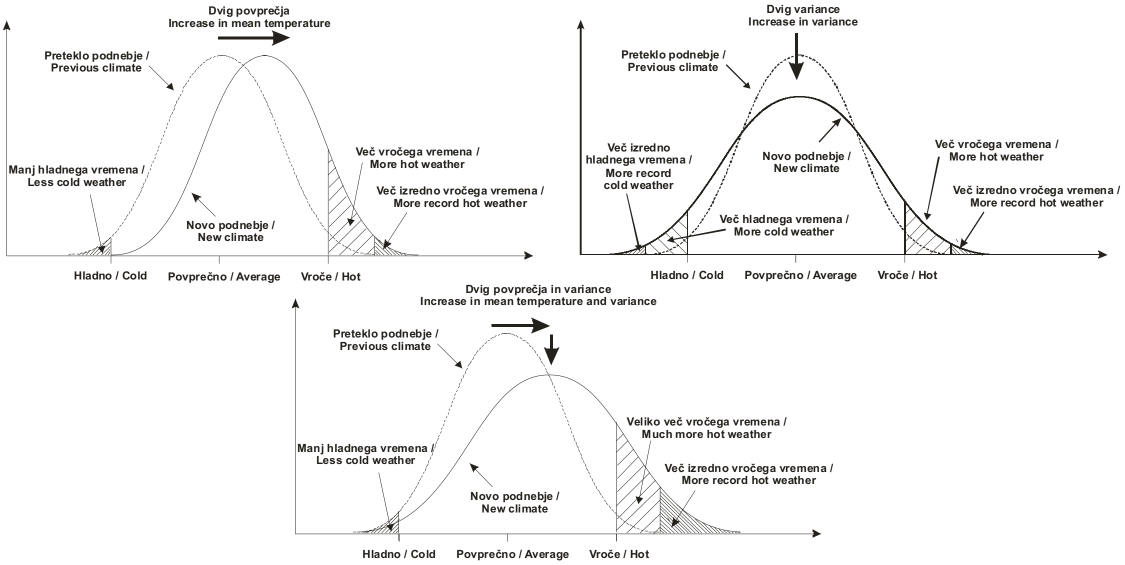
Zasnova sodobnih stavb, uporabljeni gradbeni materiali ter vgrajeni sistemi stavbnih strojnih inštalacij so v sodobnih stavbah medsebojno povezani in soodvisni. To pomeni, da lahko, oziroma moramo z povezanim načrtovanjem stavb in sistemov strojnih inštalacij izdelati stavbo za katero bodo značilni odlično bivalno ugodje, varčna raba energije in majhni pritiski na okolje. Takšen postopek je mogoč le s povezanimi računalniškimi orodji. Ta orodja omogočajo, da, glede na trenutne razmere v zunanjem okolju, geometrijski model stavbe, fizikalne zakonitosti prenosa toplote in snovi v stavbi in sisteme stavbnih instalacij, celovito in podrobno ovrednotimo stanje notranjega ugodja ter energijske in snovne tokove v navidezni stavbi ([1] in [2]). Za tako načrtovanje stavb se je uveljavil izraz celovito načrtovanje stavb.

Spreminjanje termodinamičnega stanja zunanjega okolja je zapleten pojav, na katerega vpliva vrsta naravnih in človeških dejavnikov. Opazovanje spreminjanja svetovne temperature našega planeta v 20. stoletju pokaže, da se je v zadnjem stoletju temperatura že povišala za 0,4 do 0,8 °C. Osnovo za raziskovanje pričakovanih sprememb podnebja v prihodnosti ponujajo modeli MSC. To so trirazsežni numerični modeli, v katere so zajeti fizikalni, kemijski in biološki pojavi v ozračju, oceanih, ledu in na zemeljskem površju ter povezava med temi sistemi. Mednarodni forum o podnebnih spremembah je na podlagi različnih socialno-ekonomskih scenarijev razvoja prebivalstva in gospodarstva izdelal štiri skupine scenarijev emisij toplogrednih plinov. Po teh scenarijih naj bi se

## 0 INTRODUCTION

In modern buildings their schemes, the building materials used and the built-in building services installations are linked and interdependent. This means that we can or rather have to - with the help of interactive planning - construct a building that will offer excellent living conditions, economical energy usage and not put too much pressure on the environment. Such a process is possible only with linked computer tools. These tools enable us to thoroughly and in detail evaluate the state of internal comfort, energy and material currents in a fictive building, while taking into account the present circumstances in the external environment, the geometrical model of the building, the physical elements of heat and material transfer in the building and its building service installations ([1] and [2]). The term integral building planning was coined for such planning.

The changes of the thermodynamic state of the external environment are a complex phenomenon affected by a number of natural and anthropological factors. The observation of the changes of our planet's global temperature in the 20th century showed a temperature increase of between 0.4 and 0.8°C. The MSC (Mesoscale) models offer a basis for researching the expected climate changes in the future. These models are 3D models that include physical, chemical and biological processes in the atmosphere, oceans, ice and on the earth's surface as well as the interactions between these systems. On the basis of various socio-economic scenarios of population development and economy the international forum on climate changes (the Intergovernmental Panel on Climate Change - IPCC) worked out four groups of scenaria for the emissions of greenhouse gasses. According to these



Sl. 1. *Prikaz podnebnih sprememb; dvig povprečja, sprememba variance ter njun skupni vpliv [3]*
Fig. 1. *Climate change: increase in the mean temperature, increase in the variance of temperature and increase in the mean and variance of temperature [3]*

temperature na zemeljskem površju oz. troposferi povišale od 1,4 do 5,8 °C. Napovedujejo tudi da se bodo povišale tako najvišje kakor najnižje temperature, zato bo več vročih in manj mrzlih dni. Pogostejši bodo tudi vročinski valovi in zmanjšal se bo dnevni temperaturni razpon (sl. 1) [3].

Predvidene podnebne spremembe bodo vplivale tudi na rabo energije v stavbah. Dosedaj objavljene raziskave, ki navajajo povezavo med napovedanimi podnebni spremembami in rabo energije v stavbah ugotavljajo, da se bo raba energije za ogrevanje zmanjšala od 10% do 55%, ob povečani rabi energije za hlajenje od 50 % do 200% ([5] do [8] in [10]). Skupno vsem tem raziskavam je dvig temperature okolice glede na pričakovano celovito spremembo te meteorološke spremenljivke. Spremembe drugih spremenljivk ne upoštevajo. Tako dobimo neko sintetično leto, kar pa ne ustreza zahtevam metode oblikovanja testnih referenčnih let ([11] in [12]). Za področje Slovenije sicer obstajajo napovedi podnebnih sprememb ([13] do [15]), toda niso bile uporabljene na prilagojenih testnih referenčnih letih (PTRL). Zato v tem delu prikazujemo metodo prilagoditve krajevnega TRL, glede na več napovedanih scenarijev podnebnih sprememb v Sloveniji. Zaradi najbolj obsežnih arhivov meteoroloških podatkov smo za napovedovanje izbrali mesto Ljubljana. Tako

scenaria the temperatures in the boundary layer or troposphere would increase by 1.4 to 5.8°C. They also predict that the highest as well as the lowest temperatures will increase; therefore, we will have more hot and fewer cold days. Heat waves will be more frequent and the daily temperature span will be smaller (Fig. 1) [3].

The expected climate changes will also affect the energy usage in buildings. The published research dealing with the connection between the predicted climate changes and the energy usage in buildings ascertains that the energy use for heating will reduce by between 10% and 55%, while the use of energy for cooling will increase by 50% to 200% ([5] to [8] and [10]). Common to all of these researches is the temperature increase of the environment, taking into account the expected global change of this meteorological variable. They do not, however, consider the changes of other variables. In this way we get a sort of synthetic year; however, this does not suit the demands of the TRYs method ([11] and [12]). There are climate change predictions for the territory of Slovenia ([13] to [15]); however, they were not applied to the corrected test reference year (CTRY) method. This is why we showed the local TRY method for a number of predicted scenaria for Slovenia. Due to them being the most comprehensive archives of meteorological data we used Ljubljana for our prediction. Corrected TRY data (CTRY) in such a prilagojena TRL (PTRL) bomo združili z modelom toplotnega odziva stavb in napovedali spremembo rabe energije v izbrani stavbi in spremenjeno učinkovitost sistemov stavbnih inštalacij, ki uporabljajo naravne vire.

## 1 UGOTOVLJENE IN NAPOVEDANE SPREMEMBE PODNEBJA V SLOVENIJI

Meritve temperature zraka in drugih meteoroloških spremenljivk kažejo, da se podnebje spreminja tudi na območni ravni. Torej tudi v Sloveniji, kjer se je temperatura zraka v zadnjih 50 letih v povprečju zvišala v območju med 0,4 in 1,6 °C. Spremembe drugih veličin so manj izrazite, saj na primer v letnih količinah padavin v Sloveniji ni zaznati sprememb, izjemi sta Kočevje in Rateče, kjer se je v zadnjih 50 letih količina padavin zmanjšala med 16% in 21%. Pogostost skrajnih padavinskih dogodkov po Sloveniji se ni spremenila, statistično značilno pa se je spremenila jakost izrednih padavinskih dogodkov: v gorskem svetu so izredne padavine manj močne, v sredogorju bolj močne, ob obali in na ravninah v notranjosti pa sprememb jakosti izrednih padavin ni zaznati [15].

Klimatski scenariji za Slovenijo v naslednjem stoletju predvidevajo dvig temperature ozračja in povečanje sončnega obsevanja, medtem ko za padavine scenariji niso enotni [16]. Glede na rezultate simulacij s petimi MSC in upoštevanjem dveh scenarijev emisij, lahko sklepamo, da se bosta temperatura in sončno obsevanje v Sloveniji v 21. stoletju brez dvoma povečala. Pri tem ni izrazitih razlik med posameznimi območji Slovenije. Zanesljivost predvidevanj je veliko manjša za količino padavin, v splošnem pa prevladuje negativna usmeritev pri spremembah padavin. Če upoštevamo le najbolj verjetne spremembe za prvi dve tridesetletji 21. stoletja, potem velja za spremembe temperature obseg od + 1 °C do + 4 °C, za spremembe energije svetovnega obsevanja obseg od 0 % do +6 % in za spremembo padavin obseg od - 20 % do + 20 %. V preglednici 1 so prikazane napovedane spremembe izbrane vplivne spremenljivke in oznake najverjetnejših podnebnih scenarijev, ki jih bomo uporabili v naši raziskavi ([16] in [17]).

## 2 METODA OBLIKOVANJA PRILAGOJENIH TESTNIH REFERENČNIH LET

Prilagojena testna referenčna leta, ki vključujejo napovedane podnebne spremembe, smo

way will be merged with the model of the building's thermal response and thus we will predict the change in energy usage for a chosen building as well as the changed effectiveness of the building services installations that use natural sources.

## 1 DETECTED AND PREDICTED CLIMATE CHANGES IN SLOVENIA

Measurements of meteorological variables clearly indicate climate changes on a regional scale. The most significant changes in Slovenia were detected in temperature, which has risen between 0.4 and 1.6 °C on average over the past 50 years. The changes of other meteorological variables are less significant; in particular, there is no significant change in precipitation, with the exception of the measurement sites at Rateče and Kočevje, where the precipitation amount has fallen by 16% and 21%, respectively. The frequency of extreme precipitation events has not changed; however, there is a significant change in the intensity of precipitation events: precipitation is less intensive in the mountainous region, more intensive in the sub-Alpine region, and without change in the costal and lowland regions [15].

All climate-change scenaria show an increase in temperature and solar radiation energy in the next century for the entire area of Slovenia, while the predictions for precipitation are not homogenous [16]. According to the results of five different GCM and two different emission scenarios, we can state with high certainty that the temperature and the amount of solar radiation energy will increase in the 21st century in Slovenia. The reliability for precipitation scenarios is less certain, both an increase and decrease is expected, although the positive trend in precipitation is prevailing. If only the scenarios with highest likelihood are considered, than in the first 60 years of the 21st century the estimated change in Slovenia is between 1°C and 4°C for temperature, between -20% and +20% for precipitation and from +0% up to 6% in solar radiation in comparison to the mean 1961-1990 values. The possible combinations of the predicted changes for all three meteorological variables that were considered in our analysis are presented in Table 1 ([16] and [17]).

## 2 METHODOLOGY FOR CORRECTED TEST REFERENCE YEARS

CTRYs, which include expected changes of meteorological variables, are corrected on the basis

Preglednica 1. *Kombinacije sprememb vplivnih meteoroloških spremenljivk in oznake v različnih scenarijih podnebnih sprememb v Sloveniji*
Table 1. *The changes of influential meteorological variables for different climate-change scenaria for Slovenia*

| | Povišanje temperature<br>Temperature rise<br>°C | Povečanje sončnega obsevanja<br>Solar radiation energy rise<br>% | Sprememba padavin<br>Precipitation change<br>% |
|---|---|---|---|
| sedanje TRL<br>contemporary TRY | 0 | 0 | 0 |
| scenarij A<br>scenario A | 1 | 0 | 0 |
| scenarij B<br>scenario B | 1 | 3 | 0 |
| scenarij C<br>scenario C | 3 | 0 | 0 |
| scenarij D<br>scenario D | 3 | 6 | 0 |
| scenarij E<br>scenario E | 1 | 3 | +20 |

oblikovali na podlagi dolgoletnih meritev samodejne meteorološke postaje v Ljubljani. Sicer redke manjkajoče vrednosti spremenljivk nadomestimo z interpolacijo. To smo naredili z metodo časovno-prostorske interpolacije z zlepki ([18] in [19]) interpolirali za čas manjkajočih podatkov, pri čemer so bili vozli zlepka zadnja meritev pred ustavitvijo in prva meritev po ustavitvi meritev ter vmesne meritve klasičnih zaznaval ob 7., 14. in 21. uri. Število vozlov je bilo odvisno od dolžine manjkajočega niza, v vsakem primeru pa smo imeli vsaj dva robna vozla. Edini pogoj za zlepek je bil, da je bila v vozlih zvezna, ne pa tudi zvezno odvedljiva (gladka), ker je običajno premalo podatkov, da bi lahko izračunali vse parametre polinoma druge stopnje. Funkcija $f_k(t)$ na odseku med zaporednima vozloma ($x_i$ in $x_{i+1}$), kjer poznamo vrednosti, zapišemo:

of year-long measured meteorological variables from an automatic weather station (AWS) in Ljubljana. Otherwise rarely missing values of variables (the gap) are substituted with a spatial-temporal interpolation using spline functions ([18] and [19]). The knots of the interpolated function are the last measurement before the gap, the first measurement after the gap, and the measurements from classical stations in climatological terms at 7 a.m., 2 p.m. and 9 p.m. at the same location. The number of knots depends on the length of the gap; nevertheless, there are always at least two edge knots. The only condition for the function is that it is continuous in the knots, since there were usually not enough data to derive all the parameters for a continuously derivable function. The function $f_k(t)$ in the sequence segment between two successive knots ($x_i$ and $x_{i+1}$) is:

$$f_k(t) = g(t) - \left[g(t_i) - x_i\right] + \frac{\left[g(t_i) - x_i\right] - \left[g(t_{i+1}) - x_{i+1}\right]}{t_{i+1} - t_i}\left[t - t_i\right]$$

kjer so:

$t_i$ - čas v $i$-tem vozlu,
$t_{i+1}$ - čas v $i$+1. vozlu,
$x_i$ - robna vrednost funkcije $f_k(t)$ v $i$-tem vozlu,
$x_{i+1}$ - robna vrednost funkcije $f_k(t)$ v $i$+1. vozlu,
$g(t)$ - potek meteorološke spremenljivke v času na sosednji postaji,
$g(t_i)$ - vrednost meteorološke spremenljivke v $i$-tem vozlu na sosednji postaji,
$g(t_i)$ - vrednost meteorološke spremenljivke v $i$+1. vozlu na sosednji postaji.

Najbolj razširjene metode oblikovanja PTRL, ki vključujejo napovedane spremembe podnebja so:

where:

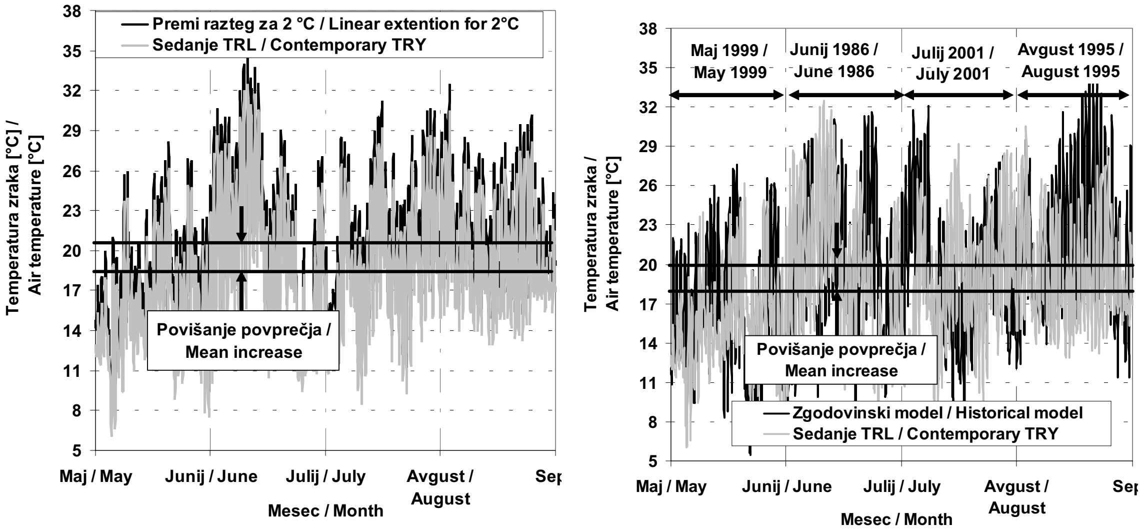
$t_i$ - is the time in the $i^{th}$ knot,
$t_{i+1}$ - is the time in the $i+1^{th}$ knot,
$x_i$ - is the value of the $f_k(t)$ in $i^{th}$ knot,
$x_{i+1}$ - is the value of the $f_k(t)$ in $i+1^{th}$ knot,
$g(t)$ - is the dependence of the meteorological variable on the time on the neighboring station,
$g(t_i)$ - is the value of the meteorological variable on the neighboring station in the $i^{th}$ knot,
$g(t_i)$ - is the value of the meteorological variable on the neighboring station in the $i+1^{th}$ knot.

The most frequently used approaches to adopt CTRY on climate-change scenarios are: a linear premi razteg TRL ([13] do [15]), uporaba naključnostnih generatorjev vremena ([20] in [21]) ter uporaba zgodovinskega načina oblikovanja PTRL [22]. Na sliki 2 sta shematsko prikazana načina oblikovanja PTRL s premim raztegom in uporaba zgodovinskega načina oblikovanja PTRL.

Zadnji dve metodi sta računsko in časovno zahtevni, medtem ko je premi razteg izredno preprosta metoda. Pomanjkljivost vseh treh metod je, da ne upoštevamo spremembe porazdelitve in spremenljivosti meteoroloških spremenljivk zaradi podnebne spremembe, ampak upoštevamo le spremembo njene povprečne vrednosti. Pomanjkljivost nizov, oblikovanih z naključnostnim generatorjem vremena, je, da lahko pride do nesmiselnih zvez med posameznimi spremenljivkami, kar pa je izredno moteče pri kasnejši napovedi toplotnega odziva stavb. V tem primeru je še posebej pomembna smiselna zveza med temperaturo, vlažnostjo ozračja in sončnim obsevanjem. Kot najbolj primerno metodo zato izberemo metodo oblikovanja PTRL na zgodovinski način. Torej poiščemo iz obsežne baze krajevnih meteoroloških podatkov neko drugo delno obdobje (niz, običajno mesec dni), ki najbolj ustreza pričakovanemu, oziroma napovedanemu stanju. Tako ostajajo spremenljivke smiselno povezane, nekaj težav bi lahko predstavljala le nezveznost med posameznimi časovnimi obdobji (meseci), ki pa v primeru analize toplotnega odziva stavb ne pomeni velike pomanjkljivosti zaradi razmeroma velike toplotne vsebnosti gradbenih konstrukcij.

extension of the TRY ([13] to [15]), stochastic weather generators ([20] and [21]) and a historical approach [22]. In Figure 2 there are schematic representations of two methodologies to adopt the CTRY: a linear extension and a historical approach.

The last two methods have high computational and time requirements, while a linear extension is a very simple method. The weak point of all three described methods is that they do not consider the changes of the distribution and the variability of the meteorological variables, they only consider the changes of mean values. The weak points of the series constructed with the stochastic weather generator are the strange relations between the meteorological variables, which do not match reality, and could affect the predicted thermal responses of buildings. For thermal response modeling it is very important that there is a logical correlation between the temperature, the humidity and the solar radiation. The most suitable method, that fulfils that criterion, is the historical approach. From the database of hourly meteorological variables a month was selected, which is in all meteorological variables the closest to the average or predicted month. The correlations between the variables stay logical and natural; a minor problem is the discontinuity on the borders between months, which does not represent difficulties in the thermal response simulation, since buildings have a relatively large thermal capacity.



Sl. 2. *Shematični prikaz oblikovanja PTRL s premim raztegom TRL in na zgodovinski način iz baze krajevnih meteoroloških podatkov*

Fig. 2. *Schematic presentation of a linear extension methodology and a historical approach for the construction of the TRY*

Izbiro posameznih nizov smo naredili na podlagi dnevnih podatkov meteoroloških postaj, ki jih ARSO sistematično zbira v digitalni obliki v zadnjih dvanajstih letih. Sončno obsevanje smo izračunali iz trajanja sončnega obsevanja s preprostim parametričnim modelom. Za vsakega od scenarijev smo PTRL oblikovali kot skupek mesečnih nizov iz baze zgodovinskih krajevnih meteoroloških podatkov. Posamezni niz smo izbrali z uporabo Finkelstein-Schaferjeve statistike (FS) [22]:

$$FS(p,m,y)=\sum_{i=1}^{N_m}\left|CDF(p_i,m,y)-CDF(p_i,m,N_y)\right|$$

kjer so:

*FS(p,m,y)* - Finkelstein-Schaferjeva statistika za meteorološko spremenljivko p, mesec m in leto y,

$CDF(p_i,m,y)$ - zbirna porazdelitvena funkcija povprečnih dnevnih vrednosti meteorološke spremenljivke p za mesec m in leto y,

$CDF(p_i,m,N_i)$ - zbirna porazdelitvena funkcija povprečnih dnevnih vrednosti meteorološke spremenljivke p za mesec m in več let (referenčno obdobje ali scenarij).

FS je sešteta po vseh obdobjih vrednosti zbirne porazdelitve (Nm). Za izbiro mesecev, ki sestavljajo posamezne referenčne nize, so nekatere meteorološke spremenljivke bolj pomembne od drugih. Teža posamezne spremenljivke pri izbiri je v največji meri odvisna od namena uporabe referenčnega niza. Na rabo energije za ogrevanje in hlajenje v največji meri vplivajo temperatura zraka, sončno obsevanje in vlaga. Kot ključne spremenljivke za izbiro mesecev za sestavo testnih nizov za referenčno leto (1961-1990) in za scenarije posameznih podnebnih sprememb smo zato izbrali povprečno dnevno temperaturo, mesečno vsoto celotnega obsevanja in padavin. Kljub vplivu vetra na rabo energije te spremenljivke nismo uvrstili kot ključne spremenljivke za izbiro ustreznega meseca, zaradi izjemno slabe kakovosti in neustreznosti meritev vetra pred letom 1990. Poleg tega je veter spremenljivka z zelo veliko spremenljivostjo in njene spremembe v prihodnosti so za zdaj nenapovedljive, torej jih v scenarijih spremembe podnebja nismo zajeli. Zbirno porazdelitveno funkcijo (CDF) smo izračunali za referenčno obdobje (1961-1990), za posamezne scenarije ter za vsak mesec v obdobju zadnjih 12 let (obdobje samodejnih meritev, za katerega imamo na voljo urne podatke). CDF za posamezne scenarije smo izračunali iz CDF za

The CTRY is constructed from representative months selected from the AWS hourly data, operated by the Environmental Agency of the Republic of Slovenia (EARS) in the past 12 years. The solar radiation energy was calculated from the sunshine duration. For every climate-change scenario from Table 1 the CTRY was also constructed from historical data on a monthly basis. The month was selected on the basis of Finkelstein-Schafer (SF) statistics [22]:

where;:

*FS(p,m,y)* are the Finkelstein-Schafer statistics for the meteorological variable p, the month m and the year y

$CDF(p_i,m,y)$ is a cumulative distribution function for mean daily values of the meteorological variable p for the month m and the year y

$CDF(p_i,m,N_i)$ is a cumulative distribution function for the mean daily values of the meteorological variable p for the month m and Ni years (reference year or scenario)

FS is summed up along all intervals of the cumulative distribution function (Nm). For the CTRY correction some meteorological variables are more important than others. The weight of a single variable depends on the purpose for which the CTRY would be used. Energy use for heating and cooling mostly depends on the air temperature, the solar radiation energy and the humidity. Three climate variables are identified as being critical for CTRY construction, according to the climate-change scenarios: the temperature, the precipitation and the global radiation. Even if the wind influences energy use, it was not included among the critical variables for the selection of the separate months, because wind measurements were of very poor quality in the period before 1990. Furthermore, the variability of wind is very high and for the moment unpredictable, so it was not included in the climate-change scenarios. Cumulative distribution functions (CDFs) were calculated for the reference period 1961-2000, for all treated scenarios and for every separate month of the period of the past 12 years (the period of automated weather-station measurements, for which the hourly data were available). The CDF for a separate scenario was calculated from the CDF for the reference period (1961-2000) with a linear shift in the average values of all the variables, according to referenčno obdobje 1961-1990 s premim premikom posamezne spremenljivke glede na scenarij. Mera za izbiro meseca v referenčni niz je bila utežena vsota statistike FS:

$$FS(m,y)=\sum_{p=1}^{3} W_p \cdot FS(p,m,y)$$

kjer so:

$FS(m,y)$ - utežena vsota statistike FS za mesec in leto,

$W_p$ - utež za posamezno spremenljivko (v našem primeru enaka za vse tri spremenljivke: 1/3),

$FS(p,m,y)$ - statistika FS za posamezno spremenljivko (povprečno dnevno temperaturo, mesečno vsoto padavin in trajanje sončnega obsevanja), mesec in leto.

Kot referenčni niz je bil izbran mesec z najnižjo vrednostjo statistike FS. PTRL smo nato sestavili iz tistih dvanajstih referenčnih nizov, za katere vsota statistike FS za vse referenčne nize ni presegla 24. To mejo smo določili izkustveno [23], iz primerjave letne statistike FS in povprečnih letnih vrednosti posameznih spremenljivk niza. Slika 3 prikazuje sončno obsevanje in povprečne temperature iz različnih PTRL za obdobje ogrevanja in hlajenja stavb ob upoštevanju v preglednici 1 opisanih podnebnih scenarijev. Izdelana PTRL pomenijo najboljši približek scenarijev podnebnih sprememb zgodvinskim vrednostim.

the climate-change scenario. The measure for the selection of a separate month to be included in the CTRY, the weighted sum of FS(m,y) statistics for all three climate variables, is calculated using:

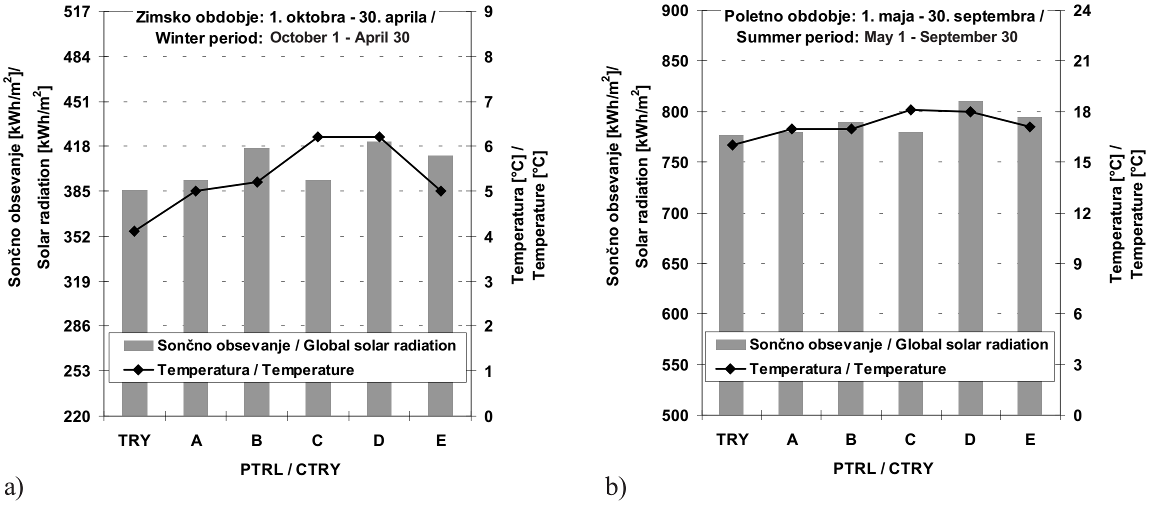
where:

$FS(m,y)$ is the weighted sum of FS statistics for the month m and the year $y$,

$W_p$ is the weight for a single meteorological variable (in the treated case all weights were equal to 1/3),

$FS(p,m,y)$ is the FS statistic for a separate variable $p$, the month $m$ and the year $y$

The month/year with the lowest value of FS statistics is selected for the construction of a reference year. The CTRYs are constructed only for those scenarios where the sum of FS statistics for all 12 months is lower than 24. The threshold of 24 is chosen empirically [23], according to the magnitude of the difference between the average and demanded values of the climate variables. Solar radiation energy and the mean temperature for different CTRYs are presented in Figure 3, separately for the heating and cooling periods. CTRYs are calculated and marked according to the scenarios from Table1. Corrected CTRYs are the best approximation for climate-change scenarios with historical measurements.



a) b)

Sl. 3. *Sončno obsevanje in povprečna temperatura okolice za a) zimsko in b) poletno obdobje iz različnih PTRL, ki vključujejo podnebne scenarije*

Fig. 3. *Solar radiation and mean yearly temperature for a) winter and b) summer period for the CTRY corresponding to different climate-change scenaria*

## 3 POVEZAVA MODELA PODNEBNIH SPREMEMB Z MODELOM TOPLOTNEGA ODZIVA STAVB

Zasnova sodobnih stavb, uporabljeni gradbeni materiali, učinkovitost sistemov stavbnih strojnih inštalacij in meteorološke spremenljivke odločilno prispevajo k energijski učinkovitosti stavb. Ob tem je pomembno, da je največji del porabljene energije v stavbah posledica zagotavljanja bivalnega ugodja. Pri tem imamo v mislih sisteme za ogrevanje, hlajenje in sisteme za prezračevanje.

V naši raziskavi smo za ovrednotenje napovedanih sprememb podnebja na toplotni odziv stavb uporabili numerični simulacijski program TRNSYS [25]. Na sliki 4 je prikazan primer toplotnega odziva izbrane stavbe. Navajamo ga lahko s temperaturami, ki se vzpostavijo v neogrevani in nehlajeni stavbi (nanadzorovani toplotni odziv) ali toplotni tokovi pri ogrevani in/ali hlajeni stavbi če temperaturo v stavbi omejimo (nadzorovani toplotni odziv stavbe). V tem primeru lahko določimo potrebno moč ogrevalnega in hladilnega sistem in tudi rabo energije za zagotavljanje načrtovanega toplotnega ugodja.

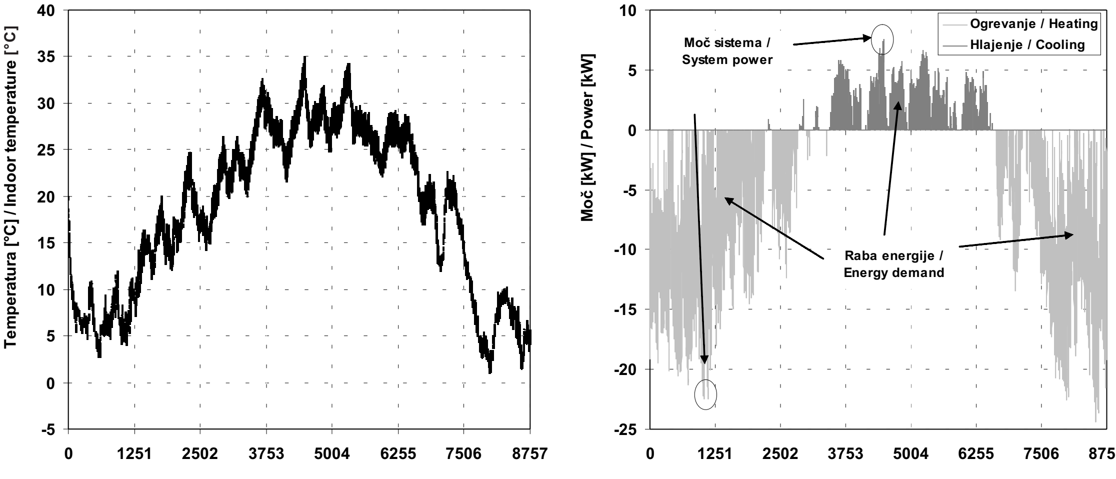
Majhna raba energije v sodobnih stavbah ne temelji zgolj na odlični toplotni izolaciji gradbenih

## 3 THE CONNECTION BETWEEN THE CLIMATE CHANGE MODEL AND THE BUILDINGS' THERMAL RESPONSE MODEL

The basis of modern buildings, the used building materials, the effectiveness of the installations and the meteorological variables decisively contribute to a buildings' energy efficacy. Along with this it is important that the biggest share of the building's used energy is used to ensure a certain level of living comfort. For this we have in mind the systems for heating, cooling and air-conditioning.

In our research we have used a numerical simulation programme called TRNSYS in order to evaluate the effect the predicted climate changes will have on the building's thermal response [25]. Figure 4 shows a thermal response example for a chosen building. We can show the example with temperatures that are present in a non-heated or non-cooled building (uncontrolled building thermal response), or the heat flux at a heated and/or cooled building when we define the inner temperature (controlled building thermal response). In this case we can define the necessary heating or cooling power as well as the energy use needed to ensure the planned thermal comfort.

The low energy use in contemporary buildings is not based merely on the excellent heat insulation of



a) b)

Sl. 4. *Toplotni odziv stavbe popisuje spreminjanje notranjega toplotnega okolja v odvisnosti od stanja v zunanjem okolju. Slika a) prikazuje primer nenadzorovanega toplotnega odziva stavbe in b) primer nadzorovanega toplotnega odziva, na podlagi katerega lahko določimo potrebno moč sistema ter rabo energije za zagotavljanje načrtovanega toplotnega ugodja*

Fig. 4. *Thermal response of house to determine the inner thermal comfort dependence from the environmental condition. Figure a) shows the uncontrolled building thermal response of a building and b) the controlled thermal response, where we can define the necessary heating and/or the cooling power and energy use to ensure the planned thermal comfort.*

elementov, temveč tudi na izrabi naravnih virov za ogrevanje (sprememba sončnega obsevanja) in hlajenje (nočno prezračevanje, hlapilno hlajenje, zemeljski prenosnik toplote). Ker poleg meteoroloških spremenljivk na toplotno ugodje v stavbi vpliva tudi njihova arhitektonska zasnova bomo v našem delu vpliv napovedanih podnebnih sprememb določili za izbrano stanovanjsko in poslovno stavbo, ki ju prikazuje slika 5. Povečanje debelin toplotne izolacije, ki je značilno za sodobne stanovanjske stavbe, zahteva svojski način gradnje stavb z lahkimi gradbenimi elementi v obliki prej izdelanih elementov. Posledica tega je majhna toplotna prehodnost, toda tudi majhna toplotna vsebnost gradbenih elementov in zato manjša učinkovitost naravnega ogrevanja s soncem in naravnega hlajenja. Zato v naši raziskavi, poleg obeh resničnih stavb, analiziramo tudi namišljeno "lahko" grajeno stanovanjsko stavbo z enakimi toplotnimi prehodnostmi gradbenih konstrukcij. Poslovna stavba ima 6 nadstropij. V sredini stavbe je atrij, ki je odprt prek vseh nadstropij in je na vrhu zasteklen. Senčenje in prezračevanje vseh stavb je izvedeno skladno z zahtevami učinkovite rabe energije v stavbah, torej mehansko z vračanjem toplote. Preostale pomembne toplotno tehnične lastnosti stavb navajamo v preglednici 2.

Numerični model toplotnega odziva stavb smo preverili v obeh zgrajenih stavbah z meritvami temperatur nenadzorovanega toplotnega odziva stavb v obeh znanih stavbah. Na sliki 6 je prikazano ujemanje izmerjene in numerično določene občutene temperature osrednjega prostora v stanovanjski stavbi v poletnem obdobju.

building elements, but also on the exploitation of a natural source of heating (transforming solar radiation) and cooling (night-time ventilation, evaporation cooling, ground heat exchanger). Since thermal comfort is not affected just by the meteorological variables but also by the architectural basis, we will deal with the impact of the predicted climate changes for a chosen residential and office building as shown in Figure 5. Increasing the thickness of heat isolation, which is typical for modern residential buildings, demands a specific method of building houses, with light, pre-factored building elements. This results in a low heat transfer as well as a low heat capacity of the building elements and therefore a lower efficiency of the natural heating and cooling. This is why we, alongside both real buildings, also analysed an imaginary 'lightweight' built residential building with equal heat transfer of the building constructions. The office building has six floors. In the centre of the building there is an atrium with a glass roof at the top. The shading and ventilation of all the buildings is performed in accordance with the demands of efficient energy use, i.e., mechanical with a heat exchanger. The other important technical and heat properties of the building are indicated in Table 2.

We verified the numerical model for the building's thermal response in both buildings by measuring the temperatures of the uncontrolled building thermal response in both existing buildings. In Figures 6 and 7 we show the accordance of the measured and the numerically defined operative temperature in the central room of the residential building and at the top of the atrium of the office building during the summer.

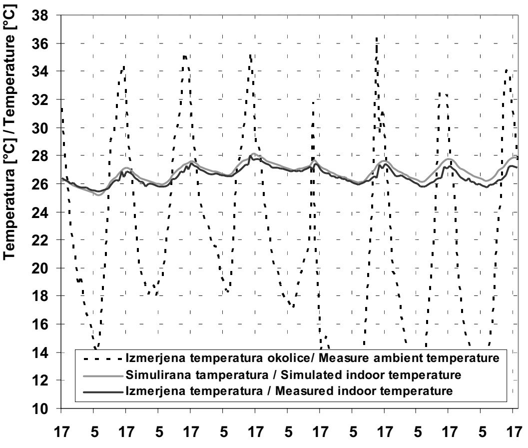
a)

b)

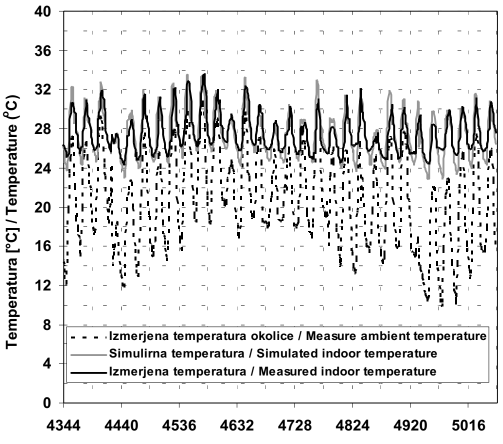
Sl. 5. *a) Stanovanjska in b) poslovna stavba v Ljubljani ([24] in [10])*
Fig 5. *a) Residential and b) office building in Ljubljana ([24] and [10])*

Preglednica 2. *Toplotno-tehnične lastnosti izbranih stavb*
Table 2. *Technical and thermal properties of the building*

| | Stanovanjska stavba<br>Residential building | Poslovna stavba<br>Office building |
|---|---|---|
| Uporabna površina<br>Living area | 101 (191) | 1986 (15063) |
| Temperatura (ogrevanje,hlajenje)<br>Temperature (heating, cooling) | 20°C, 26°C | 20°C, 26°C |
| $U_{zunanji\ zid}$ [W/m$^2$K]<br>$U_{exterior\ wall}$ [W/m$^2$K] | 0,3 | 1,3 |
| $U_{streha}$ [W/m$^2$K]<br>$U_{roof}$ [W/m$^2$K] | 0,1 | 0,4 |
| $U_{pod}$ [W/m$^2$K]<br>$U_{floor}$ [W/m$^2$K] | 0,4 | 0,6 |
| $U_{notranji\ zid}$ [W/m$^2$K]<br>$U_{inner\ wall}$ [W/m$^2$K] | 0,4 | 1,4 |
| $U_{zasteklitev}$ [W/m$^2$K]<br>$U_{glazing}$ [W/m$^2$K] | 1,4 | 1,3 |
| $g_{zasteklitev}$ [/]<br>$g_{glazing}$ [/] | 0,62 | 0,33 |
| Količnik senčenja zasteklitve Sf<br>Shading factor Sf | 0,25 | 0,4 |
| Zasedenost [h]<br>Occupancy [h] | $16^{00}$ - $7^{00}$ | $7^{00}$ - $19^{00}$ |
| Notranji viri toplote [W/m$^2$]<br>Gain [W/m$^2$] | 3 W/m$^2$ | 5 W/m$^2$ |
| Naravno prezračevanje [h$^{-1}$]<br>Infiltration [h$^{-1}$] | 0,2 | 0,2 |
| Prisilno prezračevanje [h$^{-1}$]<br>Ventilation [h$^{-1}$] | 0,5 | 0,5 |



Sl. 6. *Eksperimentalna potrditev modela toplotnega odziva stanovanjske stavbe - primerjava izmerjenih in numerično določenih temperatur v osrednjem prostoru*
Fig. 6. *Experimental verification numerical model for the residential building - accordance of the measured and the numerically defined indoor temperature in the central room*



Sl. 7. *Eksperimentalna potrditev modela toplotnega odziva poslovne stavbe - primerjava izmerjenih in numerično določenih temperatur na vrhu atrija v poletnem obdobju*
Fig. 7. *Experimental verification numerical model for the office building - accordance of the measured and the numerically defined indoor temperature on the top of the atrium*

Za preverjanje numeričnega modela toplotnega odziva stavb smo v vseh primerih uporabili izmerjene vrednosti meteoroloških spremenljivk v istem obdobju. V obeh primerih menimo, da gre za uspešno preverjanje numeričnega modela. Razlike pri stanovanjski stavbi ne presežejo ± 0,4°C, pri poslovni stavbi pa so sicer nekoliko večje (do ±2,1°C), kar je razumljivo glede na dejstvo, da so notranji viri toplote, razsvetljava, gibanje ljudi in prezračevanje med conami težje sledljivi.

## 4 VPLIV NAPOVEDANIH SPREMEMB PODNEBJA NA RABO ENERGIJE V STAVBAH

Energijsko učinkovitost stavb zagotovimo z dvema skupinama ukrepov - kakovostno toplotno zaščito in vgradnjo sistemov, ki izrabljajo naravne vire toplote in hladu. Napovedane spremembe podnebja bodo vplivale tako na rabo energije za ogrevanje in hlajenje stavb kakor tudi na učinkovitost naprav, še posebej v poletnem času. Zato bomo poleg sprememb v rabi energije, potrebni za zagotavljanje toplotnega ugodja, analizirali tudi spremembe v učinkovitosti tehnik naravnega in dejavnega naravnega hlajenja. Med slednje uvrščamo povečano nočno naravno prezračevanje, ogrevanje in hlajenje zraka za prezračevanje pred vstopom v stavbo v zemeljskem prenosniku toplote in posredno hlapilno hlajenje.

V literaturi zasledimo, da je mogoče tudi v mestnih okoljih s primernim načrtovanjem prezračevalnih odprtin in prečnim prezračevanjem zagotoviti do 13-kratno urno izmenjavo zraka v stavbi [27]. V naši raziskavi smo upoštevali 5 h-1 nočno (med 20.00 in 7.00 zjutraj) naravno izmenjavo zraka v stavbah, ko je temperatura v stavbi višja od 23 °C. Ta vrednost pomeni najvišjo pričakovano vrednost v zavetrju. Temperatura zraka, ki vstopa v stavbo je enaka temperaturi okolice. Pri zemeljskem prenosniku toplote zrak vodimo z ventilatorjem skozi primerno dolgo cev, ki je zakopana vsaj 2,5 m pod površjem. Temperaturo zraka na vstopu v stavbo določimo z numeričnimi ali izkustvenimi modeli. V našem delu smo uporabili merilni izraz, ki ga je oblikoval Mihalakakou [28]. Izstopno temperaturo zraka iz zemeljskega prenosnika izračunamo z izrazom:

In order to verify the numerical model of the building's thermal response we used the measured values of meteorological variables over a certain period. We believe that we have a successful verification of the numerical model for both cases. The differences in the residential building do not exceed ±0.4°C and in the office building they do not exceed ±2.1°C, which is understandable considering the fact that the inner sources of heat, such as lighting, the movement of people and airing are difficult to follow.

## 4 THE INFLUENCE OF THE PREDICTED CLIMATE CHANGES ON THE ENERGY DEMAND

We ensure the building's energy efficiency with two types of measure - quality heat insulation and the inclusion of systems that use natural sources for heating and cooling. The predicted climate changes will affect the energy used for heating and cooling the buildings as well as the effectiveness of the devices, especially during the summer. For this reason we will - apart from the changes in energy demand in order to ensure thermal comfort - also analyse the differences in the efficiency of the natural and active cooling techniques. Among the latter we classify the increased night-time natural ventilation, heating and cooling the air before it enters the building through ground heat exchanger and indirect evaporation cooling.

We discovered in the literature that it is possible to ensure up to 13 per hourly air exchanges, even in urban surroundings, if we apply suitable ventilation holes' planning and cross-way ventilation [27]. In our research we paid special attention to 5 h-1 per night (between 8 pm and 7 am) of natural air exchanges in buildings when the temperature in the building exceeds 23°C. This value represents the highest expected value in wind-sheltered conditions. The air temperature entering the building is the same as the surrounding temperature. With the ground heat exchanger we lead the air (with the aid of a ventilator) through a suitable long tube buried at least 2.5 m underground. We define the air temperature at the building entrance with numerical and empirical models. In our work we used the empirical expression formed by Mihalakakou [28]. We can calculate the air temperature exiting from the ground heat exchanger with the following equation:

$$T_{izst} = T_{zemlje} + \left[ \left( T_{okol} - T_{zemlje} \right) \cdot \varepsilon_{ref} \left( L \right) \cdot {}^{norm}_{Q,L}(z) \cdot {}^{norm}_{z,L}(Q) \right]$$

kjer so:

$T_{zemlje}$ temperatura zemlje na globini cevi

where:

$T_{zemlje}$ is the soil temperature at the depth of the prenosnika,

$T_{okol}$ temperatura okoliškega zraka, ki vstopa v zemeljski prenosnik,

$\varepsilon_{ref}$ referenčna učinkovitost zemeljskega prenosnika, odvisna od dolžine,

$^{norm}_{Q,L}(z)$ referenčna učinkovitost zemeljskega toplotnega prenosnika, odvisna od globine,

$^{norm}_{z,L}(Q)$ referenčna učinkovitost zemeljskega prenosnika odvisna od prostorninskega pretoka zraka.

Sodobni sistemi za mehansko prezračevanje morajo imeti vgrajen prenosnik za vračanje toplote svežemu zraku. Tak sistem lahko nadgradimo v sistem za posredno hlapilno hlajenje. Prenosno površino na strani odpadnega zraka omočimo in tako ustvarimo prenos toplote in snovi, s katerim se odpadni zrak hlapilno hladi. Posredno pa se hladi tudi svež zrak, ki prek prenosnika toplote teče v stavbo. Izstopno temperaturo zraka za prezračevanje stavbe določimo z izrazom [30]:

pipe heat exchanger

$T_{okol}$ is the air temperature at the pipe's inlet

$\varepsilon_{ref}$ is the reference effectiveness of heat exchanger, depending on the pipe's length

$^{norm}_{Q,L}(z)$ is the reference effectiveness of the heat exchanger, depending on the depth of the buried pipe below the earth's surface

$^{norm}_{z,L}(Q)$ is the reference effectiveness of the heat exchanger, depending on the flow rate of the air inside the pipe

Modern systems for mechanical ventilation have to include a heat exchanger that returns the heat to the fresh air. We can install this into the indirect vapour cooling system. We moisten the transferable surface on the waste-air side and thus create a surface for transferring heat and substances that cool the waste air. The fresh air that flows into the building through the heat transfer is also indirectly cooled. The exit air temperature for airing the building is determined by the following equation [30]:

$$T_{izst} = -1,2266 + 0,6011 \cdot T_{st} + (0,315 - 0,0028 \cdot T_{st}) \cdot T_{okol}$$

kjer sta:

$T_{st}$ temperatura zraka v stavbi [°C],

$T_{okol}$ temperatura okoliškega zraka, ki vstopa v prenosnik toplote [°C].

Izraz je oblikovan za tipični ploščni prenosnik toplote ob upoštevanju stalne 50% vlažnosti v stavbi [29].

Vrednotenje toplotnega odziva stavb ob upoštevanju različnih PTRL navajamo na dva načina:

- v primeru nenadzorovanega toplotnega odziva stavb, npr. število ur v letu, ko je občutena temperatura v stavbi višja od meje toplotnega ugodja (26 °C);
- kot spremembo v specifični rabi koristne energije za hlajenje, preračunane na m$^2$ bivalne površine;
- kot spremembo v specifični rabi koristne energije za ogrevanje, preračunane na m$^2$ bivalne površine.

Pri hlajenju stavb ne vrednotimo latentne toplote ovlaževanja ali razvlaževanja. Predstavljene tehnike naravnega hlajenja namreč ne vplivajo na absolutno vlažnost zraka, oziroma se pojavu kondenzacije celo namenoma izogibamo zaradi zdravstvenih načel. Poleg tega smo ugotovili, da PTRL, ki smo ga oblikovali glede na Scenarij E, ne omogoča smiselne prilagoditve TRL in smo ga v nadaljevanju zato opustili. Rezultate analiz navajamo najprej za stanovanjski stavbi. Na slikah 8, 9 in 10 so prikazani rezultati za masivno in lahko grajeno stanovanjsko stavbo.

where:

$T_{st}$ is the indoor temperature of the building [°C]

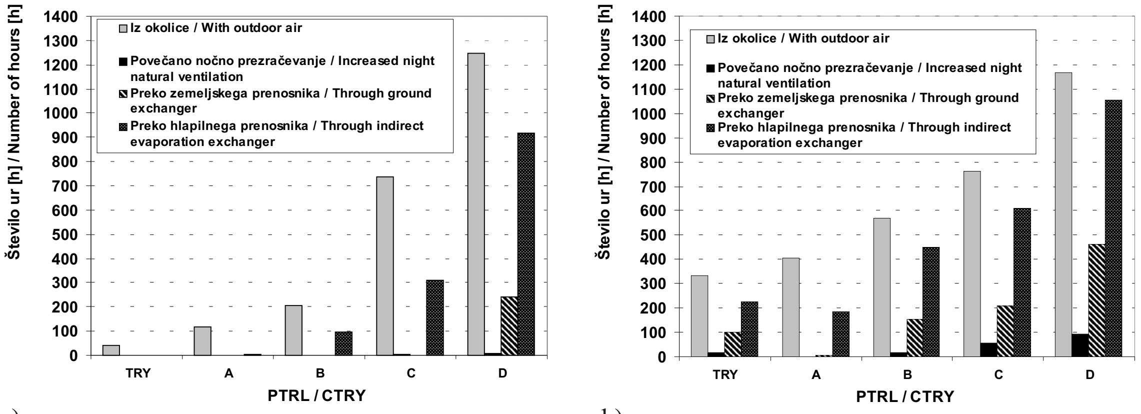
$T_{okol}$ is the ambient temperature that flows into the heat exchanger [°C]

This formula was created for a typical heat-transfer surface that considers a constant 50% humidity in the building [29].

We can indicate the building's thermal response evaluation (with regard to various CTRYs) in two ways:

- in the case of an unsupervised building's thermal response as the number of hours in the year when the temperature in the building is higher than the limit of thermal comfort (26°C);
- as the change in the specific use of energy demand for cooling, calculated per m$^2$ of living area;
- as the change in the specific use of energy demand for heating, calculated per m$^2$ of living area.

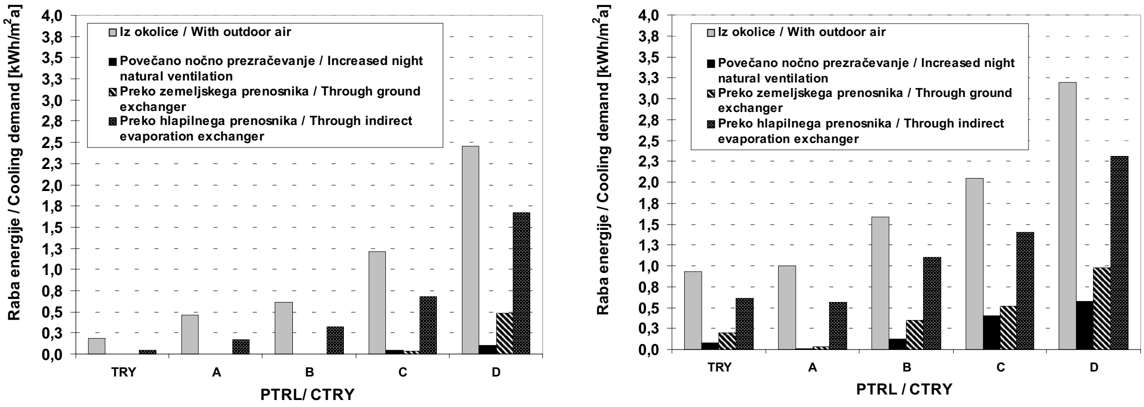
In the process of cooling buildings we do not take into account the latent heat of moistening or remoistening. Namely, the presented natural cooling techniques do not affect the absolute air humidity or deliberately avoid the condensation phenomena for health reasons. In addition, we discovered that the CTRY that we have formed for Scenario E does not enable reasonable corrections for the TRY and therefore we have omitted it. Firstly, we presented the analysis results for the two residential buildings. Figures 8, 9 and 10 show the results for heavyweight and lightweight built residential buildings.



a) b)

Sl. 8. *Število ur, ko je pri nenadzorovanem toplotnem odzivu stanovanjske stavbe občutena temperatura v stavbi nad 26 °C; a) za masivno in b) za lahko grajeno stavbo*

Fig. 8. *The number of hours when for an uncontrolled thermal response of the building the operating temperature is higher than 26°C a) for heavyweight and b) for lightweight built building*



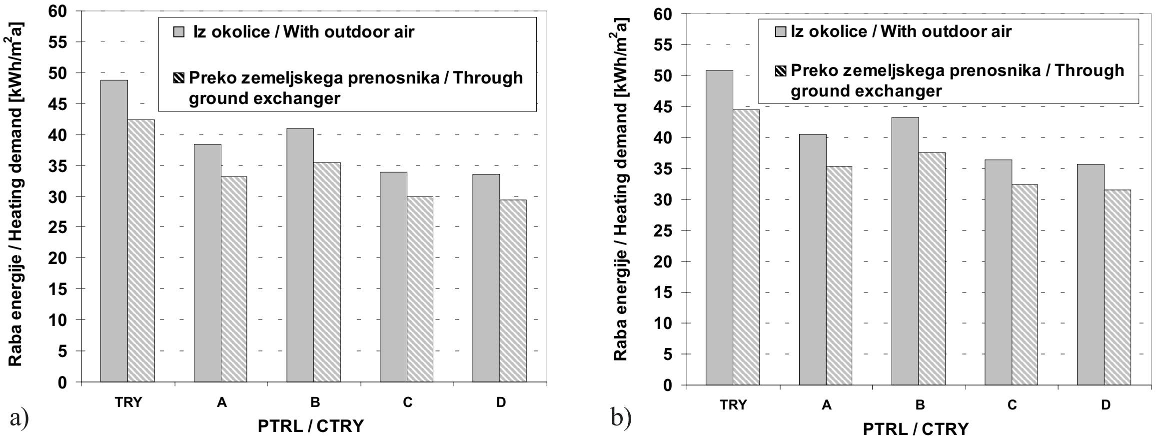
a) b)

Sl. 9. *Specifična raba koristne energije za hlajenje pri nadzorovanem toplotnem odzivu stanovanjske stavbe; a) za masivno in b) za lahko grajeno stavbo*

Fig. 9. *Specific use of energy demand for cooling, calculated per m$^2$ of living area for the controlled thermal response for a residential building a) for a heavyweight and b) for a lightweight built building*

Poslovna stavba je prezračevana z mehanskim prezračevanjem in hlajena. Velike potrebne količine zraka za prezračevanje in pogosto omejena velikost zemljišča, kjer bi lahko namestili zemeljski prenosnik toplote, onemogočata uporabo te tehnike naravnega hlajenja. Zato jo v nadaljevanju ne obravnavamo. Ker povečanje nočnega prezračevanja vpliva na velikost celotnega prezračevalnega sistema, smo v raziskavah upoštevali poleg 5-kratne urne izmenjave zraka ponoči, tudi nižjo 2,5-kratno urno izmenjavo, ki jo lahko zagotovimo z manjšim prezračevalnim sistemom ob manjši porabi energije za delovanje sistema. Rezultate raziskav prikazuje slika 11.

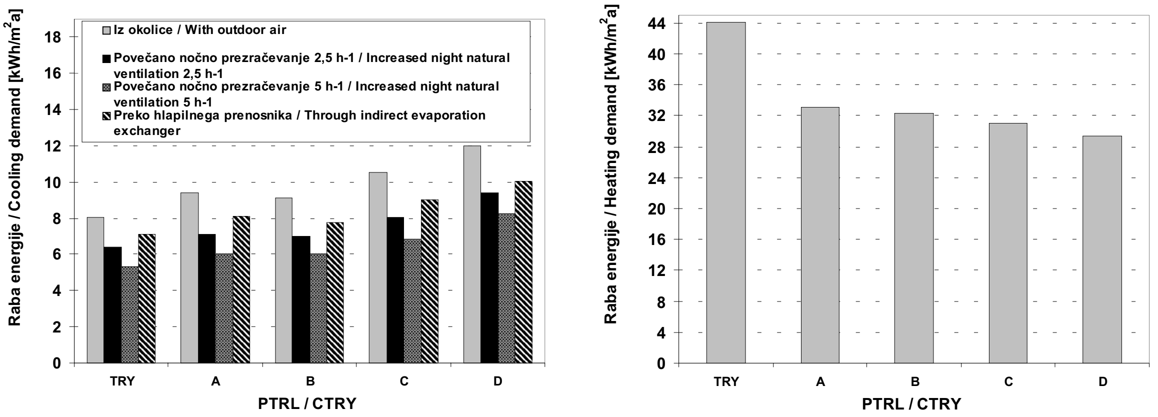
The office building is aired and cooled with a mechanical ventilation system. The large quantity of air needed for ventilation and the often limited size of the building site where the ground heat exchanger system could be placed make the use of this natural cooling technique impossible. For this reason we do not deal with it in the remainder of this paper. Since the increase of night-time ventilation affects the size of the entire ventilation system we have not only included the 5 exchanges per hour during the night, but also the 2.5 exchanges per hour that can be ensured with a smaller airing system with lower energy use. The results of the research are shown in Figure 11.



a) b)

Sl. 10. *Specifična raba koristne energije za ogrevanje pri nadzorovanem toplotnem odzivu stanovanjske stavbe; a) za masivno in b) za lahko grajeno stavbo*

Fig. 10. *Specific energy demand for heating, calculated per m$^2$ of living area for the controlled thermal response for a residential building a) for a heavyweight and b) for a lightweight built building*



a) b)

Sl. 11. *Specifična koristna energija za hlajenje a) in ogrevanje b) poslovne stavbe*

Fig. 11. *Specific energy demand for a) cooling and b) heating, calculated per m$^2$ of living area for the controlled thermal response for a business building*

## 5 SKLEP

Iz pregleda dosedanjih objavljenih raziskav ([4] do [10]), ki povezujejo scenarije podnebnih sprememb in toplotni odziv stavb, lahko povzamemo, da avtorji napovedujejo zgolj spremembo v rabi energije, ne pa tudi vpliva podnebnih sprememb na toplotno ugodje. Tudi ne zasledimo raziskav o vplivih na učinkovitost tehnik naravnega hlajenja. Poleg tega podobne raziskave za podnebne značilnosti v Sloveniji še niso bile izdelane.

Pričakovano se bo raba koristne energije za ogrevanje stavb zmanjšala. Glede na napovedane podnebne scenarije za celinsko področje Slovenije za 1,5 % do 31,4% pri vseh stavbah, ki smo jih

## 5 CONCLUSION

From a review of the published studies ([4] to [10]) that link the climate-change scenarios we can conclude that the authors predict merely a change in energy use and not the influence that climate changes will have on thermal comfort. We also failed to find any research that looked at the influence on the effectiveness of natural cooling techniques. Moreover, similar researches on climate characteristics in Slovenia have so far not yet been elaborated.

As expected the use of final energy for heating buildings will reduce. According to the predicted climate scenarios for the Slovenian continental part it will be reduced by between 1.5%

analizirali, oziroma med 0,5 in 15,3 kWh/m$^2$a. Značilna večja raba energije za ogrevanje lahko grajenih stavb (v povprečju +6,1 % ali + 2,1 kWh/m$^2$a) bo ostala sorazmerna v primerjavi z masivno grajenimi stavbami. Verjetno pa je v tem primeru bolj kot navajanje specifične rabe energije za ogrevanje izbranih stavb, pomembno dejstvo, da pri oblikovanju zahtev o toplotni zaščiti stavb državnih ciljev ne smemo zastaviti tako nezahtevno, da bi jih namesto novih tehnologij "izpolnile" pričakovane podnebne spremembe. V poslovnih stavbah bo vpliv različnih napovedanih scenarijev podnebnih sprememb manj izrazit - specifična raba toplote za ogrevanje se bo zmanjšala za 10,9 do 14,8 kWh/m$^2$a, torej okvirno med eno četrtino in eno tretjino. To pripisujemo večjim notranjim virom toplote, večjim steklenim površinam in časovnemu vzorcu zasedenosti, ki so značilni za poslovne stavbe.

Bistveno bolj bodo napovedane podnebne spremembe vplivale na toplotno ugodje v stavbah poleti. Tudi v masivno grajenih stanovanjskih stavbah, ki so naravno prezračevane in v katerih je dandanes ustrezno toplotno ugodje, bodo primerne temperature poleti presežene za 20% do 33% časa, če se bodo uresničili najbolj neugodni scenariji (C in D). Lahko grajene stavbe so na videz manj občutljive za napovedane podnebne spremembe, kar pa je posledica večjih dnevnih sprememb temperatur. Pregrevanje v teh stavbah bo sicer časovno krajše, toda bolj izrazito. Učinkovitost zemeljskega prenosnika toplote, vgrajenega v prezračevalni sistem masivno in lahko grajenih stanovanjskih stavb se bo zmanjšala le pri skrajni spremembi podnebja, ki ga napoveduje scenarij D. V vseh obravnavanih primerih se hlapilno hlajenje kot tehnika dejavnega naravnega hlajenja izkaže kot zelo občutljivo za podnebne spremembe. Nasprotno pa velja, da je za vse obravnavane primere povečano nočno prezračevanje edina tehnika, s katero preprečimo pregrevanje stavb.

Za zagotavljanje primernega toplotnega ugodja bo potrebno stavbe hladiti s hladilnimi sistemi. Specifična raba na ravni koristne energije se bo v stanovanjskih stavbah povečala med 0,3 in 1,63 kWh/m$^2$a, oziroma 2 do 40 krat glede na sedanje stanje in različne upoštevane scenarije podnebnih sprememb. Relativne spremembe v rabi energije za hlajenje poslovnih stavb bodo manjše, toda absolutno večje, saj se bo raba energije za hlajenje v primeru izpolnitve najbolj neugodnega podnebnega scenarija povečala za 4 kWh/m$^2$a.

and 31.4% in all analysed buildings, which is between 0.5 and 15.3 kWh/m$^2$a. The characteristic larger amount of energy for heating lightweight constructed buildings (on average +6.1% or + 2.1 kWh/m$^2$a) will remain proportional in comparison to the heavyweight constructed buildings. Probably more important than stating the specific energy use for heating the chosen buildings is the fact that we must not set our national goals in forming the demands on the building's heat insulation so non-ambitiously, that the expected climate changes would realise them instead of the new technologies. The influence of the various predicted climate-change scenarios will be less distinctive in office buildings - the specific energy demand for heating will be reduced by between 10.9 and 14.8 kWh/m$^2$a, i.e., between 25% and 33%. This will take place due to the larger inner heat sources, larger glass surfaces and time of occupancy typical for office buildings.

The climate changes will have a greater influence on the thermal comfort in buildings during the summer. Even in heavyweight built residential buildings that are naturally aired and where today there is a suitable thermal comfort, the suitable temperatures during the summer will be exceeded for 20% to 33% of the time, if the most unfavourable scenarios come true (C and D). Lightweight built buildings are apparently less sensitive to the predicted climate changes, which is a consequence of the larger daytime temperature amplitudes. Overheating in these buildings will be shorter as regards time, but it will be more intensive. The effectiveness of a ground heat exchanger included in the ventilation system in heavyweight and lightweight built residential buildings will be reduced only in the extreme climate change predicted by scenario D. In all the discussed examples the evaporation cooling as an active natural cooling technique proves to be very sensitive to climate changes. In contrast, it is true that increased night ventilation is the only effective technique with which we can prevent overheating.

To ensure suitable thermal comfort it will be necessary to cool the buildings with cooling systems. The specific demand of fine energy will increase in residential buildings between 0.3 and 1.63 kWh/m$^2$a or 2-to-40 fold, according to the present conditions and the various climate-change scenarios. Relative changes in energy use for cooling office buildings will be smaller, but they will be bigger in absolute terms, since the energy use for cooling in the event of the most unfavourable climate scenario will increase by 4 kWh/m$^2$a. Amongst the natural cooling methods

Med tehnikami naravnega hlajenja, ki bi dopolnjevale hlajenje s hladilnimi sistemi, je najučinkovitejše povečano naravno nočno prezračevanje. Torej je treba pri zasnovi stavb, ki so mehansko hlajene, uporabiti tudi to tehniko. Potencial varčevanja energije z uporabo hlapilnega hlajenja, ovrednoten z zmanjšano specifično rabo energije, ki znaša v tem trenutku približno 14 %, se bo ohranil tudi pri vseh napovedanih scenarijih podnebnih sprememb.

Kakor smo že omenili, smo v naši raziskavi uporabili PTRL, izdelana z zgodovinskim modelom. Primerjava med pričakovanimi spremembami vplivnih meteoroloških spremenljivk, ki jih navaja preglednica 1 in značilnostmi PTRL, ki jih prikazuje slika 3, kažejo, da za vse načrtovane podnebne scenarije ni mogoče oblikovati povsem ustreznih PTRL. To dejstvo pripišemo dolgemu tesnemu nizu (mesec), ki smo ga uporabili v našem primeru. Tako bomo v prihodnje raziskali tudi desetdnevni in tedenski niz. Tako bi lahko raziskali tudi nekatere izjemne podnebne scenarije, kljub kratkemu časovnemu obdobju (12 let) popolnih baz meteoroloških podatkov, ki je na voljo na Agenciji R Slovenije za okolje. Ob tem bi bilo smiselno preučiti tudi primernost uteži W za posamezno meteorološko spremenljivko.

that would complement the cooling with cooling systems the most efficient is increased natural night-time ventilation. Therefore, it is necessary to use this technique in the future projecting of buildings that are mechanically cooled. The energy-saving potential with the use of evaporation cooling, evaluated with a reduced specific use of energy, which currently amounts to approximately 14%, will also be preserved in all the predicted climate-change scenarios.

As mentioned, we have used the CTRY in our research, elaborated with a historical model. The comparison between the expected changes of influential meteorological variables stated in Table 1 and the CTRY characteristics shown in Figure 3 indicate that it is not possible to form a totally suitable CTRY for all the predicted climate scenarios. We attribute this fact to the long series (one month) and the tight period of the meteorological hour database (only 12 years). In the future we will also research the decade and week series. Therefore, we could also research some extreme climate scenarios, despite the short time period (12 years) of the complete meteorological database available at the Agency for the Environment of the Republic of Slovenia. At the same time it would also be sensible to examine the adequacy of the weight W for individual meteorological variables.

## 6 LITERATURA
## 6 REFERENCES

[1] J.A.Clarke (2001) Domain integration in building simulation, *Energy and Buildings*, Volume 33, Issue 4, 303-309

[2] S. Citherlet (2001) Integration in building physics simulation, *Energy and Buildings*, Volumne 33, Issue 5, 417-518

[3] IPCC (2001) An assessment of the intergovernmental panel on climate change, *Synthesis Report*, Wembley, United Kingdom, 24-29 September, 2001

[4] T. Frank (2005) Climate change impacts on building heating and cooling energy demand in Switzerland, *Energy and Buildings*, Volumne 37, Issue 11, 1175-1185

[5] M.Christenson (2005) Climate warming impact on degree-days and building energy demand in Switzerland, *Energy Conversion and Management*, Volume 47, Issue 6, 671-686

[6] M.R. Gaterell (2005) The impact of energy externalities on the cost effectiveness of energy efficiency measures applied to dwellings, *Energy and Buildings*, Volume 37, Issue 10, 1017-1027

[7] C. Cartalis (2001) Modifications in energy demand in urban areas as a result of climate changes: an assessment for the southeast Mediterranean region, *Energy Conversion and Management*, Volume 42, Issue 14, 1647-1656

[8] K. Kaygusuz (2003) Energy policy and climate change in Turkey, *Energy Conversion and Management*, Volume 44, Issue 10, 1671-1688

[9] R. Matthias (2005) Regional energy demand and adaptations to climate change: Methodology and application to the state of Maryland, USA, *Energy Policy*, In Press, Corrected Proof, Available online 23 June 2005

[10] M. Camillieri (2001) Impacts of climate change on building performance in New Zealand, *Building & Information* 29, Volume 6, 440-450

[11] M. Santamouris, et al. (2006) Environmental design of urban buildings: An integrated approach, *James & James*, London

[12] B. Vidrih (2003) Računalniško modeliranje in eksperimentalna potrditev toplotnega odziva stavb, Diplomska naloga univerzitetnega študija, *Univerza v Ljubljani, Fakulteta za strojništvo*, Ljubljana

[13] B. Vidrih (2004) Vpliv klimatskih sprememb na toplotno ugodje v prostoru, Podiplomski seminar, *Univerza v Ljubljani, Fakulteta za strojništvo*, Ljubljana

[14] B. Černe (2003) Vpliv klimatskih sprememb na rabo energije v naseljih, Podiplomski seminar, *Univerza v Ljubljani, Fakulteta za strojništvo*, Ljubljana

[15] A. Sušnik - urednica (2003) Ranljivost slovenskega kmetijstva in gozdarstva na podnebno spremenljivost in ocena predvidenega vpliva, Poročilo za vlado RS, *Agencija RS za okolje*, Ljubljana

[16] K. Bergant (2003) Projekcije simulacij globalne klime na lokalni nivo in njihova uporaba v agrometeorologijo, Doktorska disertacija, *Univerza v Ljubljani, Biotehniška fakulteta*, Ljubljana

[17] L. Kajfež-Bogataj (2005) Podnebne spremembe in ranljivost kmetijstva, *Acta agriculturae Slovenica*, 85, 25-40

[18] C. DE Boor (2002) A practical guide to plines, Second edition, *Springer*, New York.

[19] L. Schumaker (1981) Spline functions, Basic theory, *John Wiley and Sons*, New York.

[20] L. Adelard (1999) Elaboration of a new tool for weather data sequences generation, *Proceedings of IBPSA Conference*, Kyoto, Japan

[21] A. Aguiar (1999) Assesing the value of typical meteorological years built from observed and from synthetic data for building thermal simulation, *Proceedings of IBPSA Conference*, Kyoto, Japan

[22] G. Levermore (2003) Climate change test reference years for buildings and urban environment. *Proceedings of ICUC Conference*, Lodz, Poland.

[23] M.Dolinar (2005) Predicted changes in energy demands for heating and cooling due to climate change

[24] C. Schittich (2003) Solar architecture (Strategies, Visions, Concepts), *Birkhausen - Publishing for Architecture*, Basel, 2003

[25] TRNSYS 15 (2000) A transient system simulation program, Reference manual, Solar energy laboratory, *Univesity of Wisconsion*, Madison.

[26] M. Umberger, (2004) Prve pasivne stavbe v Sloveniji, *Zgradbe, energija in okolje 2004*, Terme Čatež, Slovenija, 9-14

[27] V. Geros (2005) On the cooling potential of night ventilation techniques in the urban environment, *Energy and Buildings*, Volume 37, Issue 3, 243-257

[28] G. Mihalakakou (1995) Parametric prediction of the buried pipes cooling potential for passive cooling applications, *Solar Energy*, Volume 55, Issue 3, 163-173

[29] J. Fechner (2002) Altbaumodernisierung, Der praktische Leitfaden, *Springer-Verlag*, Dunaj.

[30] C. Arkar, B. Cerkvenik, S. Medved, M. Dimnik, S. Grum, A. Poredoš, L. Tavčar (2005) Raziskava učinkovitosti lamelnih rekuperatorjev toplote VING. *Fakulteta za strojništvo, Laboratorij za ogrevalno, sanitarno in solarno tehniko*, Ljubljana.

Naslovi avtorjev: Boris Vidrih
Termo d.d.
Trata 32
4220 Škofja Loka
boris.vidrih@fs.uni-lj.si

Mojca Dolinar
Agencija RS za okolje
Vojkova 1b
1000 Ljubljana

prof.dr. Sašo Medved
Univerza v Ljubljani
Fakulteta za strojništvo
Aškerčeva 6
1000 Ljubljana
saso.medved@fs.uni-lj.si

Authors' Addresses: Boris Vidrih
Termo Ltd.
Trata 32
4220 Škofja Loka, Slovenia
boris.vidrih@fs.uni-lj.si

Mojca Dolinar
The Environmental Agency of RS
Vojkova 1b
1000 Ljubljana, Slovenia

Prof.Dr. Sašo Medved
University of Ljubljana
Faculty of Mechanical Engineering
Aškerčeva 6
1000 Ljubljana, Slovenia
saso.medved@fs.uni-lj.si

Prejeto:
Received: 23.1.2006

Sprejeto:
Accepted: 22.6.2006

Odprto za diskusijo: 1 leto
Open for discussion: 1 year