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Analysis of thermal energy demand and saving in industrial buildings: A case study in Slovakia

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A B S T R A C T

Energy saving through incorporation of automation techniques in buildings is usually too complicated and costly and it is necessary to protect environment. Presently, there is no single directive and standard method to estimate and validate the energy consumption process in industrial buildings for heating to maintain a comfortable environment for working. The purpose of this study was to find and develop a practical method for analysis and calculation of thermal energy consumptions and saving in buildings. The energy required for heating in an industrial building in Kosice, Slovakia was studied using measurements, calculations and dynamic simulations. The energy needed for heating was determined according to the Slovakian and Austrian national standard methods using the simplified calculation method that is applied for non-residential buildings and the ESP-r and BuilOpt-VIE simulation programs. The repeatability of the experimental data and possibility of rapid assessments in an optimized process using these methods were studied. It was found that the clear definitions of the heat consumers inside the building, including all machinery and occupants, are very important for evaluation of energy needed for heating. Using dynamic simulation, it is not possible to reproduce actual temperatures at various heights without prior knowledge of the exact functionality of the heating and cooling systems. The simulations results also indicated that integration of lighting, heat recovery and door opening automation can significantly reduce the heating energy consumption.

1. Introduction

The world energy demand and consumption is rapidly growing that requires further energy supply to meet the larger future demands. Moreover, other issues, such as shortage of energy from natural resources and some environmental concerns, make the large energy consumption more serious. The International Energy Agency (IEA) has published alarming data on energy consumption trends. While the total primary energy supply (TPES) was doubled from 1973 to 2010 (from 6107 to 12,717 million tons of oil equivalent, MTOE) and crude oil production increased almost 40% (from 2869 to 4011 million tons), the total final energy consumption showed 31% increase (from 2815 to 3691 MTOE). Interestingly, in the last two decades the oil price has increased nearly five times. In the same period of 1973–2010, the CO_2 emission was also doubled (from 15,637 to 30,326 million tons CO_2) [1]. On the other hand, buildings consume more than 40% of energy, 25% of water, and 40% of resources, and emit nearly one third of the greenhouse gas emission [2]. Moreover, the buildings provide the greatest potential for reducing emission at relatively low cost. The consumed energy for heating the interior of buildings involves a major part of the total energy usage; therefore, energy efficiency in buildings, and the energy system at large, mainly depends on several physical, climatic, and human variables [3].

There have been a significant number of attempts to analyze the energy consumptions in buildings and to find methods for saving

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energy through various ways in different climate conditions and different kinds of buildings [4–53]. The thermal energy demands have been studied in: cold climates, such as in Finland and Turkey [6,19,46,48]; hot and humid climate, such as in Persian Gulf region, south Asian and African countries [16,17,24,31,40,41,48]; home and residential [15,18,22,32–34], high-rise [47,48] and low-rise apartment buildings [49]; non-residential and commercial [5,20,38,39,42], and industrial [13,53] buildings; and special buildings, for instance museum [35] and university [37]. The review of these papers highlights the fact that the results strongly depend on the types of climate and buildings. In most of these studies, the focus has been on thermal energy consumption analysis in the residential and commercial buildings and there are insufficient investigations on the industrial buildings, particularly in cold climate conditions that heating is very critical.

Building designers attempt to apply innovative technologies and methods to achieve low energy consuming building designs. For decades, advancing the manufacturing performance has been the ultimate goal of industries. Increase of demand, public pressure for minimizing the greenhouse gas emission to protect environment and increase of energy costs have made energy efficiency a critical issue in industrial sector. Greenhouse gas emission is mainly produced from burning of fossil fuels and significantly influences the climate and environment. Energy-efficient optimization has become the aim in industrial buildings designs for the establishment of manufacturing facilities and halls with optimum performance.

Chung has recently reviewed various mathematical methods to evaluate the energy performance in buildings [3]. The methods included simple normalization, ordinary least square (simple regression analysis), data envelopment analysis, stochastic frontier analysis, model-based method, and artificial neural network. Based on the rating models, two types of systems (public and internal) were categorized and the mathematical models were compared according to these categories for various types of buildings (school, residential, hotel). The thermal energy consumed in buildings for heating based on the kind of the building has also been reviewed [43]. Greenhouse gas emission directly relates to the amount of energy consumed in the buildings; therefore, reduction of energy usage significantly decreases the emission from the buildings. Taylor et al. recently studied the decrease of greenhouse gas emission from UK hotel buildings and found that 50% reduction in greenhouse gas emission from hotels is technically possible using mainly passive and practiced technologies [54].

The effects of buildings designs, materials and some other factors on their environment, internal climate and energy consumption have been studied [8,9,13,55]. The performances of buildings for energy consumption were investigated, leading to the conclusion that the required information about the energy can be collected at three stages with a special approach [14].

Many industries have recently reformed their energy consumption plans and policies to a more efficient use of electricity and heat to reduce costs and thus to improve their competitiveness in the present tough global economical conditions. For this reason, using automation in a new building is now possible via modeling and simulation in the serial production systems [56,57]. In spite of increasingly rigorous energy use reduction necessities in all other sectors, new industrial units are only needed to meet the minimum pre-registered thermal conductance and U-values of the building envelope in Slovakia and Austria. Presently, there is no formal program in practice for certification of energy in industrial buildings. Moreover, certificates for energy consumption are not legally necessary for these kinds of buildings, which may change in future.

The energy system in Slovakia mainly depends on the imported fossil fuels via an extensive natural gas distribution system with 29% share of energy. Industries are the major energy consumers, constitute 42% of the final energy and 50% of the electricity consumptions. Compared with the EU-average, the energy intensity in Slovakia is relatively high, primarily because of the significant role of energy intensive industries, such as steel, paper and chemicals. The government places high priority on improving energy efficiency, given the significant reliance on imported fossil fuels. As for the energy savings, it is expected that industry and transportation make 50% contribution, while other measures are estimated to make 30% of the savings by 2016 [58].

According to the rules for workplaces, internal climate conditions are required to satisfy the regulations. Because of the cold climate, spaces in most industrial halls of Slovakia need intensive heating, particularly in winter. The aim of the present joint project between the Technical University of Kosice and the Vienna University of Technology was to evaluate the thermal energy use through measurements, calculations and simulations applied to an industrial building. The objective was to investigate if the thermal energy can be determined through implementing various methods. The results will reveal if the thermal energy needed can be determined easily for all new industrial units and those under restoration, and if the buildings envelopes could rapidly be optimized.

The motivation behind this project was to decrease the relatively large amounts of energy consumption for the heating of manufacturing halls in factories, especially in cold regions like Kosice. In Slovakia, there are no clear heating energy measurements or calculation standards for industrial buildings. Because of the large energy demand for heating factories and the policy and public pressure to reduce energy consumption, many companies are looking for a verification method to purposefully optimize the energy consumption in their manufacturing buildings.

The performance of EN ISO 13790 standard method for calculation of the thermal energy consumption in cold climate conditions has been studied [6]. The authors found that this method provides as much as 46% larger or 59% smaller heat demand by buildings compared with the simulation tool in local conditions—depending on the building style and thermal inertia. It was concluded that the results can be calibrated for the residential buildings with the correct selection of the numerical variables for local climate conditions. The thermal energy consumptions in the selected factories were evaluated via measurements, simplified calculations and dynamics simulations. The first part of the analysis was related to in-situ examinations in a case study of manufacturing hall in a factory, applying Slovakian national standard of energy consumption evaluations for residential buildings [59–61]. The objective of this work was to find a mathematical model connecting the measured values in real conditions. In the second part, the energy demand values for heating of the industrial building were calculated according to the Austrian simplified method of EN ISO 13790 for non-residential buildings using the simulations programs [62]. The thermal energy consumptions were measured in-situ in winter in a selected industrial building. Various calculation methods are available for determining the heating energy use in the residential buildings. It is also possible to perform on-site measurements of the thermal energy use by the residential buildings. In this study, the applicability of the calculation method for thermal energy consumed for heating recommended by the standard methods was investigated and new numerical factors of the utilization suitable for the case study in Slovakia climate conditions were determined.

2. In-situ monitoring thermal energy consumption

The selected manufacturing hall in this case study was monitored according to the Slovakian national standard method of STN

73 0550 [59]. The energy consumption values were measured during the winter while the uses and occupancy activities inside the hall were carefully checked. The measurements were conducted in accordance with the standard protocols used for validation of residential and public buildings considering a number of regression models in the evaluation of energy consumption for heating. The applied standard method defines the connections between the preconditions of the resulting values of energy consumed by the heat exchanger before entering the building (usually at the building foundations). The aim of the standard is to validate the operational energy required for all types of residential building, outlining the same assumptions for internal climate conditions. In factories, the usage of buildings is relatively different from those of the residential buildings. For this reason, the other task in this study was to review the extension by which the relationships criteria for the measurement of energy consumption for heating are relevant to assessments of factories. In literature survey, we found some cases of the energy consumption analysis in industrial buildings using different methods [13,53,63–65].

3. Manufacturing hall information and model

This study was conducted on a typical industrial building with manufacturing halls. In the study, both light and semi-heavy industrial buildings were monitored according to Slovakia national standard of STN 73 5105 [66]. The floor plan and 3D model of the manufacturing hall with an exterior picture are shown in Figs. 1 and 2, respectively. The building is located in Kosice, Slovakia, with an elevation of 208 m above the sea level and geographical coordinates of N 48°43′1″, E 21°15′0″ [67]. Kosice is located in the mild zone, relatively warm and humid in summers and cold in winters. Temperatures may rise up to 30 °C in summer with stretches of rainy weeks at a maximum of 15 °C, while in winter it is mostly below zero for several weeks with significant snowfall and maximum temperatures of −10 °C [68].

The structural system of the selected manufacturing unit is a kind of steel-concrete framework. The hall length is 36 m with an 18 m span and an overall height of 7 m. The hall envelope is 375 mm thick composed of porotherm style hollow clay block bricks (CDm) and lime mortar. The glazed elements consist of single-pane glazed walls reinforced with wires and single-pane skylights transparent plastic sheets of poly(methyl methacrylate) reinforced with wires and steel framing.

The building envelopes were modeled and the thermal energy usage and temperature profile were determined using ESP-r (www.esru.strath.ac.uk/Programs/ESP-r.htm) [69,70] and BuildOpt-VIE software simulation programs. The details of the procedures to use these programs are available in their websites. The dynamic building thermal simulation program of ESP-r was particularly selected and used for the simulation of the machineries in the hall and air movement. This program has been widely used in buildings for various modeling and simulation purposes, such as for absorption chiller [71–73], solar irradiation distribution inside a basin-type solar still [74], energy in a solar chimney [75], heat consumptions in apartments [76], reversible ventilated window [77], heat transfer and air movement through a window [78], thermal simulation of gypsum composites [79], and heat demand in cold climate by apartment and office buildings and detached houses [6].

The BuildOpt-VIE software is a simulation tool that was originally developed at the Research Centre of Building Physics and Sound Protection, the Vienna University of Technology [80]. It is a type of multi-zone model for the entire building hygrothermal calculations that is able to determine more than 6000 interacting zones. In this program, special consideration is given to calculate the solar radiation for each window and wall taking into account the shading of adjacent buildings and overhangs [7]. Buildings were simulated with controlled volume method using an explicit time schedule. This program was confirmed with the data by the IEA Annex 41 by the entire building heat, air and moisture responses [81] and by several experimental studies on various types of buildings [82–91].

Because the studied hall is an existing building, additional investigations were made to ensure that the construction data from floor plans were correct and accurate. During a cold period of winter, the temperatures of the building were observed and recorded through thermography technique using an infrared (IR) camera. The IR camera used was an NEC/Avio H2640 (NEC Avio Infrared Technologies Company, Tokyo, Japan) with a high temperature-range sensor and maximum recording capability of 30 frames per second, operating in a long-wavelength infrared band with a spectral range of 7.5–13 μm. The thermal resolution of the camera was smaller than 0.08 K at 30 Hz and 30 °C and it was able to record images at large resolution of 640 × 480 pixel with a size of 3.2 MPa and accuracy of 2% with a total measuring temperature range from −40 to 500 °C in four different temperature ranges. The focusing depth range of the camera was from 30 cm to infinity. The examinations were performed to confirm the constructions data and the component connections of thermal bridges. Fig. 3 shows the thermal images, indicating the temperatures of the various hall surfaces taken with the IR camera.

Because the manufacturing hall and the machineries inside were very different, it was extremely difficult to illustrate them correctly in the simulation program. In this study, the machines were entered as boxes in the simulation program with their electric power required and the dissipated thermal energies. Fig. 4 shows

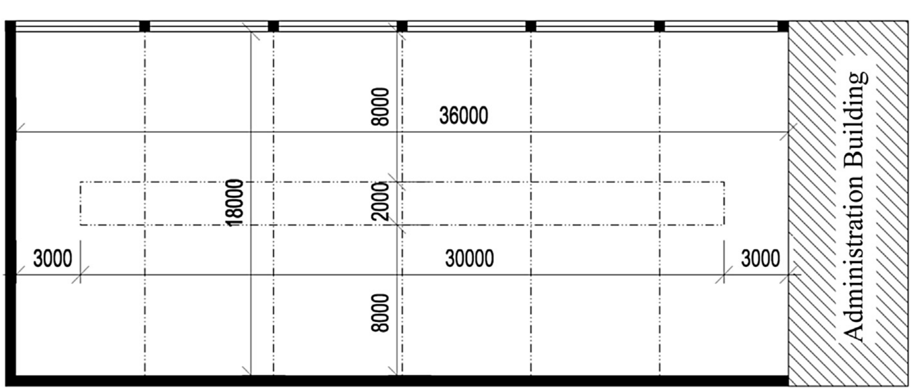

Fig. 1. Floor plan of selected manufacturing unit (dimensions in millimeters).

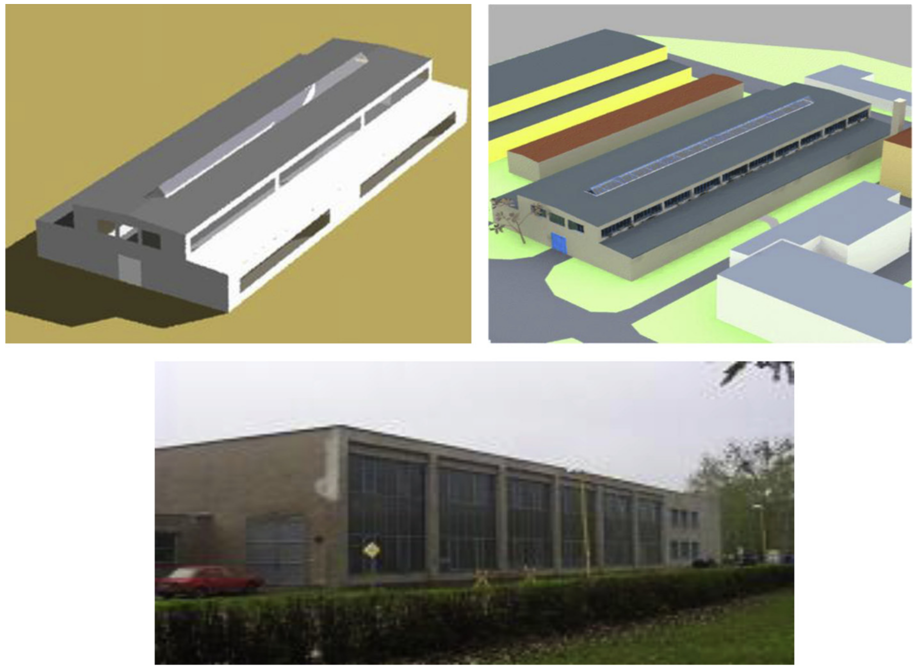

Fig. 2. Picture and 3D models of studied manufacturing unit.

pictures of the investigated manufacturing hall and the simulation model.

4. Experimental data and monitoring conditions

The purpose of the measurements was to obtain data to predict the annual energy consumption for heating of the manufacturing unit according to Slovakian national standard of STN 73 0550 [59]. This procedure is commonly used for prediction of the annual energy consumption in the buildings based on short measurement intervals (at least 30 days); however, it is primarily used for the residential or commercial buildings. In this work, the energy consumption for heating was monitored from Dec 23, 2009 to Jan 24, 2010 for a total time of 32 days. The average exterior air temperatures in this period were below zero, as shown in graph of Fig. 5. This period was recommended by the standard procedure, required that the measurement period to be over 30 days.

The indoor environmental variables (heat flow, relative humidity, air and surfaces temperatures) of hall together with the thermal energy consumptions were measured. For the measurements, 30-min intervals were considered. The indoor air temperature was measured at seven different heights with steps of 1 m and in the center of the operation space floor. Because this was not in agreement with the requirements for a sensor position to measure a maximum space of 50 m^2, we measured the temperatures at the particular heights. The main goal was to establish the temperature stratification in a hall type building. We also wanted to show that methodologies carried out for measurements of temperature in residential or commercial buildings are not appropriate for industrial buildings. Fig. 6 shows the measured indoor temperatures at seven various heights in the period of Dec 23–29. In general, determining reliable calculation criteria of the average daily indoor temperature of an industrial unit is complicated. The plots in Fig. 6 indicate that the variations of the temperatures in the space are very large in both horizontal and vertical directions. To find out the contributions of various building elements in the energy consumption due to the construction heat losses, the surface temperatures of selected elements (walls and windows) were also measured in the period of Dec 23–28 (Fig. 7). The graphs of the results disclose significant differences between temperatures on the surfaces of various elements made from different materials.

The measurement of the total thermal energy consumption was carried out to calculate the validity of the connection criteria for determining the thermal energy consumption for heating on site for the manufacturing process. The variations of the daily and cumulative thermal energy consumption values that were obtained

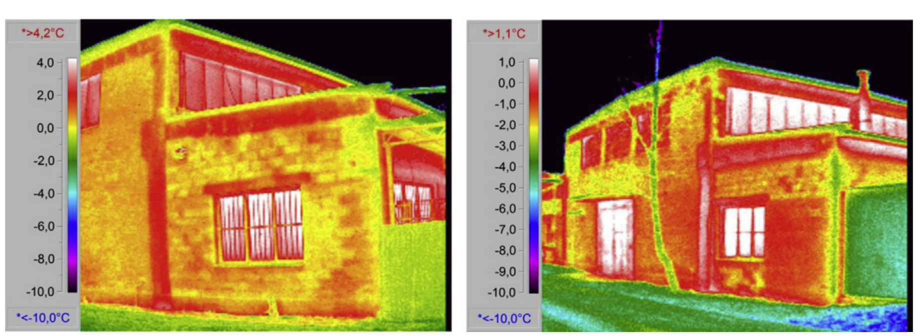

Fig. 3. Images of manufacturing hall taken with infrared camera indicating the temperature profile.

Fig. 4. Interior view and model of selected manufacturing unit.

from the heat exchanger station during Dec 22 to Jan 23 are shown in Fig. 8. The results clearly shows that on the colder days (Dec 25–27) the amounts of energy consumed for heating were several times of those on less cold days (Jan 20 and 21). This observation indicates the poor insulation system of the building and large potentials of saving energy consumed for heating.

5. Results analysis

The data were collected and the results were calculated and analyzed based on Austrian [62] and Slovakian [59] national standard methods. The statistical analyses were examined by a statistics expert. Presently, there is no guideline that requires an energy certificate for industrial units. Regarding this issue, the Article 4c of directive 2010/31/EU of the European Parliament and of the Council of May 19, 2010 [92] makes the application of the requirements for improvement of the energy performance of some buildings, including industrial plants and workshops, non-compulsory for the member states. The power needed for heating and cooling of a building or building elements in Austria are calculated in accordance with EN ISO 13790 standard method [62] using the monthly balance scheme. The energy certificates (i.e., the monthly energy demands for heating) are necessary to be calculated only for the non-residential buildings listed in Table 1. In all these kinds of buildings, the heat gain from lighting was identified and separated from the heat transmitted from the workers and machineries. In Table 1 the typical values for the internal heat gain from machineries and people (q_h) and the typical electrical lighting output (p) in a unit of gross floor area (GFA) are listed for the non-residential buildings according to Austrian national standard of ÖNORM B 8110-6 [93].

The thermal energy demand was determined in two steps. In the first step, the thermal energy in the manufacturing hall was calculated according to the Austrian monthly balance method using

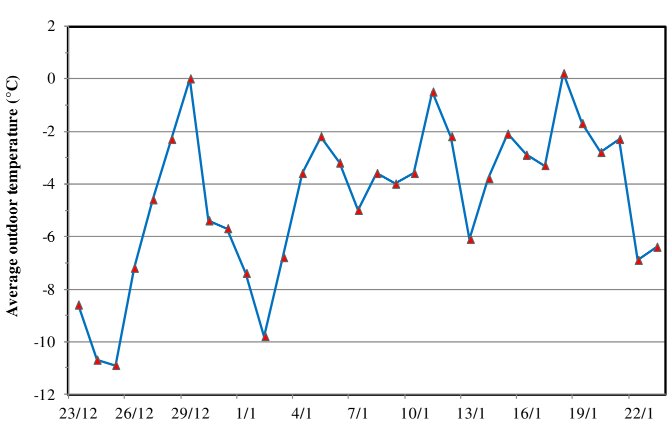

Fig. 5. Variations of average daily temperatures outside of selected manufacturing unit in the study period from Dec 23 to Jan 29.

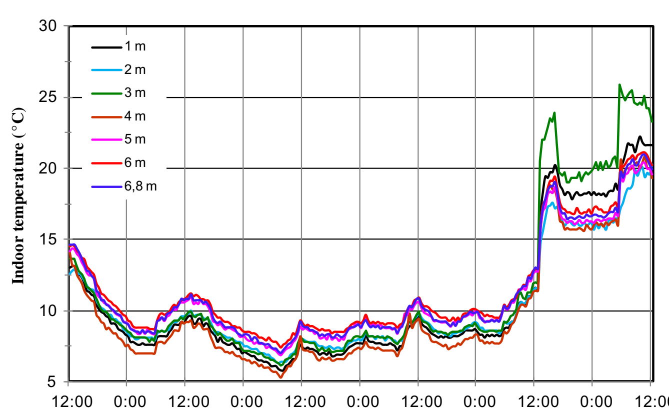

Fig. 6. Variations of temperatures inside of manufacturing unit at various heights of 1–6 and 6.8 m in the study period of Dec 23 to 29.

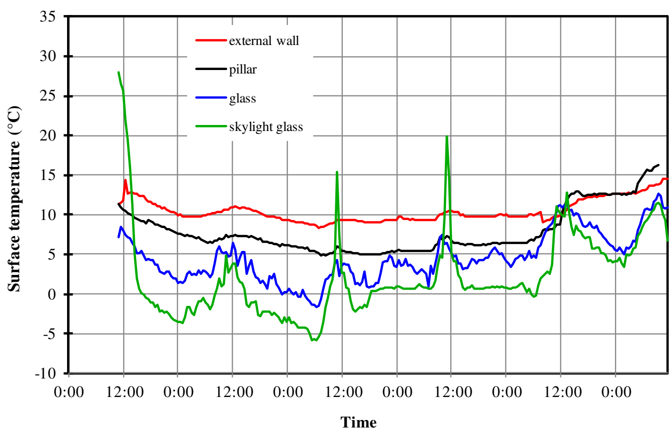

Fig. 7. Variations of temperatures on the selected building elements (external wall, glass in external wall, glass in skylight, load bearing pillar) in the study period of Dec 23 to 28.

Table 1
Typical internal heat gain values from appliances and persons (q_h), and typical average lighting levels (p) for non-residential buildings based on ÖNORM B 8110-6 Austrian standard [93].

Building types	q_h (W/m^2)	p (W/m^2 GFA)
Office buildings	3.75	3.7
Kindergarten and primary schools	3.75	2.8
Nursing homes	3.75	5.8
Pensions	3.75	3.9
Retail stores	3.75	8.1
Hospital facilities	7.5	9.4
Hotels	7.5	7.4
Restaurants	7.5	3.1
Conference centers	7.5	3.1
Sports arenas	7.5	4.3
Secondary schools and universities	7.5	2.8

the typical internal heat gain values from other non-residential building types: convention centers, sports arenas, or retail stores. The results of calculations are shown in Table 2. In the second step, from the average of 10 machines operating on site with an average power of 400 W each (total 4000 W) and the heat produced by 20 workers (total 4000 W), the total was considered as internal heat generated in the calculations. The internal heat gains per unit area were found as 12.35 W/m^2 from machinery and 4.5 W/m^2 from lighting. The results of calculations are presented in the second row of Table 2 (calculated with real interior gains). Analysis of some values indicates that information about internal heat gains is essential for the calculation accuracy and must be defined as accurately as possible. The user profile of similar non-residential units can also be used as estimation of energy consumption in the building development phase.

The measurements were also evaluated through confirmed calculation for the monitoring period of 30 points (Fig. 9) according to the Slovakian national standard [59]. An alternative evaluation was conducted for each file, producing 16 points for two days and eight points for four days. The results were published in 2011 [94]. From the graph in Fig. 9, it is evident that the energy signature curve has a linear character presented by linear regression correlation. This observation result was obtained from the records of thermal energy use and from the temperature difference ($T_{ai} - T_{ae}$), or from the heating degree days (HDD, D_{per}). The HDD values, an estimation of fuel required for heating buildings, are calculated simply through the differences between the daily (or hourly) dry-bulb temperatures and a typical reference temperature (is called base temperature), usually daily (or hourly) outdoor temperature. The amount of heating required in a building is directly proportional to the values of HDD at a specific location. The thermal energy consumption as a function of heating degree days is required through linear regression in the form of Eq. (1):

$$E_{bp} = a\ D_{per} + b \pm 2\sigma \quad (1)$$

where a and b are regression coefficients for the linear equation according to relations in the Slovakian national standard [59], and σ is a conclusive deviation of the file calculated in accordance with the relation of the standard method, and D_{per} is the heating degree days.

The plot in Fig. 9 shows that R-squared value of the linear regression fitting is relatively small, specifying weak fit. This observation clearly indicates that the methodology used for prediction of the energy consumption according to Slovakian national standard is not suitable for industrial buildings. The in-situ thermal energy consumption measurements and calculations were also conducted using various kinds of regression analyses methods. The results were presented in another paper [95] in which the calculations were conducted for regression analysis producing three coefficients of a, b, and c.

It is possible to consider the increase in energy consumption while recording the in-situ values from the smallest to the largest without the thermal energy consumption dependency on the number of heating degrees days. In such cases, assuming energy consumption for heating follows linear trend, it can be calculated according to the linear relation of Eq. (2) from Slovakian national standard [59]:

$$y = 0.0292\,x + 0.7832 \quad (2)$$

Equation (2) was found as one of the most suitable equations fitting the measured interval in this study; however, annual energy consumption prediction did not adequately comply with this

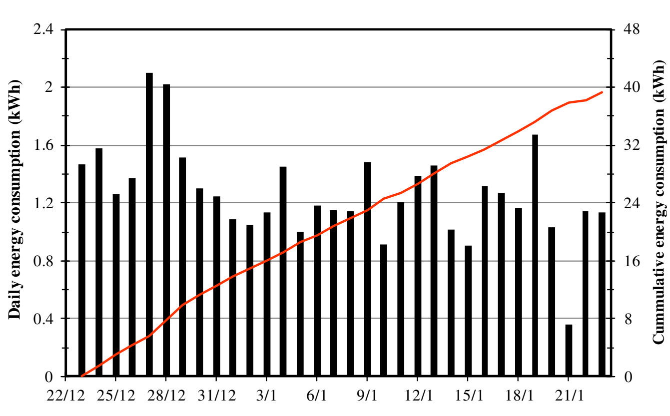

Fig. 8. Variations of daily and cumulative thermal energy consumed for heating manufacturing unit.

Table 2
Measurement and difference of thermal energy demand for heating through different user profiles of interior energy gains.

	Energy demand for heating (kWh)	Difference (kWh)
Measured	40,511.0	–
Calculated with real interior gains	40,145.4	365.6
User profile for retail stores	41,963.6	1452.6
User profile for sports arenas	41,982.1	1471.1
User profile for conference centers	42,426.5	1915.5

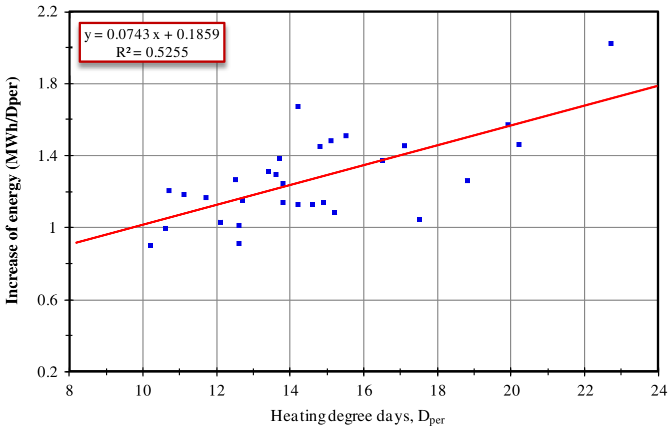

Fig. 9. Increase of thermal energy consumption in manufacturing unit during the study period as a function of heating degree days.

equation. Results of these analyses confirm that thermal energy consumption prediction of industrial buildings is definitely very complicated.

6. Dynamic simulations results

The energy consumption in the studied industrial building with contributing elements including, the HVAC systems, lighting, machineries, and occupants were modeled using ESP-r and BuildOpt-VIE software programs to simulate the thermal energy consumption. The internal loads of occupants and pieces of equipment were estimated on hourly basis. The activation of blinds, ventilation, and other building control systems were also calculated on hourly basis. The simulations were validated through comparing the results with the experimental data. The average internal temperatures were compared with the experimental data and simulation results in the selected manufacturing hall (Fig. 10). It was hard to get absolutely accurate information for input of simulation program because the ventilation system could be set at various intensities and was not clearly defined. Therefore, it was impossible to reproduce the measured temperatures at various heights in the hall.

The simulations results also revealed that the automated integration in lighting, heat recovery, and door operation can dramatically reduce the amount of energy consumption. It was also found that achieving 10–60% reduction in energy consumption is possible depending upon the building and HVAC performance qualities.

The measured thermal energy demand could be reproduced very well in the simulations after the interior heat sources were exactly entered. To calculate the total annual energy demand for heating, it is essential to use the right mean values for both users and machineries. We plan to use multi-criterion optimization and analysis methods [96,97] and a more accurate energy audit for evaluation of thermal energy consumption for heating of industrial buildings to save more energy and expenditures.

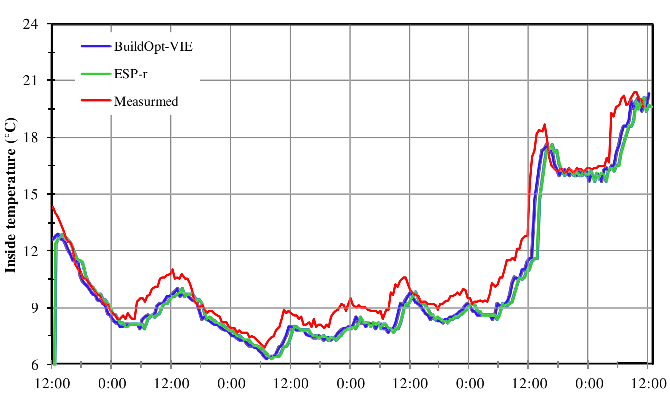

Fig. 10. Comparison of measured temperatures inside of manufacturing unit with results obtained from ESP-r and BuildOpt-VIE simulation programs.

7. Summary and conclusions

In this paper, we presented results and discussed about the optimum heating and potential energy savings in industrial buildings through implementing measurements, calculations, and simulations in a selected manufacturing hall. The local climate conditions, usage, conditions inside the industrial unit, and the construction details of the building play critical roles in the total energy consumption for heating the unit. These factors establish the hall design and some other variables affect the amount of energy used for heating. Recent increase in energy costs forces new industrial hall designers to consider energy efficiency, but presently there is no regulation with defined values related to thermal energy.

The amounts of thermal energy consumption, calculated according to the present Slovakian national standard, was most closely correlated to the measured energy consumption values when the calculations were conducted with the aid of the coefficients *a* and *b* obtained from the linear regression analysis considering the heating degree days. From the regression analysis, no other function of the energy increase per heating degree day was found to predict the in-situ measurements of the amount of thermal energy consumption. The calculated results of the selected manufacturing hall using the Austrian monthly balance system using typical values from the other non-residential building types lead to the conclusion that information about the internal heat gains is significant for the calculations accuracy and must be defined as accurately as possible.

From the results of this study, it is concluded that great agreement is attainable when accurate input information is available, particularly information about equipment, building occupancy, and activities inside the industrial unit. Owing to the large diversity of the shapes and types of industrial buildings, it is not easy to make a reference or set a standard building. There are several types of manufacturing units in which the thermal energy consumption profiles are comparable. Nonetheless, changes in energy consumption for heating and types of equipment must be known and categorized to define the rules for thermal energy consumption. Moreover, energy can be saved with adjusting the heating system settings and adopting a better maintenance schedule. The main finding in this study was development of a practical method to analyze and calculate the thermal energy consumptions and saving in buildings. A multi-criterion analysis and an accurate energy audit can be implemented for a better evaluation of the amount of thermal energy consumption in industrial buildings, which will be a major part of our future studies.

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