World Transactions on Engineering and Technology Education
Vol.14, No.4, 2016

Smart project, building and city - multi-criteria optimisation of the design process in the education of architecture students

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ABSTRACT: Current building designs and urban plans are becoming more and more complicated and demand the analysis of an ever-increasing number of criteria. High technical, operational and energy parameters can be achieved only under the condition of carrying out a series of simulations during the early stages of design. The curriculum of architectural programmes should be tailored to modern needs. In order for the process of the design of buildings and urban layouts to be efficient and to provide appropriate design solutions, the curriculum needs to be comprehensively changed, so that architecture students can adopt new standards regarding design methodology and learn to use the latest computer aided design software.

INTRODUCTION

The need for change and the inability to maintain the *status quo* are at the base of every revolution. In architecture and construction, there are two fields in which the changes that have recently occurred can be called revolutionary. The first of these changes is the energy revolution, which has engulfed numerous European countries and is inevitably coming ever closer to Poland. The design of energy efficient buildings is ceasing to become an exclusive alternative, but a common necessity, arising from environmental, economic and social conditions, as well as the current legal regulations. The question here is whether the principles of energy efficient design and construction of buildings can become common or whether people are still going to be subjected to the enormous cost of purchasing energy on the one hand, and breathing air polluted by so-called *low emissions*, without any perspective for improvement on the other?

The second change is the digital revolution in architecture and construction due to the introduction of building information modelling (BIM) computer software, which enables design (understood to be the construction of a building's virtual model), to be tied with creating databases containing detailed technical and physical parameters, as well as enabling the carrying out of various types of simulations. It needs to be remembered that the architect is responsible for organising the entirety of the design process, the drafting of guidelines for the detailed documentation of other branches of civil engineering, organising cooperation with experts and civil engineers and, finally, for the overall coherence and quality of design documentation. These disciplines, which appear to be different from each other and in which the above revolutionary changes have occurred, are strictly mutually tied together. It is practically impossible to design and build an energy efficient building in a *low energy* or *passive* standard without the use of proper tools in the form of BIM software. Both, the energy and the software revolution, should also immediately revolutionise university curricula used in the education of architects.

The postulated change to the curriculum of architecture students can be divided into three distinct problem groups:

1. *Smart project* - the introduction of BIM standard software as a design tool. This enables the conduct of design in a manner, which resembles the construction of a virtual model of a building, while at the same time creating a database, which contains its detailed technical parameters. A distinct feature of design using BIM is a shift in workload towards the early phases of the design process (the conceptual design stage), where the opportunities to influence the design's effectiveness are the greatest, while lowering costs and limiting difficulties associated with it. Designs developed using BIM should then be verified using building energy model (BEM) software, which facilitates analysis of the energy efficiency of a building. The methodology of the modern design process is described as IED (integrated energy design).
2. *Smart building* - all elements of an architectural design - precisely parameterised - are important and need to be comprehensively analysed. Designs should be developed in accordance with the principles of sustainable

development. This means, for instance, the introduction of life cycle assessment indicators, which are meant to determine and evaluate potential hazards to the environment, starting at the stage of the production of construction materials, through the construction and operation stages, all the way to a building's demolition and recycling phase.

3. *Smart city* - on the urban scale, the use of BIM software makes it possible to carry out an entire range of analyses, which are either difficult or outright impossible to perform without these tools. These include daylighting and shade analyses, etc, and when more detailed documentation is concerned, urban scale energy efficiency maps.

MAIN GROUPS OF PROBLEMS WHICH NEED TO BE ADDRESSED IN THE TRADITIONAL SYSTEMS OF EDUCATING ARCHITECTS

Smart Project

The term *smart project*, in short, stands for a set of modern means of an architect's work, featuring tools that aid in design. Its implementation and spread on architecture faculties is difficult, expensive and time consuming, but is also necessary, if one wants to provide future architects with world class education.

BIM - Building Information Modelling

BIM stands for the creation of a virtual 3D model of a building along with an enormous database, which precisely defines every part of it (its structure, materials and their properties, furnishings, etc), ordered within a three-dimensional space, with the use of appropriate software [1]. A BIM design is developed with the use of three-dimensional objects, such as walls, floor slabs, roofs, ceilings, windows, doors, etc, which apart from their geometric dimensions, are assigned with appropriate parameters (physical and technical properties, etc). The integration of information within a single database enables the automatic identification of introduced changes, as well as collision detection. A building's model can be verified and added to with various types of schedules, timetables, cost assessments, etc.

The introduction of BIM software into university curricula for architects allows the design of buildings in the form of virtual three-dimensional models, which have all the parameters of a real-world building, such as having materials, their physical properties, technical parameters, costs and other elements assigned to each layer of a partition. This allows for various types of analyses and simulations to be carried out during the early stages of design. Such functionality was completely unattainable in traditional designs developed using computer-aided design (CAD) software in the form two-dimensional floor plans, cross-sections and façade drawings.

One distinct difference of design in computer-aided BIM design software is the shift of the workload to the early stages of the design process (the conceptual design stage), during which the ability to influence energy effectiveness is the greatest, while at the same time being the least expensive and the least difficult [2].

BIM design software includes such digital computer-aided design platforms as: ArchiCAD (which the author recommends), Autodesk Revit, Bentley, Nemetschek Allplan, Tekla Structrures, BIMVision, etc.

BEM - Building Energy Model

Thanks to the introduction of design featuring the use of BIM software into the curriculum of the Faculty of Architecture at Cracow University of Technology, students have been given the ability to carry out numerous energy efficiency analyses of buildings being designed. Such analyses can be carried out during the early stages of design, long before the beginning of construction and the implementation of all design solutions in the real world, with the aid of simulations termed *energy modelling*. The carrying out of such simulations requires the construction of a faithful, three-dimensional virtual model of a building with the use of appropriate computer-aided BIM design software, in which all partitions have a layered structure with properly assigned physical properties (mass, specific heat capacity, heat transfer coefficients, etc). Rooms are assigned their future functions and are being populated with people, furnished with computer equipment, being assigned technological processes, as well as operation timetables. The virtual building is, then, fitted with heating, ventilation, lighting, etc. The systems responsible for controlling all this infrastructure are also configured.

When data regarding the parameters of internal air that fills each room, which also entails setting the designed temperatures, assigning rooms to temperature zones, operation timetables, etc, are introduced to a properly modelled virtual architectural three-dimensional model made using BIM technology, it can be said that a BIM model is converted into the so-called building energy model - BEM [3].

A building energy model (BEM) allows for the impact of various design variants on energy efficiency to be studied (for instance in the form of different thicknesses of thermal insulation in a building's partitions), as well as for the testing of various variants of infrastructure, automatics, etc [4]. A BEM building model is placed in a real-world geographical location, which comes with a complete set of meteorological data. Typically, calculations made for the purposes of simulation are performed with a per hour frequency for each hour within a year (8,760 hours), which results in immensely precise results that are incomparable with the results obtained with an energy performance certificate for a building. Apart from the amount of energy broken down into various components (heating, cooling, pumps and ventilators) and various energy carriers, thermal comfort (PPD, PMV) can be analysed, and the performance of energy recuperation systems, etc, can be studied. The carrying out of various types of analyses for numerous variants and simulations makes it possible to attain optimal energy efficiency, as well as to verify and correct previously implemented design solutions [5][6].

IED - Integrated Energy Design

The combining of education in the field of architectural and construction design with energy analyses creates a methodology and a set of principles that are described as integrated energy design (IED) [7]. The methodology and principles of IED [2][8], which is becoming the standard of modern design, is defined as a process of organising design work in a manner that shifts the workload towards the early stages of design (to achieve higher efficiency and minimise the costs of introducing alterations and changes), as well as prioritising energy efficient, integrated architectural, structural and infrastructural solutions.

Integrated energy design in terms of educational practice also means a manner of organising the design process in such a way that various alternative design solutions are verified by the means of carrying out analyses of energy expenditure.

Smart Building

The term *smart building* constitutes a set of requirements that need to be met by designs developed by students in the form of a *checklist*.

Thus, designs are to be developed using the BIM standard, in ArchiCAD, and be of a scope that allows them to be converted into a so-called *energy model*. Design documentation should contain, among other things, the following parameters:

- A precisely parameterised structure of the external elements of a building (layer structures for all partitions):
  - specific thicknesses for each layer of a partition;
  - a selection of construction materials with their associated physical parameters (heat transfer coefficient for the purposes of calculations, density per cubic metre, etc).
- Openings with specified parameters regarding windows and doors:
  - translucent elements are introduced along with their U coefficient and thermal gains from sunlight;
  - opaque elements are presented along with their U coefficient, Psi values (linear thermal energy transfer coefficient [W/mK], which is used to calculate the effect of thermal bridges that occur at the connection between the window frame and the wall around the opening), as well as linear infiltration characteristics.
- The more important external elements, which form a mass that accumulates heat, divided into:
  - heavy (concrete structures), > 400 [kg/1 m^2] of useable area;
  - medium (masonry structures), 250-400 [kg/1 m^2] of useable area;
  - light (post and beam structures), < 250 [kg/1 m^2] of useable area.
- The level of air infiltration through a partition over an hourly energy balance, as well as the total air change rate per hour (ACH), with the following division:
  - 0,6 [l/s,m^2] is a low value (for a passive building);
  - 1,0 [l/s,m^2] is a medium value (recommended building);
  - 1,5 [l/s,m^2] is a high infiltration value (similar to a building fitted with mechanical ventilation).
- The properties of the designed material on the external surface of a layered structure, which affect the absorption characteristics of a given structure - the capacity to absorb solar energy by a given partition [%].

The energy model of the designed building should be developed in the following manner:

- The geometric analysis of the model is carried out on the basis of so-called zones, which are useable areas along with their clear height, inserted into all the rooms of a building. For the purposes of energy evaluation, these zones are grouped into so-called thermal blocks. A thermal block is either a single room or a group of rooms within a building with a similar layout, usage profile and internal temperature requirements (requirements regarding thermostatic control with a 24-hour timetable). These zones do not necessarily need to be connected with each other or even be adjacent to each other in order to be combined into a single thermal block. After configuring the thermal blocks, the virtual BIM model becomes a BEM building energy model.

The following principles regarding the defining of zones within a building should be followed:

- Separate zones should be modelled for each level of a multi-storey interior space (like a staircase or an atrium);
- The walls of the shape of the building, which delineate heated rooms are so-called adiabatic walls, which do not conduct heat;
- Determining a threshold for the minimum surface area of elements allows to filter out small elements, which are insignificant for energy balance and obtain a more concise list of elements;
- The parameterisation of openings highlights the outlines of zones in internal and external openings of a building along with physical properties, which are important for an energy simulation.

The design should include a precise geographical location with precisely stated parameters regarding the environment, climate and the building's immediate surroundings:

- Location;
- Weather data:
  - air temperature;
  - relative humidity;
  - insolation;
  - speed and direction of dominant winds.
- Type of soil;
- Immediate surroundings of the building;
- Location's elevation above sea level;
- Level of vulnerability to wind (the direction and force of dominant winds);
- Degree of horizontal shade.

In order to perform an energy evaluation, the following elements that have a significant impact on energy efficiency need to be determined:

- The types of a building's infrastructure:
  - heating - externally or locally powered (using renewable or non-renewable fuel);
  - cooling - the type and parameters of cooling mechanisms;
  - domestic hot water - the final temperature provided in ºC;
  - ventilation - natural or mechanical (with or without thermal recuperation).
- Energy sources and costs - data that allow for calculation of the needs for the main sources of energy (renewable or non-renewable), CO_2 emission, as well as yearly cost per unit of useable surface area.
- The usage profiles of thermal blocks - each thermal block is to be assigned a separate usage profile. Each usage profile is tied with a daily timetable that includes the following information, for each hour for a full year (for a total of 8,760 hours):
  - form of use - whether a room is used for residential or non-residential purposes and the associated range of interior temperature:
    - interior temperature - the permissible temperature range inside the building (maximum and minimum) during the day;
    - internal heat gain - factors which cause energy emission (internal reuse of heat) during the day, per m^2 of useable surface area [W/m^2]:
      - the number of users;
      - lighting - the type of lighting (light intensity for a given type of lighting);
      - equipment - a value describing the amount of equipment (like television sets, computers, home appliances);
    - thermal gains from occupants - the amount of heat generated by the bodies of persons inside the building (W per person);
    - energy needs for the purposes of heating water - the amount of hot water needed per person, appropriate to the associated form of use of the building (one per day per person);

- o humidity load - the amount of humidity that enters the air inside the building due to its operation (one per day).

Detailed analyses of energy expenditure for a building allow the so-called energy balance of a building to be determined, which reflects the proportions between thermal losses and gains.

Smart City

The term *smart city* reflects transferring the problem of teaching design using BIM to the scale of urban design.

The main advantages and innovation associated with the use of BIM software in urban design curricula can be described in the following manner:

Currently most of the growth of the human population takes place in the cities. Urban areas are becoming more densely populated. At the same time, cities are recognised as the leading producers of CO_2 emissions. For these reasons, in the coming years, reducing energy use and mitigating air pollution in 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 the factors, the environment and urban microclimates on citywide scales is a complicated challenge. Only in recent years, has the development of BIM computer software enabled the carrying out of comprehensive large-scale simulations and analyses of urban environments. 3D-CAD software modelling tools include an interactive virtual environment that examines the dynamic physical processes associated with energy use and pollutant dispersion in settings ranging from neighbourhoods to cities and metropolitan areas.

Studying existing energy efficiency on an urban scale has never been more justified. With the capabilities of modern software, such a task is feasible and economically viable. The study should be based on simplified models of 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 ventilation system that is used in the building.

Placing parameterised models on an oriented map, which features the position of the sun and the parameters of the local climate enables the creation of an energy map of a city. One or more parameters, such as, for example, the amount of energy needed for heating can be assigned to a specific building on the city map. This way it is easy to convert traditional map into an energy map - just by assigning corresponding colours to the digital data. At the same time, modern engineering software allows to enter data relatively quickly and easily.

Modern analysis and simulation tools, as well as the skills used in the evaluation and development of urban designs should take into account the following in terms of thermal energy and the impact of the sun:

- Energy/thermal maps - the estimation of energy consumption and heating demand of the urban fabric and the quantification (estimation) of energy demand, use as a support tool for energy action plans;
- Solar access - the number of hours of direct exposure to the sun (or accumulated shade), solar accessibility maps of urban areas that feature hourly shadow maps, the quantification of surfaces affected by direct exposure to the sun or by shadow, shadow density maps for open areas and the superimposition of hourly shadow maps, used for the evaluation of solar accessibility conditions of urban forms or designs;
- Solar irradiation - solar irradiation maps of urban areas that feature a quantification of the total irradiation of surfaces (roofs, open spaces, etc) for the purposes of estimating possible solar energy production;
- Thermal discomfort critical maps, showing potential thermal discomfort in open areas, used for programming of pinpoint interventions in urban spaces.

A virtual model of a city also allows further, detailed analysis depending on the needs, for instance:

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

CONCLUSIONS

The introduction of modern design support tools in the form of BIM software into the education system of architecture students, as well as of the methodology of the so-called integrated energy design is a revolutionary change, with an impact comparable to the previous revolution regarding the design tools that architectural design employs that happened in the 1990s, when 2D CAD software was introduced as a tool for architects, for whom the standard had previously been the drafting of design documentation by hand. The change being faced today, just as the one that was faced back then, is inevitable.

The transformation of the traditional manner of developing architectural designs to designs in the form of virtual BIM models is another milestone in the development of civilisation, which is currently being reached. In order to go past that milestone and not be left behind, it is imperative that the education system of architects be adapted to these new standards.

It is also important to mention another aspect of introducing the BIM standard. Young people, who are currently learning and who will have the option of spending their time on mastering new design tools in the form of BIM, will be able to take advantage of never before seen opportunities on the job market, as BIM is, or is soon going to become, the required standard of design in most European countries and the demand for architects who work in this standard is going to rise rapidly.

Should the Polish job market be entered by architecture faculty graduates equipped with the appropriate knowledge and skills that can allow them to use modern design support tools, then, success in this field will only be a matter of time. However, should this fail to happen, then, all that will be experienced is failure, which is going to cause civilisational backwardness that will be difficult to escape, as well as a lack of competitiveness.

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