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Metrological Array of Cyber-Physical Systems. Part 3. Smart Energy-Efficient House

Ihor HNES, Marta YATSYSHYN, Yaroslav LUTSYK
National University Lviv Polytechnic, Institute of Architecture and Institute of Computer Technologies, Automation and Metrology, Bandera str., 12, Lviv, 79013, Ukraine
Tel.: +38-0322-37-50-89
E-mail: yaroslav.lutsyk@gmail.com

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Abstract: Smart energy-efficient houses as the components of Cyber-Physical Systems are developed intensively. The main stream of progress consists in the research of Smart houses' energy supply. By this option the mentioned objects are advancing from passive houses through net-zero energy houses to active houses that are capable of sharing their own accumulated energy with other components of Cyber-Physical Systems. We consider the problems of studying the metrology models and measuring the heat dissipation in such houses trying to apply network and software achievements as well as the new types of devices with improved characteristics. *Copyright © 2015 IFSA Publishing, S. L.*

Keywords: Cyber-physical System, Smart energy-efficient house, Energy supply and production, Smart sensor, Smart energetics.

1. Introduction

Smart house is a building in design, construction or operation which utilizes modern technology to manage the total lifecycle of an object and its subsystems as a whole, providing the modern level of assured operation of engineering subsystems, optimized utilization and economic consumption of energy and other resources. A distributed control system of building, such as LonWorks-based technology, combines sensors, controllers and actuators network by means of routing units.

Open architecture and the only communication protocol in network allow the use of system equipment and devices from different manufacturers, which significantly reduce the cost of system, its maintenance and operation. Controllers and sensors make up the basis of the network. The degree of system integration can be quite high and includes the controls of environment and energy supply, alarm and fire sensors subsystems, as well as security functions, access control features, check presence and residence time, control lighting, lifts and parking, video identification, and the monitoring of house engineering subsystems, its temperature and humidity.

An important factor in Smart Energy-Efficient House (further – SEEH) is engineering equipment providing comfortable accommodation. SEEH is inherent in two basic available units which are air handling unit with heat recovery and heat pump which minimize heat and energy costs; so, the inclusion of renewable energy sources in this system makes the building entirely independent.

2. The State of Problem

In this case, we are interested in underpinning functions of SEEH development. Such a function emerges as a relationship between human comfort and energy consumption what is currently the most important. Therefore, we are to study below the different aspects of researching SEEHs in this area.

Smart house, as a component of Cyber-Physical Systems (CPS), is in many aspects of its construction and operation among a number of other CPS components, which interact at different structural levels. For example, there is a direct relationship between Smart Houses and Smart Energetics that consists in principally new possibilities of power structures of SEEHs to generate energy, including electricity, and transmit it to power supply. On the other hand, Smart house can be represented as any house in line: passive house → NZE-house → active house (Fig. 1). This is due to the use of modern information-based technologies, including the use of Smart Sensors and other achievements of metrology, capable within their intellectual ability of forming their own conduct, especially in the field of energy efficiency → energy saving → energy generation, and of forming independent structure of type of Smart Houses' Grid.

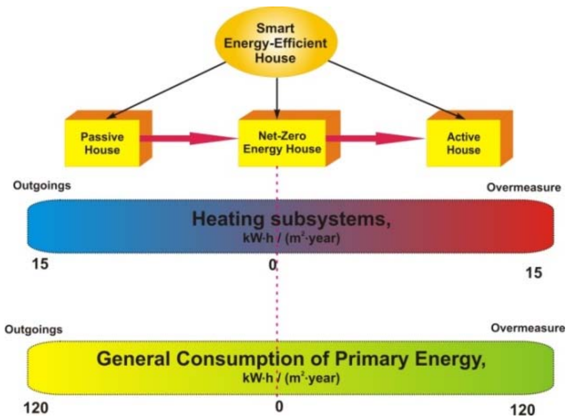

Fig. 1. Evolution of Smart Houses and level of energy consumption / generation.

For this, Smart house as an element of the latter exchanges information with central management network and determines the need for the real-time implementation of the operation. It is known that electric power supply cannot exceed its consumption in each given moment of time. That is, SEEH, with its own energy-accumulating capabilities, acts as an additional power supply unit.

The relationship between Smart House and Smart Manufacturing manifests itself in another defining bond, since electrical power and the whole infrastructure of house can be frequently applied to organizing modern production, for instance, chip crystals, or, on the contrary, to creating the high-performance SEEH with building nanostructured materials [1] and special black coverage [2].

Appropriate attention is paid to the relationship between Smart House and Smart Life Safety. As for the proper safe operation of Smart House the latter is inevitably equipped with a number of security subsystems for electricity, gas, and extremely dangerous to humans carbon monoxide, and others. Finally, already today the emergence of Smart Transports makes it possible to discuss the aspects of the interaction of this CPS component with SEEHs.

3. Shortcomings

In all cases, the effectiveness of relationships between CPS's different components is determined by their sensor equipment, management means, installed software, etc., particular attention to which is paid in [3]. However, the detailed systematic study of energy efficiency of Smart house, including the monitoring of its leading characteristics, is not sufficiently conducted, and obtained data are fragmented and unstructured resulting in the need of recurrent measurements at each object.

4. Aim of the Work

Aim of the work is to research the heat energy monitoring system of Smart house fitted with Smart sensors, and basing on the analysis of their data to develop the real-time model of energy efficiency as well as to modify the Smart Energy-Efficient House's construction.

5. Energy Aspects of Smart Houses Evolution as CPS Objects

In this regard, Program [4] perfectly appropriates for CPS Objects and namely involves "Developing measurement science that will enable rapid design-to-product transformation; in-process sensing, monitoring, and model-based optimal control; performance qualification of materials, processes and parts; and end-to-end digital implementation of … processes and systems". For SEEHs the similarly can be expressed as follows. Due to the deploy of measurement systems, energy monitoring, horizontal and vertical interlinks of CPS's various types, we have to achieve the real-time and efficient management of the Smart Houses on the basis of procedures for ongoing assessment of SEEH situation, power input/output regulation while considering energy state, reserve, environmental conditions, etc.

5.1. Heat and Energy Approaches

Primarily, we consider the passive house. Its main feature seems to be low power consumption, equal to

~10 % of the specific energy per unit volume that is consumed by ordinary buildings. Lower consumption is achieved especially by reducing the heat loss of the building.

Architectural concept of the passive house is based on the principles of compactness, high-quality and effective heat insulation, lack of cold bridges in materials and junctions sites, the correct geometry of the building, and orientation to the cardinal point. From among active methods in a passive house one can propose, for instance, the obligatory application of balanced ventilation with heat recovery. Ideally, such a passive house becomes energy independent (NZE House). The latter does not require energy expenditure on a comfortable temperature support. Recently two new Passive House Standards were introduced by Canadian Passive House Institute to the North American audience in the keynote address by Dr. Wolfgang Feist: Passive House Plus and Passive House Premium.

Heating a passive house should take place thanks to energy that has been released by appliances and people who live in it. If additional heating is necessary, it is desirable to use alternative energy sources. Hot water may also be supplied by the units of renewable energy, such as heat pumps or solar water heaters. To solve the problem of cooling (conditioning), the house is also provided with a corresponding architectural decision and, if necessary, with additional cooling at the expense of alternative energy sources, such as geothermal heat pump.

Energy criteria in the construction of passive houses are shown in Fig. 1. Here the specific heat energy consumption for heating determined by [5] should not exceed 15 kW·h/(m²) per year. And the total primary energy consumption for all the household needs (heating, hot water and electricity) must not exceed 120 kW·h/(m²) per year.

5.2. Construction and Architecture Industry Development

5.2.1. The Current State of Materials Science, Construction and Architecture

It is necessary to consider how much this state reflects the aims of the American development program in the field of CPS [3], which, in our opinion, is ideally suited to the development of construction and architecture industry of CEEHs. The Program [4] focuses on four areas which are closely interrelated: (1) material characterization (in this paper it corresponds to Materials Science, Construction and Architecture), (2) real-time process control (here, the operation of constructed buildings), (3) process and product qualification (the choices of projects based on new materials and technologies), and (4) systems integration concerns here the implementation of projects and built houses in the environment at the 1st stage and at the 2nd stage of the formation of Smart houses' community with appreciation of their interdependent relations and impact on significantly greater areas of this very environment.

The characterization of construction materials means that they should be described by the same parameters during their operation as parts of the ready structures of buildings. However, at this stage of the formation of the modern construction industry it has not been done. Moreover, CPS metrological support principles, namely the real-time monitoring of buildings (the 2nd item of program implementation), has not been performed. The 3rd item is considered to be the main qualification process and the product which in the case of smart buildings ensures their energy efficiency at a certain level (≤-15 kW·h/(m²) per year for passive house) through zero consumption for NZE House to positive level for an active house that transmits its produced and accumulated energy to the electrical network. The 4th item relating system integration presupposes not only the integration of multiple subsystems within one building, but also vertical integration, including energy, within the set of SEEHs of local community.

5.2.2. Technical Requirements for Smart Energy-Efficient House and Its Construction

The thermal insulation of exterior walls must be sufficient to ensure closing the indoor space by covering heat shell; then, winter indoor temperature should be comfortable and exceed 15 ^{0}C. The shell creates heat insulation in every place of the house; the minimum thickness of shell insulation makes at least 25 cm while thermal conductivity coefficient λ is equal to 0.04 W/(m·K). Passive House average heat flow U of wall is equal to 0.1 W/(m^2·K), whereas for the best windows U = 0.5 W/(m^2·K).

The technology and method of performing heat insulation are essentially arbitrary. Beyond the correctly insulated ordinary walls and roof significant attention is paid to details trying to prevent the emergence of cold bridges. Even if high-quality insulation of shell is performed, there happen to be energetically unprofitable low temperature zones in the vicinity of cold bridges or other places of insulation shell discontinuity. Insufficient tightness of shell construction causes the flow of air passing into the building. In summer this means cumbersome, too high temperature in rooms, while in winter air becomes dry and, as a consequence, deteriorates the health of people. The shell is checked out with a special examination entitled the Blower Door test. By pumping air into the room and its spontaneous leakage for the given pressure difference inside and outside of the building, the total volumetric and mass flow rates of air are measured. Air exchange is considered to be optimal when all the air of the room is replaced within one hour at an excess pressure of 50 Pa. Then uncontrolled leakage through the gap in the shell should not exceed 60 % of the total volume of the space V (factor of 0.6) that is described by the expression: $50 \cdot n = 0.6 \cdot V$, m^3/h., where n is the constant.

The heat loss through the walls, roof and windows of maximum-insulated passive house is effectively reduced. Additional energy saving is possible due to the reduction of energy losses at ventilation. Therefore, the ventilation equipment with recuperative function (the degree of recovery being not lower than 75 %) is embedded. The optimal energy savings are achieved with the help of two effects. On the one hand, by means of controlled system the so-called "comfort" ventilation provides the constant flow of optimum outdated air; on the other hand, entering fresh air is warmed up in a heat exchanger by the energy of the former.

The south direction of the main facade of the building (allowed deviation from the axis being 30 % in the west or east) ensures solar energy optimum utilization. Thus, windows operate as batteries that "collect" solar energy heating the space located behind them. Special windows with triple glazing and heat transfer factor of 0.75 W/(m^{2}K) become a source of significant solar heat savings. Window space filled with special gases, such as argon or xenon, substantially reduces heat transfer. Since the building during the heating season loses energy through its external enclosure surface, the passive house construction standards require the ratio of the building's shell to the total volume of its space as small as possible.

6. The Metrological Aspects of Smart House Evolution as a CPS Object

6.1. The Methodological Basis of Consolidated Heat Engineering Calculation Method

6.1.1. Materials and Construction Elements

It becomes necessary to measure the heat conductivity of building materials during their production. For builders and architects it is sufficient to examine in projects only the certified materials products and components (windows, etc.) with known thermal characteristics. Then, the previous assessment of buildings' thermal efficiency can be carried out at the design stage. This will make it impossible to yield the heat outdoor. Building SEEH is a bit more complicated than ordinary house, though the design and construction stages require increased attention to all the details.

For example, to reduce the heat loss, it is not enough to take possibly thicker heat insulation and to cover with it the outer surface of the building. This eliminates the so-called heat bridges, where, due to the violation of the integrity of insulation shell, the heat transfer is enhanced. Unfortunately, at the design stage, having some practical experience one can eliminate some of the "cold bridges" in the enclosing shell structures. The rest of the "cold bridges" appear during the house construction and can be detected only during its operation, i.e. at temperature drop existent between the indoors and outdoors.

6.1.2. Evaluation of Heat Loss by Combined Method

Already today in the building design there should be set such characteristics of heat loss which ensure the possibility of human habitation as well as the operation of water supply and sewage in case of heating subsystem failure. Therefore, in the given work we focus on the working out thermal energy optimization principles for achieving the controlled parameters, including temperature.

6.1.3. Principles and Methods of Heat Loss Assessment

Understanding the loss origins is deemed to be helpful in simplified calculation. The latter requires the application of specific techniques based on the possibility to analyze each impact. First of all, the influence of relative size or relative parameters of thermal conductivity of different construction materials is important. Further calculation is performed according to the methodology that is more suitable for architectural design stage. The number of "effective restrictive surfaces" (walls) in each embodiment is predetermined for this aim. Hereinafter, 1-, 2-, 3-, 4- and 5-floor buildings with different length to width multiplicity are analyzed.

The number of "effective restrictive surfaces" N is the factor in the expression $Q_\Sigma = Q \cdot N$, which determines the total heat loss due to the heat conduction of restrictive surfaces that are further reduced to one apartment. In other words, N is the amount of "walls" which should be considered for assessing the total heat loss of separate apartment in a passive house; Q is the effective heat loss of averaged restrictive surface, accounted below for different values of surface area S_x and the specific effective thermal conductivity U_x of construction materials. Simultaneously the heat loss through the ceiling and the floor the area of which is larger than wall area is considered to be approximately equal to the loss through the wall. It is due to the higher heat conductivity of the latter. Then the heat loss of a single-storey passive house may be equal to 6Q, where "6" corresponds to the number of restrictive surfaces.

The heat loss of a two-storey building made of similar thermal insulation materials slightly increases, but is relatively smaller since the ceiling of ground floor serves as the basis of the next floor. Heat loss reduced to one floor is defined as $Q_{red} = Q_{\Sigma} / 2 = 5 \cdot Q$. The heat loss of a three-storey house is gradually growing, and being reduced to one floor constitutes $4.67 \cdot Q$. Whereas for a four-storey building similar loss is equal to $4.5 \cdot Q$.

The equation for estimating heat loss due to the transfer through "effective wall" is:

$$Q = U \cdot S \cdot (T_{int} - T_{ext}) \cdot t, \quad (1)$$

where the specific heat conductivity of wall U is normalized with the help of the coefficient of heat transfer resistance R. It is determined by the calculated thermal conductivity l and the thickness of insulation layer d:

$$R = d / l = 1 / U, \text{ W / (m}^2 \cdot \text{K)} \quad (2)$$

A rather interesting factor of influence is deemed to be a relative value of windows total area in the efficient wall area of a projected house $X = S_{wind} / S_{\Sigma}$. With it increasing, light intensity and room comfort grow; however, simultaneously, heat losses caused by convection and radiation also increase. Then the relative total area of pure wall without windows is determined as $1 - X$ and it becomes possible to replace the sum of products $U \cdot S$ of two constituents in the expression below with the smaller quantity of variables:

$$U_{\Sigma} S_{\Sigma} = U_{win} S_{win} + U_{wal} S_{wal} = [U_{win} X + U_{wal}(1-X)] S_{\Sigma} \quad (3)$$

Thus, the general formula for calculating heat loss reduced to one house's apartment of a certain size and shape (according to the solution adopted by an architect of a designed house) is defined as:

$$\begin{aligned} Q_{\Sigma} &= U_{\Sigma} S_{\Sigma} N (T_{int} - T_{ext}) \cdot t = \\ &= [U_{win} X + U_{wal}(1-X)] S_{\Sigma} N (T_{int} - T_{ext}) \cdot t = \\ &= aT_{int} - aT_{ext}, \end{aligned} \quad (4)$$

where a is the coefficient; T_{int}; T_{ext} are the temperatures inside and outside the house, respectively. Apparently, within studied linear model the extreme dependence on any of the set of variables is absent.

6.1.4. Development of Optimization Principles of Temperature Indoors Mode

Subsequently we concentrate our attention on parameter describing comfort conditions in a passive house with its small energy consumption. This parameter is temperature which should be established in inner rooms individually, for instance, at the level equal to 20 ± 1 °C (293 ± 1 K).

Basing on the consideration of heat energy balance, as the amount of heat revenue\expenditure energy flows, including radiation flow, one may obtain the nonlinear algebraic equation of the 4th degree concerning the indoor temperature. It is suitable for searching the optimal solution, which would be the desired temperature mode:

$$A - aT_{int} + aT_{ext} - bT_{int}^4 + bT_{ext}^4 = 0, \quad (5)$$

where A is the parameter bound with interior spaces additional heating units that include ground heat accumulator, heat exchanger, etc. The time t is included as a factor in constants A, a, b. When all the parameters are averaged over a certain period, for example, over one year, t is eliminated. So, energy balance is transformed into the power one.

For studying the operation efficiency of an auxiliary heating system the mentioned approach is ineffective. Hereinafter in the equation (5) we consider t as an additionally selected variable. The dimension of the rest of products in (5) corresponds to the sources power:

$$At_H - at_C T_{int} + at_C T_{ext}(t) - bt_R T_{int}^4 + bt_R T_{ext}^4(t) = 0, \quad (6)$$

where t_H is the duration of turned on additional heat sources (electric and gas heating, ground accumulator heating, etc.); t_C is the duration of conductive heat removal; t_R is the duration of radiant heat withdrawal (through the windows). Of course, these variables are of different magnitude.

When determining diurnal period, the main tasks are to evaluate the impact of periodic (night-time) turned on heating, for example, at t_H = 8 hours duration; to accept the average duration t_C of cooling by heat conduction through the shell enclosing; to take into account the acquisition of solar energy during the day-time (additional component in $A \cdot t_H$), and lowered heat loss due to curtained radiant cooling during the night within duration t_R. The indoor temperature T_{int} is determined from the following equation:

$$\begin{aligned} &A(t)t_H - at_C T_{int} + at_C T_{ext}(t) - bt_R T_{int}^4 + bt_R T_{ext}^4(t) = 0 \\ &at_C T_{int} + bt_R T_{int}^4 = A(t)t_H + at_C T_{ext}(t) + bt_R T_{ext}^4(t) \end{aligned} \quad (7)$$

It retained a permanent by automatics intervention, in particular, the precise level as a result of additional heating system temperature sensors operation. Temperature $T_{int} = F[T_{ext}(t); a; b; t_C; t_R; t_H; A(t)]$ depends on a number of impacts. Most magnitudes of the given above variables excluding parameter A are considered known values that are bound with interior heating by additional energy sources. The latter becomes possible to be set by the thermometer indications in apartments automatically adjusting electricity, gas or other heating power.

To compensate heat loss the required energy has to be replenished by the heat accumulator energy, since there is no restriction on its reception. The amount of accumulated energy is of primary importance in this process.

For this purpose, we estimated the energy of heat accumulator located in the house's 100 m^3 basement. The accumulator could be charged during the summer season (for known specific heat capacity and mass of basalt filler) by 3200 kW·h. It can deliver each day of winter-time up to 4.4 kW·h. of heat energy within 8-hour operation.

The polynomial roots of algebraic equation of the 4th degree are defined at its numerical solution if the totals of the mentioned equation constituents tend to approach zero. Thus, for the best solution this equation should be recorded in a specified form. Within the energy concept, the following equation the constituents of which include a temporal factor was obtained:

$$\begin{aligned} &bt_R T_{\text{int}}^4 + at_C T_{\text{int}} - at_C T_{ext}(t) - bt_R T_{ext}^4(t) - A(t)\,t_H = 0 \\ &bt_R T_{\text{int}}^4 + at_C T_{\text{int}} - C = 0, \end{aligned} \tag{8}$$

The equation (8) can be simplified in power concept while carrying out further settlements:

$$\begin{aligned} &bT_{\text{int}}^4 + aT_{\text{int}} - A(t) - aT_{ext}(t) - bT_{ext}^4(t) = 0 \\ &bT_{\text{int}}^4 + aT_{\text{int}} - C = 0 \end{aligned}, \tag{9}$$

The numerical values of the coefficients in equations (8) - (9) are determined for diurnal calculation in winter conditions: $b = C_0 K_{tr} X S_\Sigma P$, where the constant C_0 = 5.67 ·10^{-8} W/m^{2}K^4 ; K_{tr} is the transmittance of infrared radiation by window panes accepted as 0.5; X is the ratio of windows area to wall area, its value is chosen 0.2; 0.3; 0.4; S_Σ is the area of mean wall (set as 36 m^2 that corresponds to the input data of the project, based on the model standard cubic area with 12 m sides at height of 3 m); N is the number of walls reduced to one storey (N = 3.5 for a 4-storey building at 4-fold length). As a result, for X = 0.2 the coefficient b can be assessed: $b = 5.67 \cdot 10^{-8} \cdot 0.5 \cdot 0.2 \cdot 36 \cdot 3.5 = 72.7 \cdot 10^{-8}$ W/K^4. For X = 0.3; 0.4 factor b is equal to 109.0•10^{-8} and 145.4•10^{-8} W/K^4 respectively.

The constant a in the expressions (8) - (9) dependent on heat conductivity is determined for X = 0.2; U_{wall} = 0.1 W/m^{2}K; U_{win} = 0.7 W/m^{2}K, which together adjust the thermal conductivity of the wall to the value of U_{red}= 0.7•0.2 + 0.1•0.8 = 0.22 W/m^{2}K. The constant $a = U_{red} \cdot S_\Sigma \cdot N$ = 0.22•36•3.5 = 27.7 W/K is defined for accepted 36 m^2 area of the wall at N=3.5. For X = 0.3; 0.4 coefficient b is equal to 35.28 and 42.84 W/K respectively.

Also, t_C is considered to be equal to 24 hours, since conductive cooling takes place continuously. It is assumed that during the winter night of 8 hours closing window blinds completely overlaps inner radiant heat exchange with the environment; so t_R is equal to 16 hours. The factor C in (8) has 3 main components. Two of them are determined by cooling due to the thermal conductivity and radiant heat exchange with pre-determined factors a, b and the mentioned time durations. And the 3rd component relates to auxiliary heating systems the value of which is being searched. To determine them, it was previously adopted that the outdoor temperature in winter night is -3 ^{0}C = 270 K. Then aT_{ext} was defined as 27.7 W/K•270 K = 7479 W, and the reverse power radiation from the outside into apartments through windows was specified as bT_{ext}^4 = 72.7•10^{-8} ·270^4 = = 3863 W.

The solved equation of the 4th degree with pre-defined factors at unknown indoor temperature, where $A(t)$ is the power of additional energy sources (for the outside temperature of 270 K and the relative total area of windows X = 0.2), is as follows:

$$\Sigma A_i(t) t_H = 72.7 \cdot 10^{-8} t_R T_{\text{int}}^4 + 27.7\, t_C T_{\text{int}} - 479 t_C - 3863 t_R \tag{10}$$

For the outdoor temperature of 270 K and the relative total windows area X = 0.3, the last equation changes into:

$$\Sigma A_i(t) t_H = 109.1 \cdot 10^{-8} t_R T_{\text{int}}^4 + 35.3 t_C T_{\text{int}} - 9527 t_C - 5794 t_R \tag{11}$$

At the relative total area X = 0.4 and the same temperature outside, the similar equation is:

$$\Sigma A_i(t) t_H = 145.4 \cdot 10^{-8} t_R T_{\text{int}}^4 + 42.8 t_C T_{\text{int}} - 11567 t_C - 7726 t_R \tag{12}$$

The determined power of sources $\Sigma A_i(t)$ that are responsible for heating at the given duration must compensate the heat loss of one apartment area of 12^2 m^2 (external dimensions) or of 11^2 m^2 (internal dimensions).

Energy sources should be divided into special types (heat accumulator with solar collector, insolation through windows, air/water heat exchanger, geothermal heat pump, solar batteries, etc.) and reserve types (boilers with gas and electric heating and others similar devices). The latter are not considered below believing that for the proper execution of the project one can get rid of them.

6.1.5. The Determination of Indoor Temperature in Winter

To begin, we assume that A = 0 and by applying software we define the temperature inside T_{int}, at which the value of the left side of (12) tends to 0. Then the increment of temperature is set and the necessary heating power is determined. Calculation results are shown in Table 1. As one can see, at the relative total windows area of $X = 0.2$ and power of $A = 1.63$ kW the acceptable temperature of 293 K is reached.

The calculations given above relate to one embodiment of the architectural and construction project that combines the use of specific building materials and of certain architectural methods to reduce heat loss to a tolerable level. If to use other building materials, techniques and approaches, it becomes necessary to change the values of factors in calculations. To accelerate and reduce the cost of designing, it should be automated with advanced computer technology application. For its creation we used the following expression that summarizes the formulas above.

Table 1. The required additional heating power A of a 4-storey passive house (at the outside temperature of 270 K) depending on the preset indoor temperature T_{int}, K for different values of factor X.

T_{int}, K / X	280	285	290	293	295	300
0,2	0,68	1,04	1,41	1,63	1,79	2,18
0,3	0,98	1,48	2	2,33	2,55	3,11
0,4	1,24	1,89	2,56	2,98	3,29	3,99

The values of power A include the heat power radiated by electric lights, refrigerator, etc.

$$\Sigma K_i = aXS_\Sigma N_{real}T_{int}^4 + \left[U_b X + U_w(1-X)\right]S_\Sigma PT_{int} - \\ -aXS_\Sigma N_{real}T_{ext}^4 - \left[U_b X + U_w(1-X)\right]S_\Sigma PT_{ext}, \quad (13)$$

where, the total value of power minimized for different energy sources is defined as:

$$\Sigma K_i(t) = A_{H-ac}(t) + B_{Insol}(t) + C_{S\_bat}(t) + \\ +D_{Geoterm}(t) + E_{rek}(t) + F_{Res\_source}(t), \quad (14)$$

where the 1st constituent concerns the heat power of accumulator, the 2nd one is an insolation power, the 3rd one concerns an electric solar cell power, the 4th one - geothermal heat pipe power, the 5th constituent is equal to the recuperation power, and the 6th constituent is a non-renewable backup.

The expressions (7)-(9) determine the mathematical foundations and with the help of software package *Excel* form the methodology for estimating the energy / power efficiency of designed SEEHs. The latter is not based on article by article balance of heat loss and heat income, as it is recommended by [5], but is based upon the evaluation of maintaining the optimal temperature conditions in interior rooms [6]. Here the values of thermal characteristics of used building materials and structures serve as variables specified with a certain increments at a particular indoor and smoothly changing outdoor temperature ranges.

The latter corresponds to the ambient temperature and even temperature of the outer surface of walls, which do not always coincide with each other (in particular, while coating the exterior walls with a special black coverage [2]). However, the method enables us to specify certain values of transmission coefficients of window structures in infrared spectrum, to alter discretely the interior insolation during the day-time, and to reverse radiation at night-time.

As a result, at the predetermined temperature of SEEH interior (in the given case it is equal to 293 K) and gauged outdoor temperature (environment or/and wall surface), on the basis of the solution of equation (13) with specific the additional sources of energy supply described by (14) we can obtain the results of the examination for every considered architectural and engineering project at the design stage. These results could be expressed in a graphic dependency due to input data.

6.2. The Metrological Study of Heat Energy Balance

It is worth noting that according to EU Norms the buildings after reconstruction (at the area over 100 m^2) are subjects to compulsory testing on heat insulation loss not exceeding the normalized values, which are different in certain countries.

We developed three methods for the study of heat loss which are applied at various stages of research. The 1st one is based on the thermal imaging (by Fluke TI25), which gives momentary picture of the building. The 2nd method envisages the examination of heat loss over a long time, but at one point of the building shell through readings of 2 Chipset types ATMEL with built-in temperature sensors. Circuits are connected by conductor or wirelessly, and the heat loss of the given element can be determined for the known thickness of shell and its specific thermal conductivity. The 3rd method in time-spatial sense represents the superposition of the first two. According to it all the points of a gauged surface are consistently surveyed by a narrowly directed photodiode, and the direction to a particular point on the surface is given by 2 stepping motors with mutually perpendicular directions of rotation and displacement of enshrined photodiode.

Main results of the research. By applying the thermal imager we investigated the initial state of Inter-district hospital heat insulation which preceded the EU grant reconstruction. It was carried out by the outside and inside tomography in winter conditions in the presence of the operating heating system. A certain amount of cold bridges was fixed, such as construction defects, quasi-closed openings of water and gas supply, as well as points of poor quality operation of electrical equipment (extra heating of sockets), and significant heat emission through windows (Fig. 2).

Relying on performed studies by the certain (Fourier law) expression: $Q = \lambda \frac{\Delta T}{d}$, where λ is the thermal conductivity of wall; ΔT is the measured temperature drop on the wall; d is the thickness of wall; we calculated the heat losses under known λ, d.

The calculation of the impact of cold bridge (Fig. 3) seems to more complicated, since there is a priori unknown velocity of air through the given bridge.

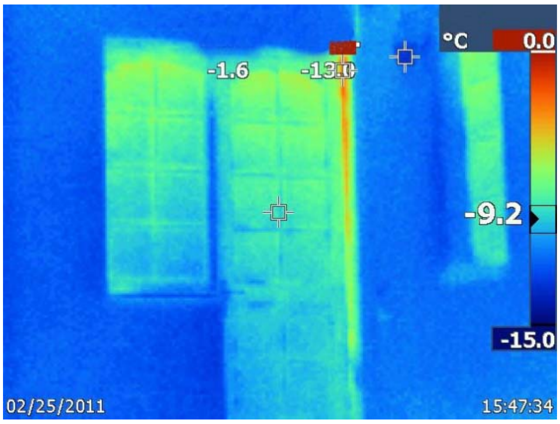

Fig. 2. Thermogram of studied building (view from outside).

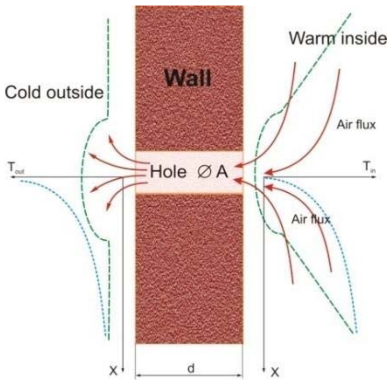

Fig. 3. Distribution of temperature outside and inside the walls of thickness *d* with an existing cold bridge of diameter *A*.

However, setting the boundary conditions for this task, basing on the obtained temperature distribution on the outer and inner surfaces of the walls, and developed mathematical apparatus [7] of solving such problems in applied heat engineering, it becomes possible to define the heat loss in our case. Thus, the error of heat flux determination depends on the error of temperature field gauging, the relative velocity of convective flux that is the function of diameter of hole.

Energy exchange devices as technical equipment are considered to be an important factor in SEEHs. Optimal living conditions can be achieved only with modern engineering. The combination of at least two units enables to reach comfortable living conditions with minimum costs and makes the building energy-sufficient (Net-Zero Energy House).

Here can be used three or more basic units of energy exchange devices. These are the heliosystem with basalt filler in SEEH basement; the solar cells on the roof or around the house as the source of additional power; balanced ventilation with heat recovery; heat pump, including a series of exchange chambers, and a device for geothermal energy usage. The energy-efficient devices that apply the heat of substance phase transition are still being developed.

However, intensive radiation through the windows (Fig. 2) worsens the energy balance of a house. Therefore, we can recommend applying electric-driven automatics for screening the windows at night-time by curtains. This decreases the heat loss through windows threefold that corresponds to the diurnal heat loss of 30 ... 40 %.

As shown above, additional energy efficiency can be achieved if air enters the building through underground duct. Then, it becomes easier to maintain the comfortable environment in SEEHs.

Taking into account mutual influence of closely located similar houses through air and ground, the grid of houses in contemporary suburbs can be regarded as a unified ecosystem with gauged and controlled reproducible characteristics. So problem of full compensation of energy losses and restoration of resources and ecological reserves should already be considered in such grid's design, construction and operation.

7. Conclusions

1. The construction of Smart energy-efficient houses requires qualified approach to architectural design which is provided not only by using the high-quality heat insulating materials and structural elements, but also by modern research methods, calculation and evaluation of heat energy characteristics. The studies of house's heat energy balance emphasize that optimal temperature mode with minimum energy consumption is achieved through a series of architectural, construction and engineering steps, including the usage of installed energy exchange devices, appropriate software and a number of special events at simultaneous monitoring the temperature mode and other modes, for example, by thermal imager.

2. Software enables to take into account a large number of parameters (the thermal conductivity of various building materials and structural elements, the relative area of glazing, etc.) and the availability of embedded smart sensors. They allow tracking the features of removal and dissipation of heat and its accumulation in the form of electric or any other energy, thus, improving the energy efficiency of a house.

3. The next stage of smart house development should be establishing the structures with adaptive

properties of enclosing shells that depend on environmental alterations. Specifications must be adapted to change, even within a day, as, for example, it is provided in the enhanced fire detectors [8].

4. The requirement of full compensation of house's energy consumption and resources' reduction results in the formation of Smart Houses Set with its impact on the environment and in strengthening the information and energy exchange with Smart Energetics Grid, improving the operation of the region's critical infrastructure.

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