MODERN ANALYSIS AND SIMULATION TOOLS AND SKILLS FOR THE EVALUATION AND DESIGN OF URBAN PROJECTS

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Abstract

Currently most of the growth of the human population takes place in the cities. Urban areas become more densely populated. Simultaneously cities are recognized as the leading producers of CO_2 emissions. For these reasons, in the coming years, reducing energy use and mitigating air pollution in the cities will be critical.

For decades, urban planners have attempted to make cities more sustainable and energy efficient. However, understanding the complex interactions among all factors, the environment and urban microclimates on citywide scales is a complicated challenge.

Only in recent years development of computer programs in BIM standard have enabled comprehensive large-scale simulations and analyzes of urban environments.

3D-CAD software modeling tools includes an interactive virtual environment that examines the dynamic physical processes associated with energy use and pollutant dispersion in settings ranging from neighborhoods to cities and metropolitan areas.

Energy inventory in an urban scale, organized by the municipal authorities is nowadays the most justified. With the capabilities of modern software such task is feasible and economically viable. Inventory should based on simplified models of the buildings with the most important parameters such as:

- basic dimensions and volume of buildings
- description of thermal insulation of the building envelope
- surface and thermal properties of windows
- the source of heating and hot water
- the solution of ventilation system in the building

Introduction - urban projects with the task of reducing CO_2 emissions

More and more urban authorities take comprehensive actions to reduce CO_2 emissions. The activities undertaken directly are intended to reduce CO_2 emissions by investing in thermal renovations and modern HVAC systems equipment. The indirect actions have to alert the local communities that they need radical changes in terms of energy efficiency. They also point to savings potential in increasing the energy efficiency.

The most important operations [1] require in the initial stage a detailed inventory of the individual buildings, including their energy parameters:

- Thermal modernization of municipal and private buildings is contribute to improving their energy efficiency, and thus to reduce the energy consumption and the cost of its purchase. As a part of the modernization measures are carried out replacement of windows, thermal insulation of walls, roofs and modernization of central heating
- Comprehensive modernization of street lighting is taken in order to reduce electricity consumption for lighting purposes of urban spaces. The investment allow for a significant improvement in energy efficiency of street lighting and significantly improve the standard of lighting and security on the streets.
- Change of the sources of heating systems in a single-family and multi-family buildings with heating furnace which use coal as a fuel. It is assumed that activities related to the change of fuel used and modernization of boiler, undertaken by the inhabitants from inspiration or with the support of the community will help to reduce emissions associated with the burning of coal for heating purposes.
- Changing of the behavior of inhabitants aftermath of promotional and educational information conducted by the municipality. This activity will be carried out various stocks of promotional and educational informations, designed to raise awareness of the inhabitants of the potential energy savings possibilities, that binds to the thermal efficiency of buildings, the change of the fuel used to heating, the use of renewable energy and a change in behavior.
- Monitoring of energy consumption. Start of the system of monitoring of media consumption, based on remote meter reading, which will allow the creation of a territorial unit of a comprehensive energy management system and identify potential energy savings opportunities. According to the data from the literature, the start of monitoring of electricity consumption allows to achieve savings of at least 5% level. These savings result from a change in the way on which consumers use energy, from organizational changes and from formal and legal rules (adjustment of tariffs, capacity ordered).

Energy inventories in the urban scale are becoming an essential element of all these activities.

Integrated Energy Design - IED

Evaluation and verification of buildings, both existing and newly designed in terms of their energy efficiency requires to use an *Integrated Energy Design* (IED) principles.

In the case of newly designed buildings *Integrated Energy Design* (IED) means adopting the following rules [2]:

- IED process is based on the well-proven observation that changes and improvements in the design process are relatively easy to make at the beginning of the process, but become increasingly difficult and disruptive as the process unfolds.
- IED aims to collaborate in the design team (builder, architect, engineer) from the earliest stages of the project.

- IED also focuses on the influence each part of the design has on the whole construction. E.g. ventilation strategies will have an effect on the thermal indoor climate, fire conditions and is affected by daylight.
- IED requires to shift the main burden of work on the stage of conception and introduction of appropriate tools supporting the design in the form of specialized software.

In the case of inventory of existing buildings *Integrated Energy Design* (IED) means introduction to project not only the dimensions of the building but also the physical data of building materials, layer systems with thicknesses of individual layers, the parameters of heating, ventilation and hot water installations, etc.

Thus inventory of existing buildings with their energy aspect on the urban scale requires, like the design of individual buildings , reorganization of process of creating virtual spatial map of the city.

The necessary tools

BIM - *Building Information Modeling* [3] means to create, using the appropriate software, a vast database to accurately define each part of the building (construction materials and their properties, equipment, etc.), and structured in three-dimensional space as a virtual 3D model.

Designing a building as a virtual spatial model, in which are conducted all the parameters of a real object, such as eg. A layer partitions with specific materials and their physical properties, performance, prices, etc. BIM allows already at a very early stage of planning to carry out various types of analysis and simulation.

BIM is a tool, which, as in the case of newly designed buildings can be used for 3D inventory of existing buildings.

Following parameters (the most important among others) should be defined already in the early stage of development of the design concept of the building:

- carefully parameterized construction of the building envelope (layered structures for all partitions)
  - predetermined thicknesses of the individual layers of partitions
  - certain building materials, along with their associated physical parameters (calculated heat transfer coefficient, density, etc.)
- window holes with the specified parameters of windows and doors frames
  - the windows surface
  - physical parameters of windows and method of fixing them in the wall
- construction of the building, as a significant mass which is accumulating heat, diverse as structures with a different weights
  - heavy (concrete structures), > 400 kg/ 1 m^2 of usable space
  - medium (masonry structures), 250-400 kg/ 1 m^2 of usable space
  - lightweight (wood- and metal-frame structures), < 250 kg/ 1 m^2 of usable space
- level of air infiltration through the building’s partitions in a hourly energy balance and total air infiltration (ACH) to the following distinction:
  - up to 0,6 l/s,m^2 is a low value (for passive building)

- up to 1,0 l/s,m^2 is an average value (as in a low-energy reference building)
- from 1,5 l/s,m^2 is a high infiltration (as in a building with a standard mechanical ventilation)
- from 3,0 l/s,m^2 is a very high infiltration (as in a building with natural, gravity ventilation)

After creating a virtual building model in BIM software we can then converts it into so-called BEM model - *Building Energy Model* [4]. This step requires to model the virtual 3D building as accurately as posible and then bring in 2 additional types of data:

- Data related to a specific location:
- geographic location and terrain altitude
- statistical average weather data
  - air temperature
  - relative humidity
  - sunlight (depending on the angle of the sun for a given location)
  - speed and direction of the prevailing winds
- nearest surroundings of the building
- degree of horizontal shading
- Indoor air data with projected temperatures in interiors with different functionalities

BEM (also like a BIM) is a tool, which as in the case of newly designed buildings can be used for 3D inventory of existing buildings.

There is not a big problem (either necessary time or technical) to collect these data from existing buildings. So the principles of integrated energy design can be effectively used also for inventory and projects in urban scale. Such a task involves on assigning to the individual, inventoried buildings more data than in the case of just purely virtual model with shape data only. These data, in the case of urban inventories must be collected (parallel to measurements of existing buildings) as a appropriate surveys and application informations, on the kind of checklist.

In the energy inventories in urban scale (before starting work) it is important only to determine the required degree of accuracy and degree of approximation accuracy of the results.

Sample group of four buildings

As an example of the procedure of creating an energy inventory map of the city it was taken 4 similar buildings, differing in technical parameters.

- The first of the buildings is energy-efficient building in "l*ow-energy standard NF40*" [5] ,
  - very good level of thermal insulation (for walls, roof, windows and doors)
  - mechanical intake-exhaust ventilation system with heat recovery
  - building located on the north-south axis with large south windows
  - temperature zoning
  - gas furnace with an efficiency of over 90% of the total system, etc.
- The second buildings is a building identical to the first but with a different orientation relative to the east-west direction (rotated by 90 degrees).

- Third of the buildings is a building identical to the first but with unheated basement, with area of 85,0 m², where there is a garage for 2 cars and cellars.
- Fourth of the buildings is a traditional building, with a standard technology solutions, with natural gravity ventilation, correct with obligatory Building Law in Poland.
  - smaller windows area
  - air tightness on a level n50 = 3.0 ac / h (building with gravity ventilation)
  - heat transfer coefficients on much worse level than in a reference building (for walls, roof, windows and doors)
  - gas furnace with an efficiency of 80% of the total system
  - building without temperature zoning
  - energy-consuming bulbs in lamps, etc.

Models are simplified although have parameterized parameters such as:

- thermal insulation of external elements of the buildings
- main construction materials with physical properties,
- surface and thermal properties of windows
- design assumptions for ventilation, heating and hot water installations
- description of the technical building equipment and lighting

These four examples show that collecting such data in the form of a questionnaire takes a very short time and it can be applied to any existing building. Also simplified dimensions of the building are available relatively fast and allow you to quickly perform virtual computer model of the building.
Based on basic dimensions and collected data each of the four buildings has been modeled in the BIM standard computer program - *Archicad 19* [6].
Energy efficiency analysis of these four buildings, have been prepared in specialized computer program for energy analysis - *Design Builder* [7].

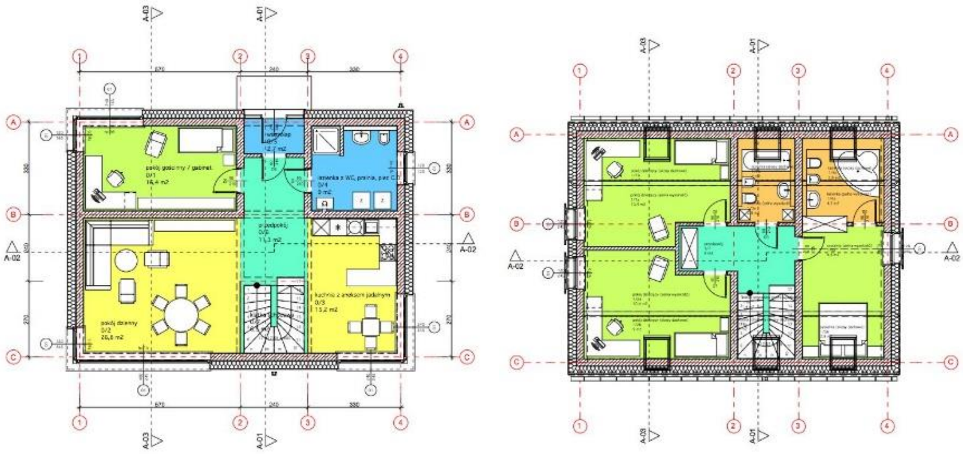
Description of a basic reference building model

In the comparative analyzes in the urban scale, which are prepared to promote buildings with high energy efficiency and to draw attention to substandard buildings, there is need to adopt a point of reference. In the example, shown in this article as a reference point, there is a family residential building with a low-energy standard.
The level of energy efficiency of buildings consists of many factors. To determine the degree of influence of each of them, as a point of reference was designed original reference building that meets the requirements for a low-energy buildings. Then, in this building, introducing a variant design solutions, were conducted comparative studies and research on the profit and loss of energy, final energy consumption and the level of comfort and overheating.

Basic model Building is a semi-detached single family house with 170 m² living area. A building with a simple geometry has been chosen in order to keep the envelope area evaluation transparent. One storey and the attic is located inside the thermal envelope.

- On the ground floor there is a living room and kitchen with dining area and an additional room that can be serve as office work place or additional guest room. Bathroom and W.C. on the ground floor, in particular version of a building without a basement, is intended to perform additional functions, ie. laundry and space for two-circuit boiler for central heating and hot water. At the entrance vestibule first part was planned as a kind of sluice, recommended in our climate zone. The open staircase separates optically the open living part.
- The usable area of the ground level corresponds to floor plan on the 1st floor, which was located more intimate part of the house - master bedroom with adjoining bathroom with a W.C. and two children's rooms and a bathroom with W.C. available from the corridor. To achieve the necessary amount of functional space under the roof slants, the construction of a pitched roof was raised on the walls on a height of 1,0 m under the eaves.

Figure 1. Horizontal plans of the ground floor and attic of the reference building



Source: original project by the author

Analysis of insolation and daylighting

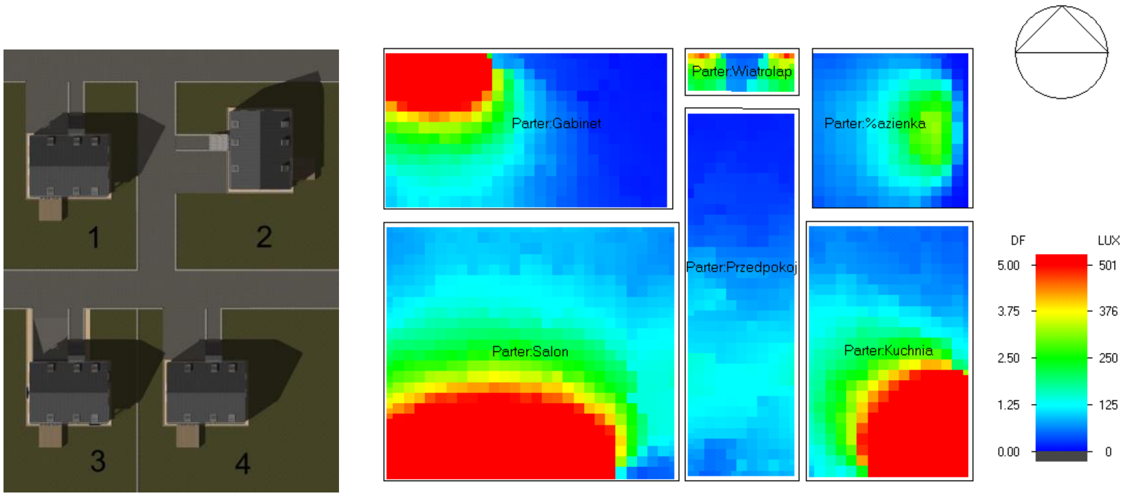
In Poland, residential buildings should be ensured duration of sunshine at least 3 hours in the days of the equinoxes (March 21 and September 21) in the 7.00-17.00. You can verify this by performing an analysis of insolation, which allows you to observe the buildings in the real situation in order to verify the conditions of sunlight at a particular location (geographic location) and time interval [8].

Exemplary analysis of sunlight for 4 buildings were prepared using ArchiCAD, with the following parameters:

- geographical location of the model and the parameters of the sun for the location in Krakow
- the date: March 21
- the time intervals:7.00 / 9.00 / 11.00 / 13.00 / 15.00 / 17.00

The analysis of insolation should be supplement with the analysis of daylighting.
Daylighting analysis is performed in order to check the quantity and distribution of natural light in the individual interiors.
Such analysis allows to determine the best and worst part of the building in terms of lighting.
Such analysis allows to select or change on the basis of allocation of rooms, surface glazing and choose the optimal distribution of furniture and workstations. On this basis, you can choose the destiny of rooms, evaluate the surface of windows and choose the optimal location of furnitures and workstations.
The daylighting analysis does not show the average annual lighting only lighting for specific conditions.

Figure 2. Exemplary analysis of sunlight for 4 buildings, date: March 21, time: 15.00 and daylighting analysis of a ground floor of reference building



Source: original project by the author, author's analysis in the *Design Builder* software

Final energy consumption analysis

In the analysis of the annual final energy consumption for 4 buildings, the total energy demand has been divided into the following components:

- the energy needed to operate electrical appliances,
- energy needed for lighting,
- energy needed to heat the building
- energy needed for hot water production

The results of analyzes of the annual final energy consumption for four example buildings are shown below. Due to the reduction of an article capacity, in the diagram shows only the first reference building. The other three buildings were analyzed in the same way *(Table 1).*

Table 1. Summary of the results of analyzes for the four buildings of the annual final energy consumption

[Wh/m^2]	1 Reference building in "low-energy" standard	2 The same building but rotated by 90^o	3 Building with unheated basement	4 Standard, correct with obligatory Building Law
Room electricity	17 065,63	17 065,63	16 927,71	17 058,40
Lighting	7 414,30	7 362,00	7 574,48	11 503,56
Heating (Gas)	**12 341,76 = 100%**	**14 467,80 = 117%**	**17 923,82 = 145%**	**38 084,71 = 309%**
DHW (Gas)	13 042,05	13 042,05	13 909,07	14764,83

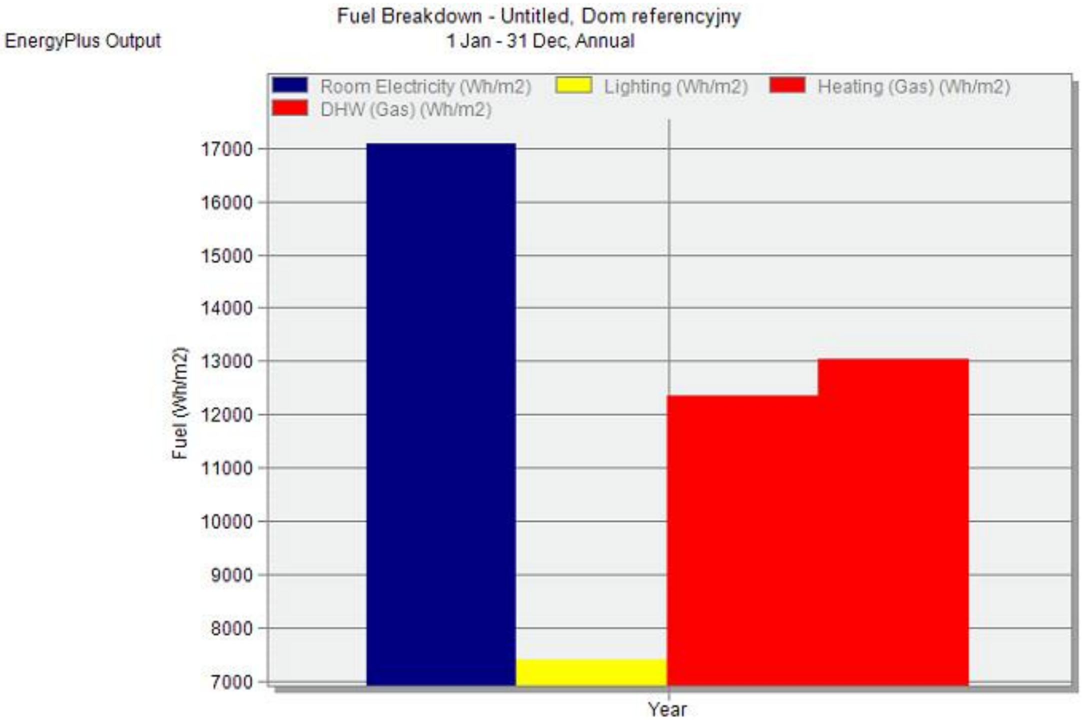
Source: author's analysis in the *Design Builder* software

Changes in final energy consumption for heating in the second building with orientation rotated by 90° stem from the fact, that basic reference house (with recommended south orientation) has the largest glazed area on the south side. If you change the orientation of the largest area of glazing, the profits from the sun decreases, and at the same time energy consumption for heating increasing.

Changes in final energy consumption for heating in the third building (with a cold basement) stem from the fact, that the basement ceiling is not insulated from the side of unheated basement space and it is a reason of a strong loss of heat from upper heating level to down.

In the fourth building (with increased energy consumption) consumption of energy for heating rises three times above the level in the reference building. Final energy needed for hot water increased due to the lower efficiency of the heating system than at reference building. Final energy to electrical equipment remained unchanged, while the energy needed for lighting increased due to the use of energy-consuming light bulbs.

Figure 3. Analysis of the annual final energy consumption for the first, reference building



Room Electricity (Wh/m2)	17065,63
Lighting (Wh/m2)	7414,30
Heating (Gas) (Wh/m2)	12341,76
DHW (Gas) (Wh/m2)	13042,05

Source: author's analysis in the *Design Builder* software

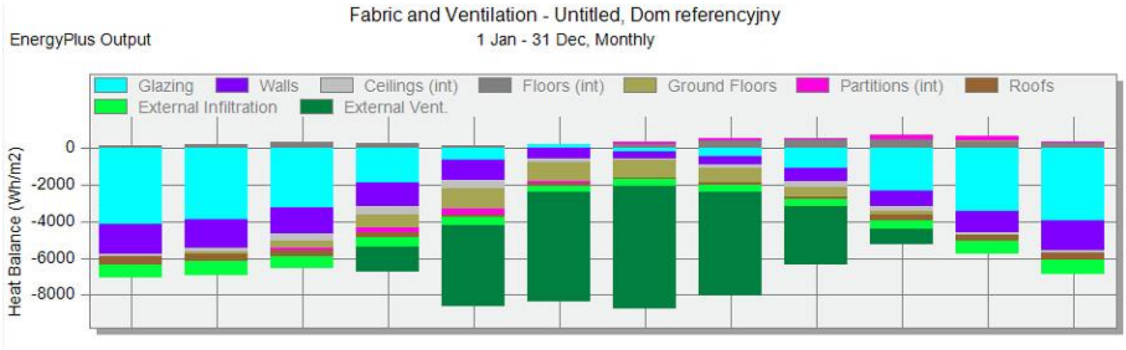
More detailed analysis

Energy inventorys of buildings, depending on their degree of accuracy, also allows a more detailed analysis.

Figure 4 shows the analysis of energy consumption, on the example of the reference building, divided into individual month periods.

Chart, showing monthly losses through partitions and ventilation allows for the conclusions - the high value of the losses by ventilation during summer time is caused by increased exchange of air through a system of mechanical ventilation supply and exhaust, in order to reduce the temperature indoors. If we assume a building ventilation by opening windows, it is the energy that we can draw from the account statement.

Figure 4. Analysis of monthly energy loss in a building - first building (low-energy standard):

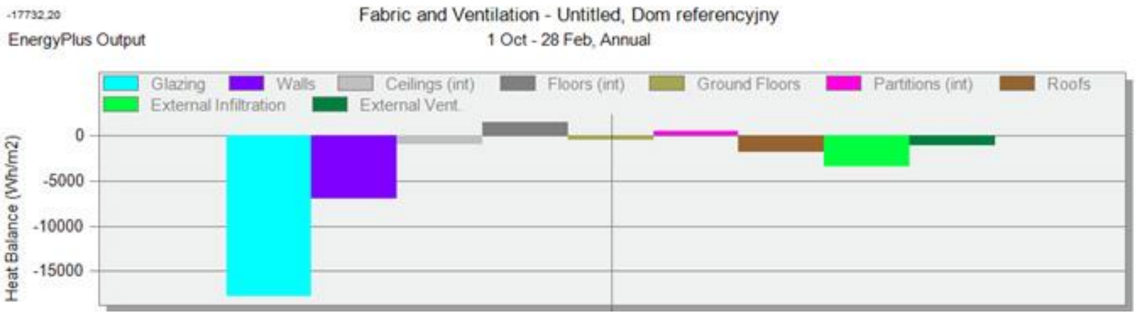


Source: author's analysis in the *Design Builder* software

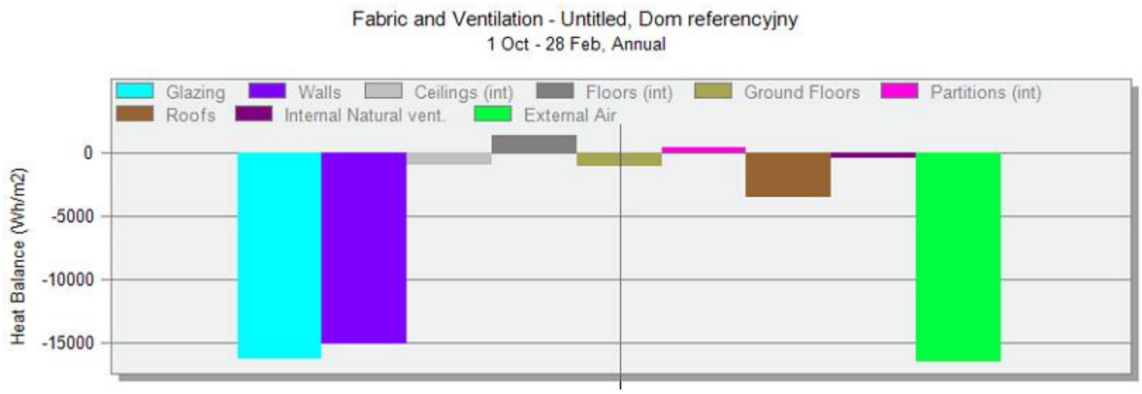
We can also reduce analysis time in a building only to a winter time and compare it with a similar analysis of the building No. 4 with a gravitational ventilation system (*Figure 5)*
Characteristic for the first energy-efficient building is the analysis of energy losses, carried out only for the winter period from 1 October to 28 February. It shows a relatively large energy losses through the window. These losses do not stem from the bad performance of windows used only with very high performance thermal insulation of external walls, with the result that the proportion of energy loss through windows grow.
Below, the analysis of the traditional building shows that the total energy losses are much higher than in the first building - energy-saving. You should also pay attention to the change in the proportion of the percentage ratio of heat loss through the various partition in both buildings.

Figure 5. Analysis of energy lost through the partition in the winter

a) First building (low-energy reference building):



b) Forth building (traditional building with gravity ventilation):



Source: author's analysis in the *Design Builder* software

Conclusions

The results of above example analyzes can be used in many ways according to the needs. Placing parameterized models to the oriented map, with location of the sun and the local climate parameters allows creating the energy map of the city. One or more parameters - such for example like the amount of energy needed for heating can be assigned to a specific building on the city map. On such way it is easy to convert traditional map into the energy map - just by assigning corresponding colors to the digital data. Simultaneously modern engineering software allows to enter data relatively quickly and easily.

No doubt it would be very beneficial if every building in the city held a kind of file with such energy analyzes, at the same time reflected graphically on the city map.

Main, modern analysis and simulation tools and skills for the evaluation and design of urban projects should concern of thermal energy and solar impact:

- Energy/Thermal Maps - estimation of energy consumption and heating demand of the urban fabric and quantification (estimation) of energy demand, use as a support for energy action plans
- Solar Access - number of hours of direct sun (or accumulated shadow), solar accessibility maps of urban areas through hourly shadow maps, quantification of surfaces interested by direct sun or shadow, shadow density maps on open areas and superimposition of hourly shadow maps, use for evaluation of solar accessibility conditions of urban forms or design projects.
- Solar Irradiation - solar irradiation maps of urban areas with quantification of collected irradiation on surfaces (roofs, open spaces, etc.) for the estimation of possible solar energy production.
- Thermal Discomfort Critical maps, showing potential thermal discomfort on open areas, use for programming punctual interventions on urban spaces

Virtual modeled city also allows further, detailed analysis depending on our needs, like:

- Wind simulations - the effect of wind between buildings
- Sound simulations - reconstruction of existing and simulation of future soundscapes in the urban environment
- Visibility Analysis - quantification of visible objects in the urban landscapes and degree of visibility of a selected object from the surrounding
- Sky View Factor - quantification of sky view factor on the ground, on roofs, on the entire urban area.
- Urban Accessibility and Connectivity - the graph of the street network, which allows the development of connectivity and accessibility indicators,
- etc.

By consuming energy, materials, and land, construction and housing is responsible for a considerable proportion of environmental burdens in a densely polulated, industrialized country like Poland. Therefore, this field of action has key importance for sustainable development. Sustainable development has to be achieved in real fields of action.
The owners of apartments and houses play a key role in influencing one-off (at the construction stage) and ongoing (in the building operation phase) energy and material flows. This group, however, is highly heterogeneous.
Analysis of these strategies delivers the basis for linking them to indicators and tools for identifying and influencing environmentally relevant effects.

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