ISSN 1392–3730 print / ISSN 1822–3605 online

JOURNAL OF CIVIL ENGINEERING AND MANAGEMENT
http:/www.jcem.vgtu.lt

2006, Vol XII, No 1, 69–75

Heat Demand for Buildings

HEAT DEMAND UNCERTAINTY EVALUATION OF TYPICAL MULTI-FLAT PANEL BUILDING

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Received 20 April 2005; accepted 05 Dec 2005

Abstract. Heat consumption of similar buildings under the same climatic conditions normally shows different values. This phenomenon has not been adequately explored yet. The purpose of the paper was to investigate the reasons and extent of heat demand variability by employing uncertainty analysis. This paper addresses uncertainties of building thermal behaviour by combining simplified heat demand evaluation methods with Monte Carlo sampling method. Output of this analysis provides an insight into the variability of the calculation result due to the variation and input parameters uncertainty. The heat demand variation range due to input parameter variation in line with standard requirements was assessed to be ±22 % of the average value.

Keywords: uncertainty analysis, Monte Carlo sampling, heat demand, heat consumption variability, multi-flat panel buildings, uncertainty sources.

1. Introduction

Uncertainty surrounds all aspects of building thermal behaviour. This is reflected in the fact that the heat demand of almost identical houses under the same climatic conditions normally shows different values. The reasons of this phenomenon and weight of possible factors have not been extensively examined yet. When trying to explain the scatter of heat consumption in uniform buildings, the statistical variation and uncertainty of input parameters has to be taken into account. Common deterministic approach, when calculations are performed with average material parameters and other conditions, cannot handle with uncertainties when evaluating heat demand in buildings. The uncertainty analysis is an appropriate way to provide a more comprehensive information for heat use for heating. It particularly allows to evaluate if similar residential houses heat consumption dispersion is natural, or this is due to the design faults and violations of the building standards.

Uncertainty defines an interval within which we suspect the true value must fall. Under uncertainty here it is assumed not only a lack of information about true value, but also variability representing existing diversity or heterogeneity of parameters. Particularly important are the actual uncertainty of thermal processes, and our perception of uncertainty in the absence of perfect knowledge about true values of different factors.

The use of uncertainty analysis integration in the building thermal performance simulation procedure was explicitly demonstrated by some authors [1, 2]. We intend to show that the uncertainty analysis can supply additional information even using simplified methods for energy use calculations.

A widely accepted calculation is applied, but the input parameters are taken not as average values, but as probability distributions. The calculations performed show how much the propagating uncertainty in value of building envelopes thermal resistance, air change rates, casual gains and indoor temperature influences the calculation output.

The main part of Lithuanian housing stock, as well as Estonian and Latvian ones, consists of multi-flat panel buildings built in 1960–80. Thus heat demand uncertainty analysis for this kind of buildings is also of practical use, as it provides insight into the nature of quite a wide range of heat consumption bills of similar buildings.

2. Uncertainty sources in building heat demand

The stochastic nature of the factors deciding heat consumption of buildings is evident. In three stages of building life cycle different sets of uncertainty sources arise as outlined in Fig 1.

By the design differences in building geometry different design solutions are assumed. The important factor is different ratio of external envelopes area to the floor area. Typical building projects characterises the old construction. Therefore building geometry design differ-

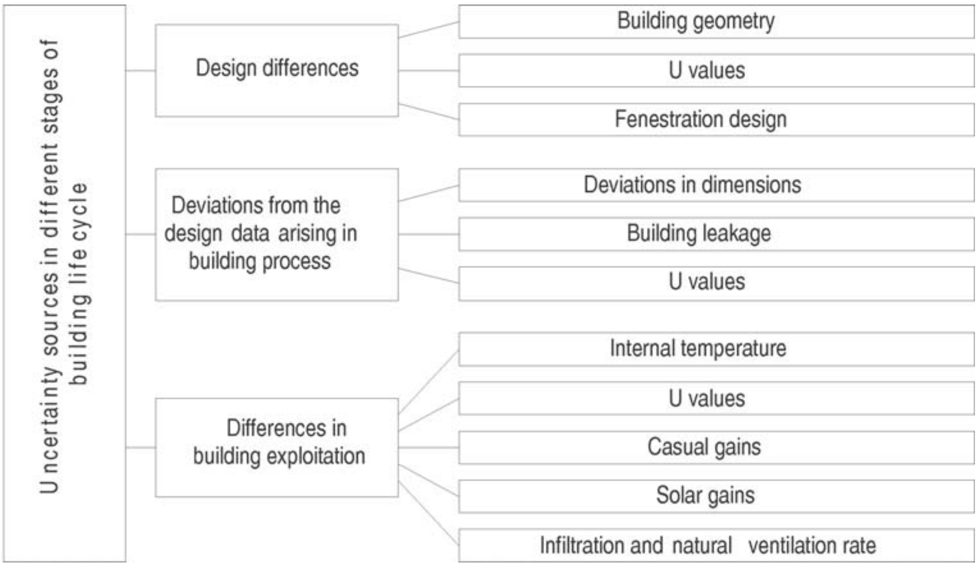

Fig 1. Sources of uncertainty in building design, construction and exploitation

ences are insignificant if buildings with the same number of storeys are to be compared.

Design U values of particular envelopes were determined by thermal regulations, where the maximum values are restricted. The better design U values are possible.

Solar gains in design phase are defined by the fenestration design (area, orientation and construction of windows) and the application of low-e coatings on the glass.

The deviations from design values can appear in construction process, as the building materials and products can fail meeting the λ values stated. Differences between real and declared building material properties are restricted by the standardised procedures of materials testing and stated values.

Therefore design process causes absolutely certain upper limits of the values. Stated values declaration procedures determine the probability in which degree real values will be worse than the stated ones.

Heat transfer coefficient deviations from the design heat transfer coefficient values appear in construction process as the building materials and products can fail meeting the heat conductivity values stated. An inconsistency between design and real values becomes even greater during the service life of a building due to temperature, moisture and time (aging).

During building service stage solar gains are conditioned also by curtains, shadows from adjacent objects.

Infiltration is greatly linked to building construction quality and usage of the building. The construction defects cause the unintended leakage of air through the buildings structure, the opening and closing of windows also affect air change rate in the building. Other uncertain and variable factors are wind speed, level of lee, other climatic and microclimatic factors.

3. Methods

Parameters uncertainty influence on the final result is evaluated by Monte Carlo method. The key advantages of this method are the ability to use different ways of defining the parameter distributions, the ability to handle complex models and the propagation of uncertainty and parameter dependencies in the model and are reflected in the model output distributions. The Monte Carlo method is extensively used, with abundant publications describing the method and its application.

This method represents the estimate of overall output uncertainty due to all uncertainties of input parameters.

The uncertainty analysis starts by identifying which input parameters are uncertain. These random variables are allowed to vary over a prescribed range, and any of such a random variables has a given probability of occurrence. This variation is called a probability distribution. The simplest type of distribution is a uniform one: the random variable may assume any value with an equal probability between the lower and upper limit (depicted on the left of Fig 2). The most common type of nontrivial distribution is the normal or Gaussian distribution (depicted on the right of Fig 2). It is a symmetric distribution that can be completely described by a mean value and a standard deviation.

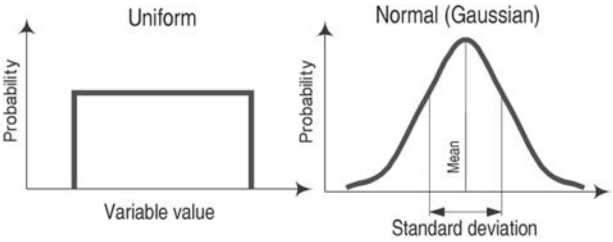

Fig 2. Probability distributions used in analysis

When a probability distribution for each input parameter is assigned, many calculation series are performed, each time random values are attributed to the parameters from their distributions. In Monte Carlo analysis the basic principle is that all uncertain parameters are perturbed by random amounts between calculations.

The number of calculation procedures was chosen based on accuracy of calculation output estimation dependence on the number of calculations. As it can be seen in Fig 3, there is initially (after a few calculation procedures) a lack of the calculated output accuracy, but the accuracy is quickly increased by marginal improvements after 800 – 1000 procedures.

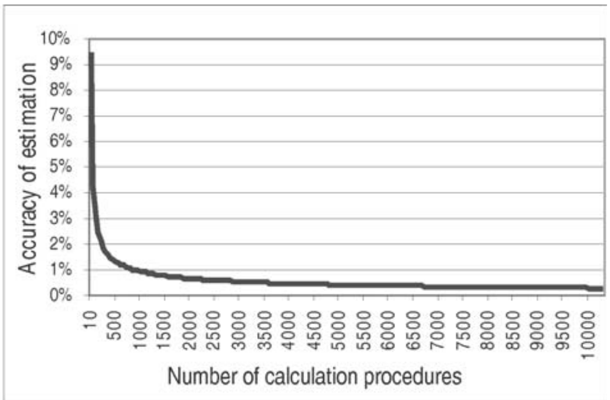

Fig 3. Calculation output estimation accuracy dependence on the number of calculation procedures with 99 % confidence level

1000 calculation procedures were undertaken and all the results analysed together. Based on central limit theorem, the output of the Monte Carlo analysis always has normal distribution, even when the distribution of input parameters is abnormal.

The Monte Carlo analysis employs the external approach. When using this approach, the calculation model is treated as "black box" and only input parameters are altered and differences in calculation outputs are examined.

The model of heat demand is composed by the simplified calculation procedure, proposed by European and Lithuanian standards [3, 4]. The calculation output q is specific heat demand for one square meter of heated area per month. This output is calculated using the following formula:

$$q = \frac{((\Sigma A_i \cdot U_i + \rho \cdot c \cdot n \cdot V) \cdot (\theta_{in} - \theta_{ex}) - \eta_o \cdot \Psi_{hg}) \cdot 730}{A_f \cdot 1000}, \tag{1}$$

where q is specific heat demand (kWh/m^2/month), U_i are heat transfer coefficients of building envelope parts (W/(m^2·K)), A_i is an area of each part of the envelope (m^2), ρ is density of air (kg/m^3), c is specific heat of air (Wh/(kg·K)), n is an air change rate (h^{-1}), V is building volume (m^3), θ_{in} is indoor air temperature (°C), θ_{in} is outdoor air temperature (°C), η_o is solar and internal heat gains utilisation factor, Ψ_{hg} is solar and internal heat gain flow (W), 730 is the number of hours per standard month, A_f is a heated floor area of the building (m^2).

If there is not any equipment of heat devices control in the premises, then only 10 % of heat gains are utilised and h_o equals 0,1 [3].

The outdoor air temperature values are set for calculation procedures. All other parameters of the model are uncertain or variable.

4. The application of the method

Case analysis of heat consumption uncertainty was conducted for an old apartment building. This analysis object was chosen as it represents the most typical building of the 1960–80s. As some field measurement data on such buildings heat consumption are available, the calculation results can be compared to a real diversity of heat consumption.

Residential houses built from prefabricated panels comprise more than a quarter of residential stock in Lithuania. Mostly it includes five and nine-story multi-flats buildings. Wall panels are made of the expanded clay concrete with 1100 – 1200 kg/m^3 density. This paper deals with a five-storey old construction apartment building that was standard in 1960–80s in Lithuania. Fig 4 presents the typical section plan of such a kind of buildings. The building analysed in this paper consists of three sections at each floor and of 15 such sections in all.

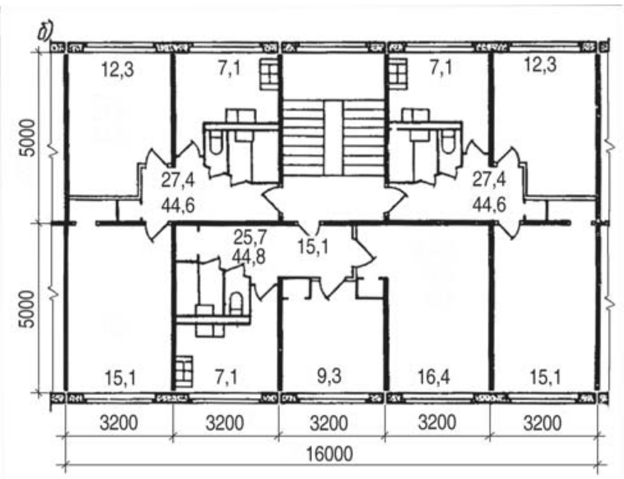

Fig 4. Typical section plan of the panel multi-flat apartment building

The total heated area of the building analysed is 2400 m^2. The areas of the building envelope parts are listed in Table 1.

External walls of the building are constructed from prefabricated large dimension panels. Concrete floor is laid down above the unheated cellar. The flat roof is poorly insulated. Windows are double glazed with timber frames.

Table 1. Envelope parts area of the building

Envelopes of the building	Area, m^2
Walls of flats	1089,75
Walls of staircases	111,60
Floor of flats	432,00
Floor of staircases	48,00
Roof of flats	432,00
Roof of staircases	48,00
Windows of flats	506,25
Windows of staircases	32,40
Outdoor doors	6,00

5. Uncertainty evaluation of the model parameters

Uncertainty is specified by the probability distribution. The judgments about what types of parametric distributions are appropriate to represent uncertainty in a given empirical quantity are to be made and parameters of each distribution are to be chosen.

A crucial problem in the uncertainty analysis is to define reasonable probability distributions of the parameters. Ideally, the estimates for probability distribution are based on empirical data. However, when a few data are available, all the relevant information must be used. All the parameters, excluding average solar radiation flow per day, are assumed to have normal distribution by relying on analysis in Macdonald's work [1]. Average solar radiation flow per day is assumed to have a uniform distribution, as all values from the range have an equal probability to exist because are defined by orientation of windows. Further, the uncertainty of each parameter is evaluated. Uncertainty of parameters having normal probability distribution can be defined by two magnitudes: mean value and standard deviation. The relative standard deviation instead of standard deviation is used as more convenient. It is expressed in percent and is obtained by multiplying the standard deviation by 100 and dividing this product by the mean value. Uncertainty of parameters that has a uniform probability is described as minimum and maximum values.

As the goal of our analysis is to examine heat demand and consumption uncertainty caused by parameter uncertainty and variation allowed by standards, wherever possible, values of input distribution parameters were based on standards prescriptions.

5.1. Thermal properties of the envelope

The variation of the thermal resistance of the envelope occurs as a result of measurement accuracy limits, moisture content and, to a lower degree, temperature variation and age. For example, the field tests have shown that the panel wall heat transfer coefficient varies in average between 1,11 and 1,14 $W/(m^2 \cdot K)$. Still there are cases when the heat transfer coefficient of such walls reaches even 1,82 $W/(m^2 \cdot K)$. The design value is 1,25 $W/(m^2 \cdot K)$ [5].

Design values of a particular envelope part heat transfer coefficient for analysis were determined by the thermal regulations, where the maximum heat transfer coefficient values for each part of envelope are restricted. Still there could be designed an envelope with better heat transfer coefficient values than required.

The uncertainty of heat transfer coefficients of the envelope was evaluated taking into account possible effects of moisture and temperature on heat conduction. The extent of such an influence was assessed according standards [6]. It was found to be approx 3,7 %.

5.2. Infiltration and natural ventilation

The standard of heat requirement calculation [3] directs to use air change rate due infiltration and natural ventilation depending on a number of open facades (one or more), tightness of the building (small, medium, and large) and level of lee (building is protected, weakly protected, unprotected from wind). In multifamily buildings the standard prescribes to assume air change rate from 0,5 $^{-1}$ to 1,2 h^{-1}, depending on the above-mentioned factors. Mean value is 0,85 h^{-1}. If to accept that 95 % of all values must fall within this range, the standard deviation will be 0,18 h^{-1}, the relative standard deviation to 21 %.

Building usage appends additional uncertainty in air change rate and this uncertainty cannot be in some way restricted. The extent of such an uncertainty could be only assumed. We assume that due to window opening the relative standard deviation increases to 30 %.

5.3. Heat gains

Heat gains consist of solar radiation gains and internal gains:

$$\phi_{hg} = \phi_{sg} + \phi_{ig} , \tag{2}$$

$$\phi_{sg} = \Sigma q_{s,j} \cdot s \cdot A_{gl} \cdot a , \tag{3}$$

where $\Sigma q_{s,j}$ is the sum of average solar radiation flow per day over all surfaces of a particular building orientation (eg vertical N, S, E and W and horizontal) in a month, s is the total solar transmittance of the surface, which is the time averaged transmittance of the non-shaded area of the glass (s = 0,75, when windows are double glazed), A_{gl} is an area of transparent surfaces (approx 75 % of window opening – reduction due to frame); a is the permanent shading factor. This factor includes shading by a curtain, adjacent buildings, trees, shading devices and depends on non-perpendicular angle of solar radiation. It varies from 0 to 0,9, mean value is 0,6. Average daily solar heat flux density for a heating season varies between 9,5 and 123,7 W/m^2 [3].

Internal gains, ie gains from lighting, equipment and occupants, are given in terms of W/m^2 of floor area, for residential houses accordingly 3,0, 2,7 and 2,8 W/m^2 of floor area. This component of heat flow is rather uncertain as heavily depends on the behaviour of occupants. The uncertainties of each named parameter of internal gains are assumed to be 10 % [1].

5.4. Indoor air temperature

Indoor air temperature is assumed to be 18 °C. This is a minimal indoor air temperature according to hygienic standards [7] and in most cases is a set point temperature contracted to maintain by heat suppliers.

Input parameters used to calculate heat demand in the building are listed in Table 2.

Table 2. Input parameters of heat demand calculations (MV – mean value, RSD – relative standard deviation, min – minimum value, max – maximum value)

Input parameters	Probability distribution
Wall heat transfer coefficient, W/(m^2·K)	Normal probability distribution, MV = 1,25, RSD = 5 %.
Floor heat transfer coefficient, W/(m^2·K)	Normal probability distribution, MV = 1,43, RSD = 5 %.
Roof heat transfer coefficient, W/(m^2·K)	Normal probability distribution, MV = 0,69, RSD = 5 %.
Window and door heat transfer coefficient, W/(m^2·K)	Normal probability distribution, MV = 2,50, RSD = 5 %.
Air change rate, h^{-1}	Normal probability distribution, MV = 0,85, RSD = 30 %.
Indoor air temperature in flats, °C	Normal probability distribution, MV = 18,0, RSD = 3 %.
Indoor air temperature in flats, °C	Normal probability distribution, MV = 12,0, RSD = 3%.
Internal heat gains from lighting, W/m^2	Normal probability distribution, MV = 4,20, RSD = 10 %.
Internal heat gains from equipment, W/m^2	Normal probability distribution, MV = 2,70, RSD = 10 %.
Internal heat gains from occupants, W/m^2	Normal probability distribution, MV = 31,05, RSD = 10 %.
Average solar radiation flow, W/m^2	Uniform probability distribution, min = 9,5, max =123,7.
Total solar transmittance of the surface s	Normal probability distribution, MV = 0,75, RSD = 10 %.
Area factor of transparent surfaces, m^2	Normal probability distribution, MV = 0,75, RSD = 10 %.
Permanent shading factor a	Normal probability distribution, MV = 0,60, RSD = 10 %.

6. Results of the method application

The analysis performed has shown that heat demand data uncertainty in months with different average outdoor air temperature, if expressed as relative standard deviation, is approximately 11,2 %. In other words, 95 % of calculated heat demand values varies ±22,4 % from average value due overall variation and uncertainty of input parameters. It can be stated with 95 % confidence that input parameter variation in limits allowed by standards and caused by normal building exploitation, determines that the maximum value of heat demand can be about 1,5 times higher than the minimum value.

Fig 5 gives the results of building heat demand calculation uncertainty at different average monthly outdoor air temperatures.

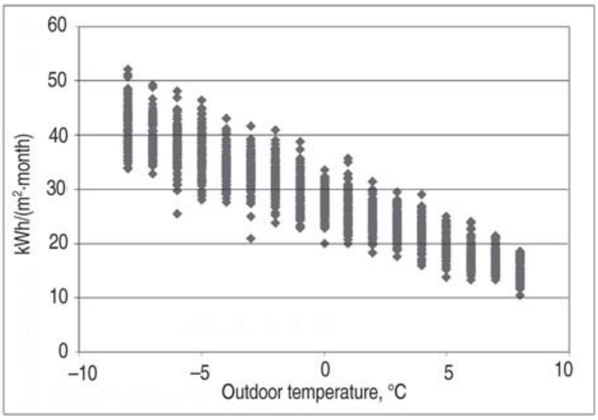

Fig 5. Heat demand per month for 1 m^2 of floor area uncertainty at different average monthly outdoor air temperatures

The heat demand calculation uncertainty analysis results shows that the mean value of heat demand in five-storey old apartment buildings is approx 28 kWh/m^2 and the values range from 18 to 38 kWh/m^2 per standard month[1] . Relative standard deviation is 2,8 (10 %) The uncertainty interval with 95 % confidence level is between 22 and 34 kWh/m^2 (±20 %). Fig 6 demonstrates results of the Monte Carlo analysis with average outdoor temperature of 0 °C in the form of histogram.

Fig 7 displays three Lithuanian towns (0,1 – 0,5 m inhabitants) heat consumption field data together with results of the theoretical heat demand evaluation. Field data comprise district heating companies billing data averaged for each month of heating season and all five-storey typical multi-flat buildings stock in each town considered. It can be seen from the figure that real heat consumption is less than calculated heat demand. The similar discrepancy between heat demand, calculated according to the official heat demand calculation proce-

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[1] Standard month has 30,4 days (730 hours) and average temperature 0 °C.

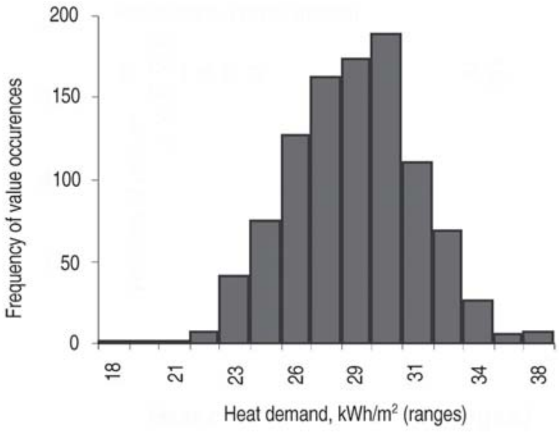

Fig 6. Uncertainty of heat demand per standard month

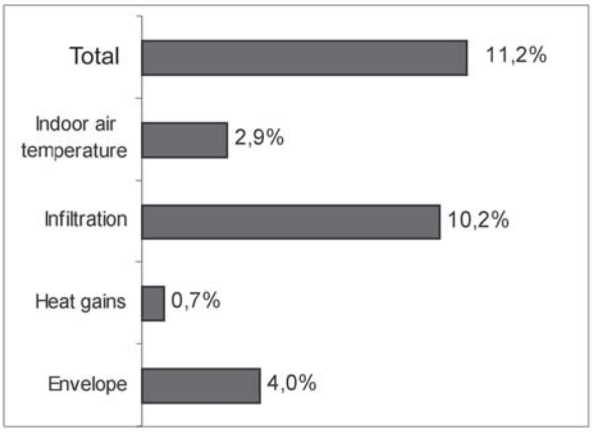

Fig 8. Output uncertainty when uncertainties of different input data groups are treated separately

dure and real heat consumption has been noted by many authors. The declination of calculated and field data points to the thermal balance temperature 17 °C shows that this discrepancy can hardly be explained by possibly low values of heat gains as taken according to the official heat demand calculation procedure.

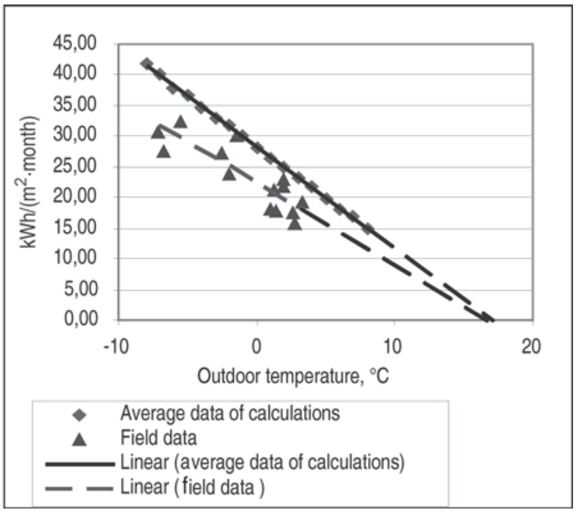

Fig 7. Monte Carlo analysis results and field data of averaged heat consumption of typical multi-flat five storey apartment buildings in three Lithuanian towns

Uncertainty and variation of different factors influence the heat demand uncertainty with different weight. Using the same model and calculation procedure, the relative standard deviation was determined by perturbing each input parameter or group of parameters (thermal properties of envelope, heat gain factors, air infiltration rate) in isolation from each other. The results of the comparison among different influence of input parameters uncertainty to output uncertainty are demonstrated in Fig 8.

The heat gains value uncertainty has the smallest impact and the infiltration uncertainty has the strongest impact on heat demand calculation results. This analysis shows that uncertainty of heat gains may be neglected when assessing the uncertainty of old residential building heat demand. This is caused by the poor regulation opportunities – heat gains have an impact on indoor air temperature, but there is neither manual, nor automatic regulation of heating system according to indoor air temperature.

7. Conclusions

1. It could be noted that uncertainty analysis, even integrated in the procedure of simplified monthly heat consumption calculation, may provide the useful information about likelihood of design or implementation faults. The way presented in the paper is the easy way to get the information about the result uncertainty.
2. The uncertainty analysis performed with 95 % confidence demonstrates that in multi-flat panel building stock the ratio between the maximum and minimum heat demand can easily be 1,5 and it should be treated as normal. This difference is quite possible, even when following standard requirements with the allowable deviations in design, construction and maintenance of buildings.
3. The determined heat demand uncertainty can be extended to assess variation of heat consumption. Heat consumption difference of 1,5 times between the similar old multi-flat panel buildings does not necessarily points to poor exploitation or building faults. But, if the heat consumption scattering exceeds these limits, this effect with 95 % confidence is due to the exploitation and building shortcomings. Buildings where the heat consumption exceeds the limits defined by the uncertainty analysis are to be foremost considered looking for heat consumption reduction possibilities.

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TIPINIO DAUGIABUČIO BLOKINIO PASTATO ŠILUMOS POREIKIO NEAPIBRĖŽTUMO VERTINIMAS

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Santrauka

Net ir tomis pačiomis klimato sąlygomis panašių pastatų šilumos vartojimas yra skirtingas. Šių skirtumų priežastys dar nėra pakankamai išnagrinėtos. Straipsnyje tos priežastys ir mastas analizuojami neapibrėžtumo analizės metodais. Šilumos poreikis vertinamas derinant supaprastintą šilumos vartojimo skaičiavimo procedūrą ir Monte Karlo atrankos metodą. Analizė atskleidžia parametrų reikšmių svyravimų (ir neapibrėžtumo) įtakos rezultatui mastą. Įvesties parametrams svyruojant standartų leistinose ribose, šilumos vartojimas nuo vidutinės reikšmės gali skirtis iki 22 %.

Raktažodžiai: neapibrėžtumo analizė, Monte Karlo atrankos metodas, šilumos poreikis, šilumos vartojimas, daugiabučiai pastatai, neapibrėžtumo šaltiniai.

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