AIR HOUSE – A SOLAR DECATHLON COMPETITION PROTOTYPE – IN-DEPTH ENERGY ANALYSES AS A TOOL FOR A HIGH-QUALITY DESIGN

Kateřina SOJKOVÁ
Czech Technical University in Prague, Fac. of Civil Engineering, Czech Rep., katerina.sojkova@fsv.cvut.cz

Martin VOLF
Czech Technical University in Prague, University Centre for Energy Efficient Buildings, Czech Republic, martin.volf@uceeb.cz

Dalibor HLAVÁČEK
Czech Technical University in Prague, Faculty of Architecture, Czech Republic, dhlavacek@fa.cvut.cz

Summary

U.S. Department of Energy Solar Decathlon is the most prestigious university competition in the field of sustainable solar architecture. 20 selected collegiate teams from all over the world are challenged to design, build and operate energy self-sufficient solar-powered houses. Buildings are judged in 10 competition disciplines. The winner of the competition is the team that best blends affordability, consumer appeal, and design excellence with optimal energy production and maximum efficiency.

The CTU team enters the competition with the "AIR House", whose goal is to have a minimum environmental impact throughout the whole life-cycle of the building and to have positive influence on the life quality of its inhabitants. Since it is rather difficult to estimate building thermal performance of well insulated building where gains and losses are similar large numbers, and even more difficult to estimate it for two different climates (LA for the competition and Czech for the succeeding building operation), variant energy analyses were performed to help with the design and decision making process. This paper provides these energy analyses and their results with their impact to the AIR House design.

Keywords: energy performance, energy need, thermal comfort, energy efficiency, electricity consumption, photovoltaic design, Solar Decathlon

1 Introduction

The AIR House concept combines a minimum interior living area with a generous outside area. The economy-sized floor plan is based on the tradition of minimal housing, where an ingenious architectural design saves space and therefore saves purchase and operating costs. The goal is to place a maximum of functional units outside the air-conditioned area and thus minimize the amount of energy needed to maintain interior comfort. The direct link between the interior and exterior areas, its simple shape and wheelchair accessibility, allow for social activities and incorporation of the household inhabitants into the local social life. It is designed as a 1 to 2 person household of pre-retirement and retirement age (ages 55+).

AIR House is designed as a zero-energy building. A grid-connected photovoltaic power system and solar collectors generate all the energy needed for the operating of the house. The “house within a house concept” uses the protected area around the climate-controlled space as a thermal buffer zone, protects the house from temperature extremes and ensures privacy of the inhabitants.

AIR House can be adapted to various climates – in the Czech Republic the design maximizes the solar gains during winter, while in California, by changing the orientation of the house, it minimizes overheating of the interior space, see Fig. 1.

The house is distinguished by low material, water and energy consumption. Energy intensity of used materials during the production and transport, and their recyclability in the end of the building’s lifecycle are important aspects of the design. Wood and wood based materials are used extensively in the load-bearing structure, thermal insulation and finishings.

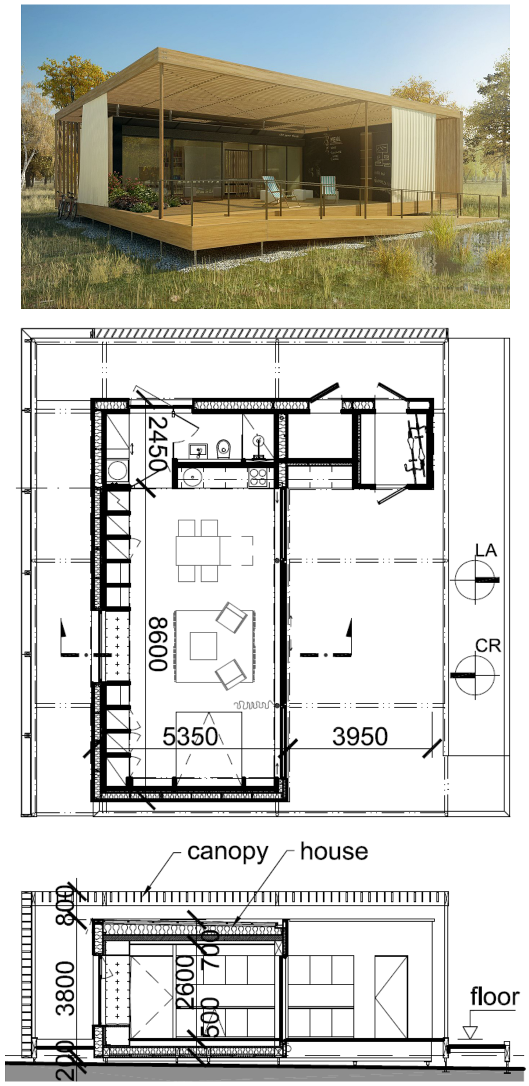


Fig. 1 AIR House – visual representation, floor plan, cross section

2 Energy analyses

The goal was to design a building with a high thermal comfort and low energy consumption during a whole year. Moreover, two different climates had to be taken into account – Californian (LA) and Czech (Prague). These climates differ significantly in annual temperature pattern, solar radiation and relative humidity, see Fig. 2. Therefore, design variants were evaluated for both annual Czech climate data ([1], [2]) and for LA climate data [3] during the contest week period. Since it is rather difficult to estimate building thermal performance of well insulated building where gains and losses are similar large numbers, and even more difficult to estimate it for two different climates, variant energy analyses were performed to help with the design and decision making process. In general, similar analyses are useful to be performed for each building for which thermal performance and a quality design are of interest.

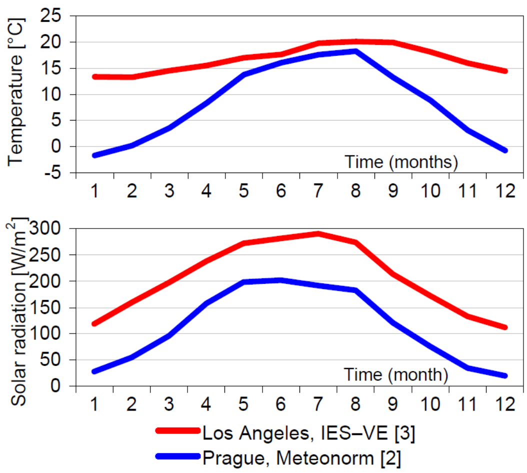


Fig. 2 Comparison of LA and Prague climate – external temperature (upper) and solar radiation at horizontal plane (bottom)

2.1 Calculation method and computational tool

2.1.1 Calculation method

Simplified dynamic simulation method with hourly time step, based on one-node model (effective capacitance model) was used for energy performance analyses, see Fig. 3 and equation (1). The equation was solved using numerical explicit method.

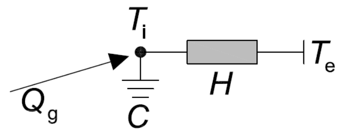


Fig. 3 *The RC scheme of one-node model used for the analyses*

$$C_{eff} \frac{dT_i}{d\tau} = Q_g - H(T_i - T_e) \tag{1}$$

where: C_{eff} is effective heat capacity [J/K],
H total heat transfer coefficient ($H = H_T + H_V$) [W/K], see [8],
Q_g total heat gains ($Q_g = Q_{int} + Q_{sol} + Q_h$) [W],
T_i^{FF} internal temperature [K],
T_e external temperature [K],
τ time [s].

The output of this method is so called free-floating temperature, that means a temperature pattern with no heating or cooling considered. This temperature provides an information how the building itself behaves with no technical systems. Thus, it can be used for defining strategies of what is the optimal pattern of the temperature for the best thermal performance, e.g. using a so-called *comfort zone* [7]. Energy need for heating or cooling can be obtained on the basis of this temperature pattern:

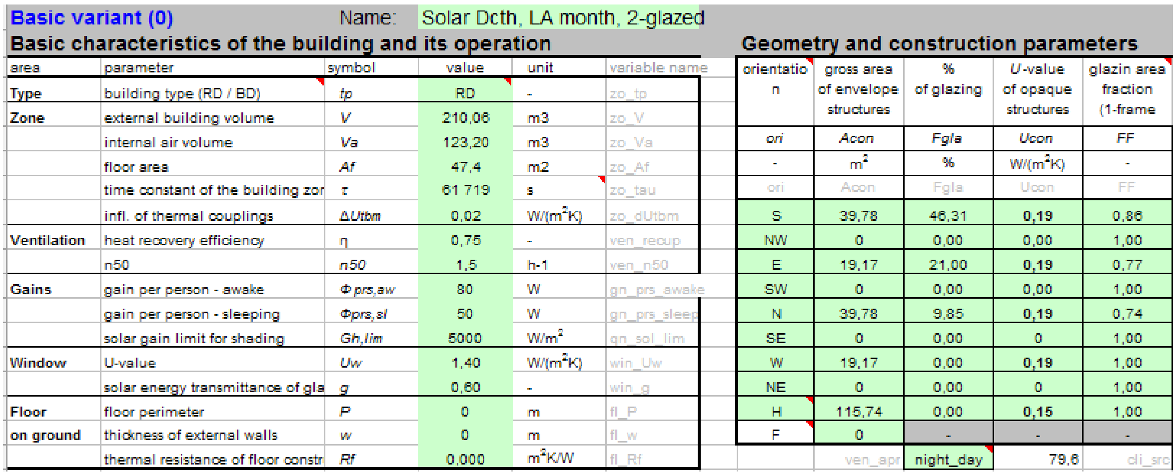
$$\Phi_p = H\left(T_{i,set} - T_i^{FF}\right), \qquad Q_p = \int_{\tau_1}^{\tau_2} \Phi_p \, d\tau \tag{2}$$

where: Φ_p is the power supplied by the heating, respectively cooling system [W].
$T_{i,set}$ set-point temperature for heating/cooling. [°C],
T_i^{FF} internal free-floating temperature [°C],
Q_p energy need for heating/cooling [W],
τ_1, τ_2 time [s].

2.1.2 Calculation tool

The calculation tool developed by author [4] was used to perform the analyses. The number of input data required in this tool is reduced, with respect to the simplified calculation method, nevertheless, sufficient accuracy of the method is maintained [6]. On the other hand, the tool allows to enter hourly occupancy and operational patterns which allows to follow a dynamic response of the building to its operation. Furthermore, the tool enables to enter more variants of a building just by entering the varying inputs, while the rest of the input data is taken from the *mother* or source variant. Thanks to this, the tool provides a way how to carry out dynamic energy analyses even in the initial stage of the project when no detailed input data are available.

Since shading is one of crucial factors influencing the energy balance, it should be modelled as exact as possible. As the AIR House canopy is rather ragged and thus difficult to estimate its shading effect, the building shape with the canopy in detail was imported to Google SketchUp and hourly correction shading factors was then calculated using [5].



Basic variant (0) Name: Solar Dcth, LA month, 2-glazed

Basic characteristics of the building and its operation

area	parameter	symbol	value	unit	variable name
Type	building type (RD / BD)	tp	RD	-	zo_tp
Zone	external building volume	V	210,06	m3	zo_V
	internal air volume	Va	123,20	m3	zo_Va
	floor area	Af	47,4	m2	zo_Af
	time constant of the building zor	τ	61 719	s	zo_tau
	infl. of thermal couplings	ΔUtbm	0,02	W/(m²K)	zo_dUtbm
Ventilation	heat recovery efficiency	η	0,75	-	ven_recup
	n50	n50	1,5	h-1	ven_n50
Gains	gain per person - awake	Φ prs,aw	80	W	gn_prs_awake
	gain per person - sleeping	Φprs,sl	50	W	gn_prs_sleep
	solar gain limit for shading	Gh,lim	5000	W/m²	gn_sol_lim
Window	U-value	Uw	1,40	W/(m²K)	win_Uw
	solar energy transmittance of gla	g	0,60	-	win_g
Floor	floor perimeter	P	0	m	fl_P
on ground	thickness of external walls	w	0	m	fl_w
	thermal resistance of floor constr	Rf	0,000	m²K/W	fl_Rf

Geometry and construction parameters

orientation	gross area of envelope structures	% of glazing	U-value of opaque structures	glazin area fraction (1-frame
ori	Acon	Fgla	Ucon	FF
-	m²	%	W/(m²K)	-
ori	Acon	Fgla	Ucon	FF
S	39,78	46,31	0,19	0,86
NW	0	0,00	0,00	1,00
E	19,17	21,00	0,19	0,77
SW	0	0,00	0,00	1,00
N	39,78	9,85	0,19	0,74
SE	0	0,00	0	1,00
W	19,17	0,00	0,19	1,00
NE	0	0,00	0	1,00
H	115,74	0,00	0,15	1,00
F	0	-	-	-
	ven_apr	night_day	79,6	cli_src

Fig. 4 *Screenshot of the input-data sheet of the computational tool for one variant. Occupancy and operational patters, climate data and shading correction factors are entered separately.*

2.2 Input data and variants of calculation

The influence of several main parameters which can significantly affect the energy balance was analyzed. It was: U-value, parameters of window glazing, occupancy and building operation, intensity of ventilation and heat storage capacity. Those parameters were varied within the analyses, other parameters remain the same for all variants, see Tab. 1 and further chapters. For combinations of the variants which were taken into account within analyses see Tab. 2 and Tab. 3.

Internal gains patterns were composed differently for LA contest week and for Prague year. Operation throughout the contest week was more or less defined within the competition schedule [11]. For Prague, occupancy and operation pattern for two pensioners was created. See Fig. 5. A high-performance appliances and lighting were assumed and their heat production was considered to be equal to electricity input. As for people, 80 W was assumed per awake person and 50 W per sleeping one.

Tab. 1 *Parameters of the building*

<table>
<tr><th>Parameters common for all variants</th><th colspan="6">Values</th></tr>
<tr><td>External building volume [m³]</td><td colspan="6">210</td></tr>
<tr><td>Internal air volume (headed space) [m³]</td><td colspan="6">123</td></tr>
<tr><td>Building thermal envelope area [m²]</td><td colspan="6">234</td></tr>
<tr><td>Floor area (heated) [m²]</td><td colspan="6">14,4</td></tr>
<tr><td>Heat recovery efficiency [-]</td><td colspan="6">0.75</td></tr>
<tr><td>airtightness n_{50} [h⁻¹]</td><td colspan="6">1.5</td></tr>
<tr><th>Variable parameters</th><th colspan="6">Values for variants</th></tr>
<tr><td>U-value – walls / roofs&floors [W/(m²K)]</td><td colspan="2">poorly insulated
0,40 / 0,35</td><td colspan="2">basic
0,19 / 0,15</td><td colspan="2">well insulated
0,12 / 0,11</td></tr>
<tr><td>Surface heat capacity [kJ/m²K] /
Time constant (approx.) [h]</td><td colspan="3">light-weight*
42 / 25</td><td colspan="3">heavy-weight*
180 / 80</td></tr>
<tr><td>Windows U-value – frame/glazing/whole window (aver.) [W/(m²K)]</td><td colspan="3">2-glazing
1,6 / 1,0 / 1,4</td><td colspan="3">3-glazing
1,6 / 0,7 / 0,95</td></tr>
<tr><td>solar energy transmittance of glazing g [-]</td><td colspan="3">2-glazing
0,6</td><td colspan="3">3-glazing
0,5</td></tr>
</table>

* Time constant τ of approximately 25 h for a light-weight construction corresponds to surface heat capacity 42 kJ/m²K and τ 80 h for a heavy-weight variant corresponds to 180 kJ/m²K according to [9].

Tab. 2 *Combinations taken into account for energy analyses for the contest week*

Var.	Climate data	U-values	Glazing	Thermal mass	Ventilation
A0	LA	basic	2-glazed	light-weight	constant
A1			3-glazed		
A2			2-glazed		intelligent
A3			3-glazed		
A4	CR (180° different orientation then in LA)		2-glazed		constant
A5			3-glazed		
A6			2-glazed		intelligent
A7			3-glazed		
A8	LA	well insulated	3-glazed		
A9		poorly insulated	2-glazed		

Tab. 3 *Combinations taken into account for annual energy analyses*

Var.	Climate data	U-values	Glazing	Thermal mass	Ventilation
B0	CR	basic	2-glazed	light-weight	intelligent, with heat recovery
B1			3-glazed		
B2			2-glazed	heavy-weight	
B3			3-glazed		
B4		poorly insulated	2-glazed	light-weight	
B5		well insulated	3-glazed		
B6		poorly insulated	2-glazed	heavy-weight	
B7		well insulated	3-glazed		

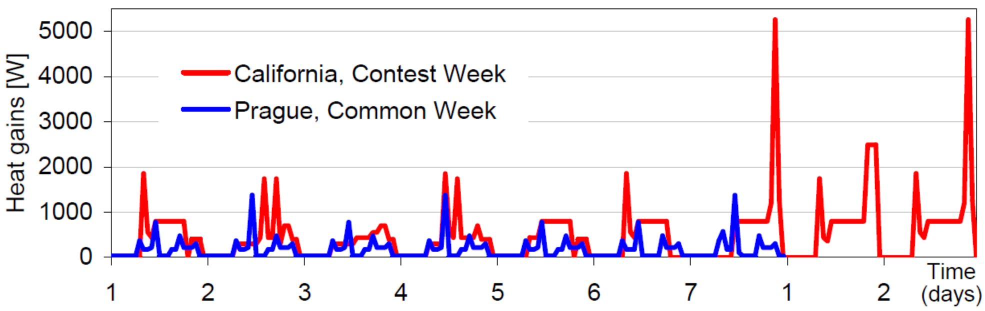


Fig. 5 *Comparison of hourly patterns of total internal heat gains (persons, appliances, lighting) throughout the contest week corresponding to given schedule and during a typical week provided occupancy by two pensioners*

2.2.1 Glazing

At the beginning a question whether double- or triple-glazed windows was of interest. Therefore, two variants of glazing were assumed within the simulation, with following parameters: 2-glazing $U_g = 1.0$ W/(m^{2}K), $g = 0.6$ and 3-glazing $U_g = 0.7$ W/(m^{2}K), $g = 0.5$. With respect to the frame parameters (aluminium frames, large sliding window), average U-value for the whole window was calculated as 1.4 W/(m^{2}K) for double-glazed and 0.95 W/(m^{2}K) for triple-glazed windows.

Almost no differences in temperature were followed neither throughout the contest week in LA nor within a whole year in CR (see Fig. 6). Rather small differences were observable in annual energy need for heating+cooling – 77,7 kWh/(m^{2}a) with 2-glazed and 62,8 kWh/(m^{2}a) with 3-glazed windows. With respect to this, other reason was taken into account for decision about which type of glazing to choose. Since 2-glazed windows are lighter and thus transport and construction would be easier and cheaper, 2-glazed windows were chosen for the final design.

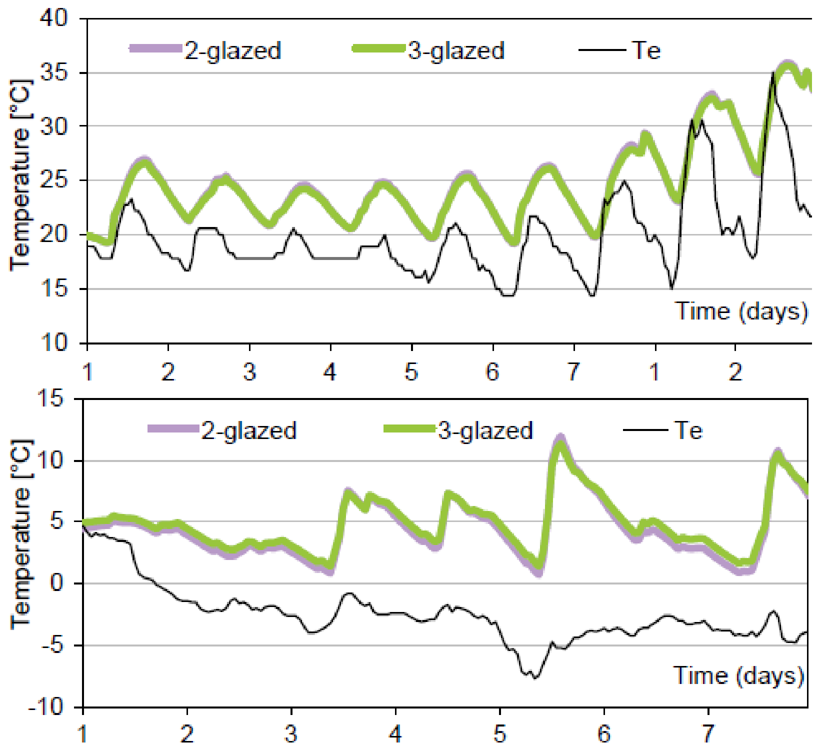


Fig. 6 *Internal free-floating temperature differences on the basis of different glazing; upper – LA, Contest week (October) [3]; bottom – CR, winter week (January 1–7, 2010 [1])*

2.2.2 Ventilation

What was important from the point of view of the contest week was ventilation. How much can controlled ventilation help to keep internal environment within given limits was of interest, so that energy need for cooling is minimized and high thermal comfort ensured. Therefore, dynamic ventilation schedule which reacts on a relation between internal, ambient and set-point temperature was compared to constant air change rate 0.5 h^{-1}. As can be seen in Fig. 7, ventilation regulation can decrease internal temperature of 3 to 4 °C. Nevertheless, to keep internal temperature within required limits of 21,7 to 24,4 °C [11], some additional cooling system will be necessary. As far as Prague operation is concerned, wider range of acceptable internal temperatures can be anticipated and thus cooling is not supposed to be necessary. The results show that intelligent ventilation can serve as an efficient way of passive cooling in case of this building.

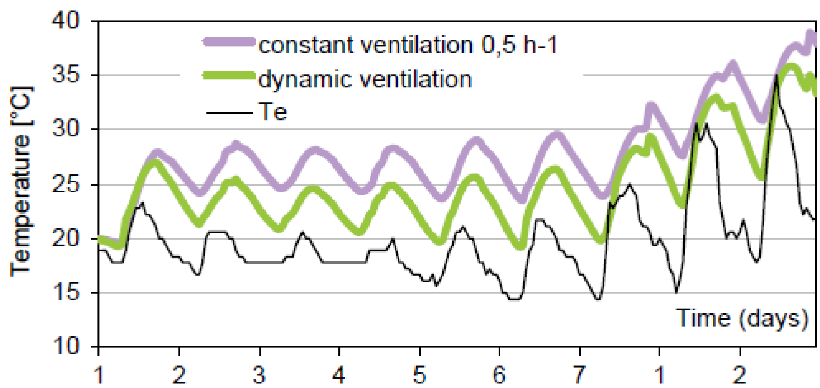


Fig. 7 *Internal free-floating temperature differences on the basis of different ventilation schedule*

2.2.3 Insulation level

Optimal insulation level was of interest. Therefore, three variants of U-values were considered, see Tab. 1. Although variant "poorly insulated" does not meet Czech standard requirements defined in ČSN 730540-2 [10], such high U-values were taken into account on purpose since they could be sufficient for the warmer Californian climate.

Differences in internal temperature for the variants were more considerable during cold days with no sun than in summer and sunny days (Fig. 8). This is also confirmed by high variances in energy need for heating and almost no variances in cooling need, which were for Prague mean climate data [2] as follows:

- Energy need for heating:
  - poorly insulated = 154,3 kW/(m^{2}a).
  - standard = 77.5 kW/(m^{2}a),
  - well insulated = 45.6 kW/(m^{2}a),
- Energy need for cooling:
  - poorly insulated = 0,2 kW/(m^{2}a).
  - standard = 0.2 kW/(m^{2}a),
  - well insulated = 0.1 kW/(m^{2}a).

It is therefore obvious that the higher insulation level the better. It seems that there is no risk of overheating connected with well insulated envelope in this case.

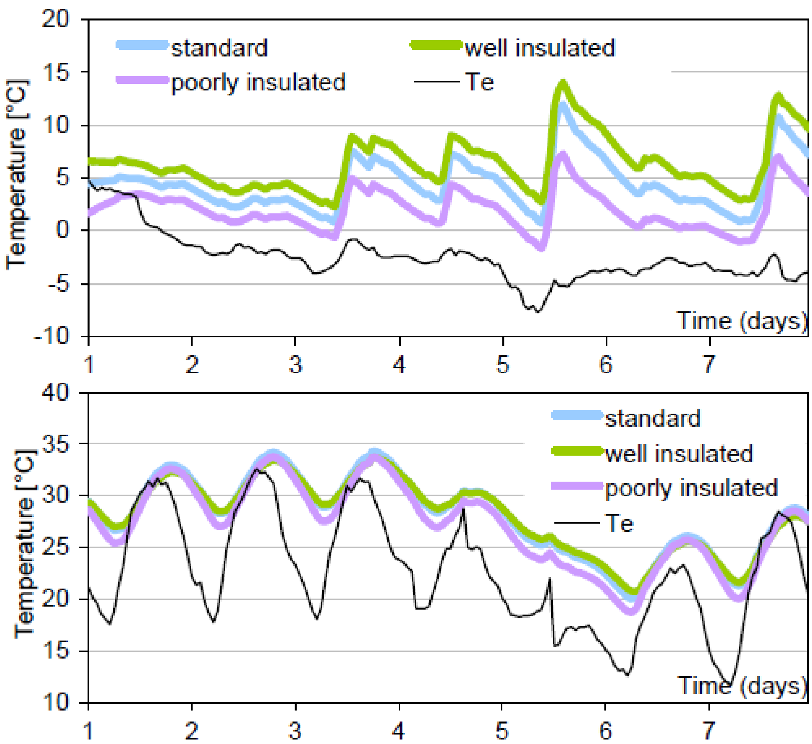


Fig. 8 *Internal free-floating temperature differences on the basis of different U-values, Prague climate data [1]; upper – winter week (January 1–7), bottom – summer week (July 2–8).*

2.2.4 Thermal mass

The influence and optimum of thermal mass was of interest. As for the contest week, fast cooling down effect is desired so that the internal temperature is lowered to required values within a half an hour after public exhibit hours. On one hand, as is known, higher thermal mass would help to keep the internal temperature lower for a longer time as gains would be storing in structures and thus the building would respond slower to increase of external temperatures or over-gains (solar or internal). On the other hand, with respect to unpredictable weather during the contest week and construction period before, light--weight-structure building would be easier to regulate from the point of view of internal temperature requirements. Moreover, light-weight structures are more advantageous as far as transport and construction are concerned. That is why a thermal mass influence was only analyzed for Czech climate and operation. For the competition building, light-weight structures was chosen.

Masonry walls and concrete ceilings are traditional in the Czech Republic. Therefore, effective heat capacity of the zone for such a variant was calculated as well, besides for the real light-weight timber structure variant. Heat capacity was calculated in accordance with ISO 13786 [9], for values see Tab. 1.

In summer period, heavy-weight building works better as it dampens internal temperature peaks and thus increases thermal comfort. The same effect can be observed in winter period, which, however, leads to gentle increase of energy need for heating. See Fig. 9. Energy need for heating/cooling for well insulated variant (Prague average climate data [2]) is as follows:

- light-weight: heating = 45.6 kW/(m^{2}a) / cooling = 0.1 kW/(m^{2}a),
- heavy-weight: heating = 52.3 kW/(m^{2}a) / cooling = 0.0 kW/(m^{2}a).

Heavy-weight-structure building seems to be better choice from the point of view of thermal performance and comfort. However, even for a light-weight timber construction the heat capacity can be increased by choice of materials used. Wood-fibre insulation, massive wooden walls or floor covering can improve heat capacity and thus help to prevent from fast temperature peaks. In the AIR House, these materials was thus used.

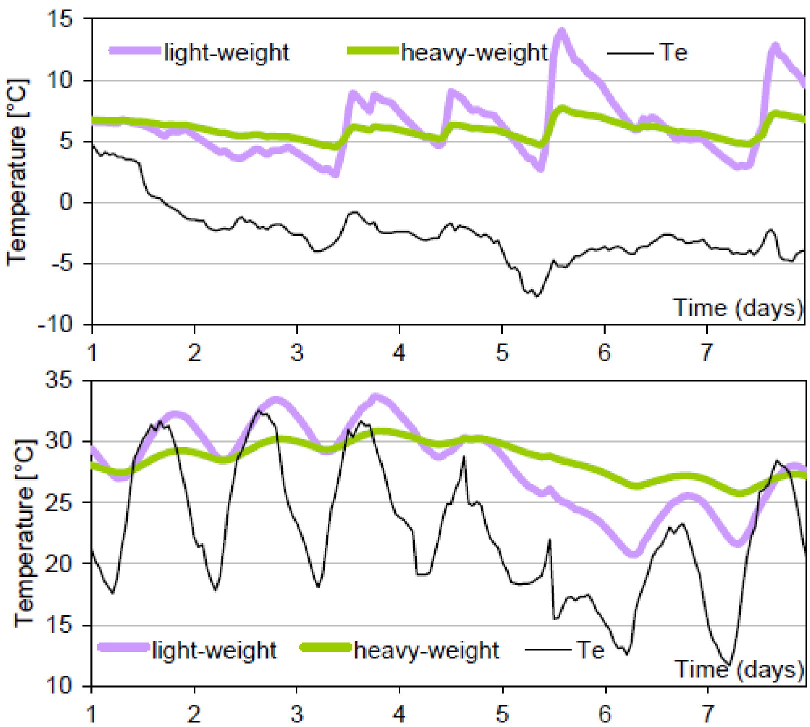


Fig. 9 *Internal free-floating temperature differences on the basis of different thermal mass, Prague climate data [1], upper – winter (January 1–7), bottom – summer (July 2–8). Time constant of the zone (approximate) [h] – light-weight/heavy-weight: 25/80 h.*

2.3 Photovoltaic design

Based on the energy analysis results, the photovoltaic system was designed. The climate data were used from the same sources. The simulation method with hourly time step was supplemented with a simple optimisation cycle, which calculated an optimal photovoltaic effective area inbound the input assumptions which are: 15% efficiency of panels, 80% efficiency of the system as a whole, horizontal orientation of the photovoltaic panels.

The main problem for the PV design lies in the completely different design conditions. Solar gains differ significantly in both climates which brings different consumption in both the value and the timing. Whereas in the CR, there is larger demand during the cold winter season when the solar gains are low, in LA conditions, the consumption is greater during the summer months thanks to high energy demand for cooling.

The electricity consumption was derived from the same operation patterns which were used for the energy analyses. For the LA situation, the simulation was performed for 9 days of competition. For the CR situation, year-round hourly calculation was performed. Also, the virtual variants A4–A7 (Tab. 2) were calculated to get the comparison of the building performance with the same operation pattern but in different climate conditions – once with the cooling demand in LA and once rather with demand for heating in Prague.

2.3.1 Results

The results of PV calculations were given for all the variants taken in account also for energy analysis.

Variant	Consumption [kWh]	Production [kWh]	Area of PV needed [m2]
A0	135,4	136,7	26,0
A1	132,3	134,1	25,5
A2	**133,1**	**134,1**	**25,5**
A3	129,6	134,1	25,5
A4	118,0	118,3	22,5
A5	115,2	115,7	22,0
A6	120,4	120,9	23,0
A7	118,9	120,9	23,0
A8	119,7	120,9	23,0
A9	135,9	136,7	26,0

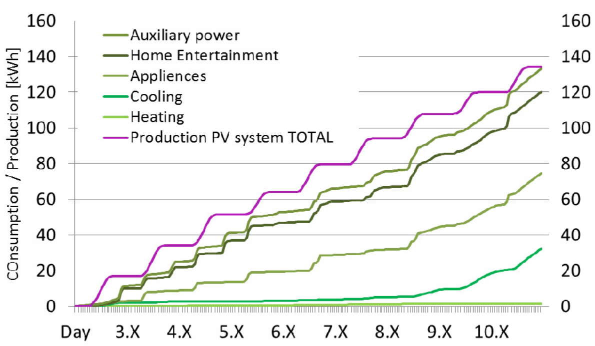


Fig. 10 *Results for LA climate variants (left) and the contest week consumption plot (right)*

Comparing results in Fig. 10 and Fig. 11, a small scatter of the minimum photovoltaic effective area can be noticed between variants under the LA climate conditions. Designing the house's PV system strictly for competition's demand would not give remarkable differences comparing the house built (and competing) in LA or in CZ. On the other hand, significant differences can be seen under the conditions of Czech climate.

Variant	Consumption [kWh/a]	Production [kWh/a]	Area of PV needed [m2]
B0	4959,1	4985,7	41,6
B1	4249,6	4254,3	35,5
B2	**4641,2**	**4646,1**	**38,8**
B3	4009,1	4033,8	33,7
B4	8598,8	8627,1	72,0
B5	3438,6	3464,7	28,9
B6	8307,6	8311,8	69,4
B7	3753,9	3758,8	31,4

Fig. 11 *Results for CR climate variants*

The AIR House PV system is optimized for the competition conditions. In the real building operation, the battery installation would be advantageous, especially for the Czech climate, where the consumption peak is coming in different time than the production peak. Unfortunately, the Solar Decathlon rules do not allow this kind of installation.

3 Conclusions

There is a number of requirements concerning building thermal performance and many of them are contrary to each other. The building design is thus based on compromises. As it can be difficult to estimate relations and the influence of particular parameters on energy performance, simplified dynamic energy simulations with hourly time step proved to be a useful tool which can help to improve the design even in an initial design stage. It provides answers to how the building behaves on the basis of various boundary conditions, structure parameters, operation assumption and the like. In case of the AIR House, results of energy analyses led to a high-quality building design from the point of view of energy performance. Several parameters were adapted on the basis of the energy simulations results. Analyses further proved that the AIR House will not cope with overheating in the Czech climate. Under the LA contest week conditions, certain amount of cooling energy will probably be necessary to keep comfortable indoor thermal environment, which is however strongly dependent on particular weather and operation during the competition. However, this cooling energy demand together with all appliances and equipment demand can be fully covered by electricity produced by PV panels installed on the roof.

Acknowledgement: *This work has been supported by the European Union, OP RDI project No. CZ.1.05/3.1.00/13.0283 – Intelligent Buildings, and by the Grant Agency of the Czech Technical University in Prague, grant No. SGS12/106/OHK1/2T/11.*

References

[1] Climate data Prague–Karlov 2010. ČHMÚ.

[2] Prague average climate data generated by Meteonorm, average temperature set for years 1996–2005, solar radiation for years 1981–2000. Meteonorm.

[3] Climate data for Los Angeles. IES–VE.

[4] SOJKOVÁ, K. Calculation tool for variant analyses of thermal performance of buildings, developed in MS Excel and VBA environment. Release January 2013.

[5] STANĚK, K. Hourly-correction-shading-factors calculation tool developed in Matlab, using environment and modules of Google SketchUp. Release February 2013.

[6] KOPECKÝ, P. Experimental validation of two simplified thermal zone models. In *Proceedings of NSB 2011 9th Nordic Symposium on Building Physics, Tampere, Finland, 29 May–2 June 2011*. Ed. J. VINHA, J, PIIRONEN, K. SALMINEN, Tampere: Tampere University of Technology, 2011. Vol. 1, p. 139–146. ISBN 978-952-15-2575-9.

[7] BURMEISTER, H.; KELLER, B. Climate surfaces: a quantitative building-specific representation of climates. *Energy and Buildings*, 1998, Vol. 28, Issue 2, p.167–177. ISSN 0378-7788.

[8] ČSN EN ISO 13790. *Energetická náročnost budov – Výpočet spotřeby energie na vytápění a chlazení. (Energy performance of buildings – Calculation of energy use for space heating and cooling)*. 2009.

[9] ISO 13786: 2007. *Thermal performance of building components – Dynamic thermal characteristics – Calculation methods*. 2007.

[10] ČSN 730540-2. *Tepelná ochrana budov – část 2: Požadavky*. 2011. ÚNMZ.

[11] U.S. Department of Energy Solar Decathlon 2013 Rules. U.S. Dept. of Energy. 2012.