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Method for Building Information Modeling Supported Project Control of Nearly Zero-Energy Building Delivery

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Abstract: With the increasing number of nearly zero-energy buildings (NZEB) due to increase of global awareness on climate change, the new concepts of design and control must be developed because of great NZEB dependency on detailing and multidisciplinary approach. This paper proposes a three-level gateway control method for NZEB project delivery by using digital representation of the building in building information modeling (BIM) environment. These controls (C1, C2 and C3) are introduced before three main phases of any project delivery—design phase, construction phase and handover. The proposed project control procedure uses black-box building energy modeling within the BIM environment, so the paper explores the reliability of one tool for direct energy modeling within the BIM-authoring software. The paper shows two types of validation tests with satisfactory results. This leads to conclusion that analyzed tool for energy simulation within BIM environment can be used in a way that is described in a proposed project control procedure. For further research it is proposed to explore reliability of tools for energy simulation connected to other BIM-authoring software, so this project control procedure could be independent of BIM-authoring software used in the paper.

Keywords: nearly zero-energy building; building information modeling; project delivery; project control; building energy modeling

1. Introduction

Due to the European Union (EU) policy measures concerning increasing the energy performance of the building sector and therefore decreasing the greenhouse gas emissions, massive delivery of Nearly Zero-Energy Buildings (NZEB) started in EU Member States. According to Energy performance of buildings directive [1,2], NZEB "means a building that has a very high energy performance, as determined in accordance with Appendix I. The nearly zero or very low amount of energy required should be covered to a very significant extent from renewable sources, including sources produced on-site or nearby." Appendix I from [1,2] defines the framework for European Union member states to define the performance criteria that define NZEB. Outside the EU, NZEB energy criteria usually follow energy scheduling techniques (e.g., demand side management, [3,4]) that assess the efficiency of NZEB as well as the energy efficiency of a neighborhood. NZEB in EU standards must be achieved in both new buildings and renovated ones, as it is assumed that from all the buildings in 2050 the majority of them (75–90%) exist already today [5,6]. Achieving the NZEB standard is not only beneficial for the environment, but also for the end user of the building as with energy savings also comes the difference in price for delivered energy when comparing the conventional building and the NZEB [7]. The NZEB design and therefore the payback time is strongly dependent on a climate of the building location [8], so there is no universal solution for design/retrofit of the building up to the NZEB standard.

One of the key factors in deploying the NZEB (alongside with Heating Ventialtion and Air Conditioning—HVAC systems design) is to minimize the heat transfer through the building envelope. For that reason, it is important to pay attention on design and construction of details in all delivery phases—from schematic and design phases up to the construction phase. The reason why the construction details are more important when delivering the NZEB comparing to conventional building, lays in the decrease of the thermal bridge impact on heat transfer and in achieving the designed airtightness so building details should be both-well designed and well constructed. In the design process of NZEB, one should be also careful how their decisions impact the indoor air quality. If the airtightness of a building is low and it is not ventilated right (mechanical ventilation with heat recovery—MVHR is recommended), occupants may face a problem with mold in areas that are cooler than the rest of the envelope (in most cases on thermal bridges). When relative humidity (RH) increases, the dew point also increases, which can be seen in psychometric charts. The psychometric charts are usually used for thermal comfort analysis [9], but can also serve for defining the RH or the dew point of cooler spots on envelope. Right temperatures with right RH form a good environment for mold growth [10] (these conditions could occur even cyclically [11]). Decisions considering openings on building envelope have great impact on energies for heating and cooling. For that reason, they must be wisely chosen based on climate where NZEB will be built. The above-mentioned decisions that form good NZEB are shown on Figure 1.
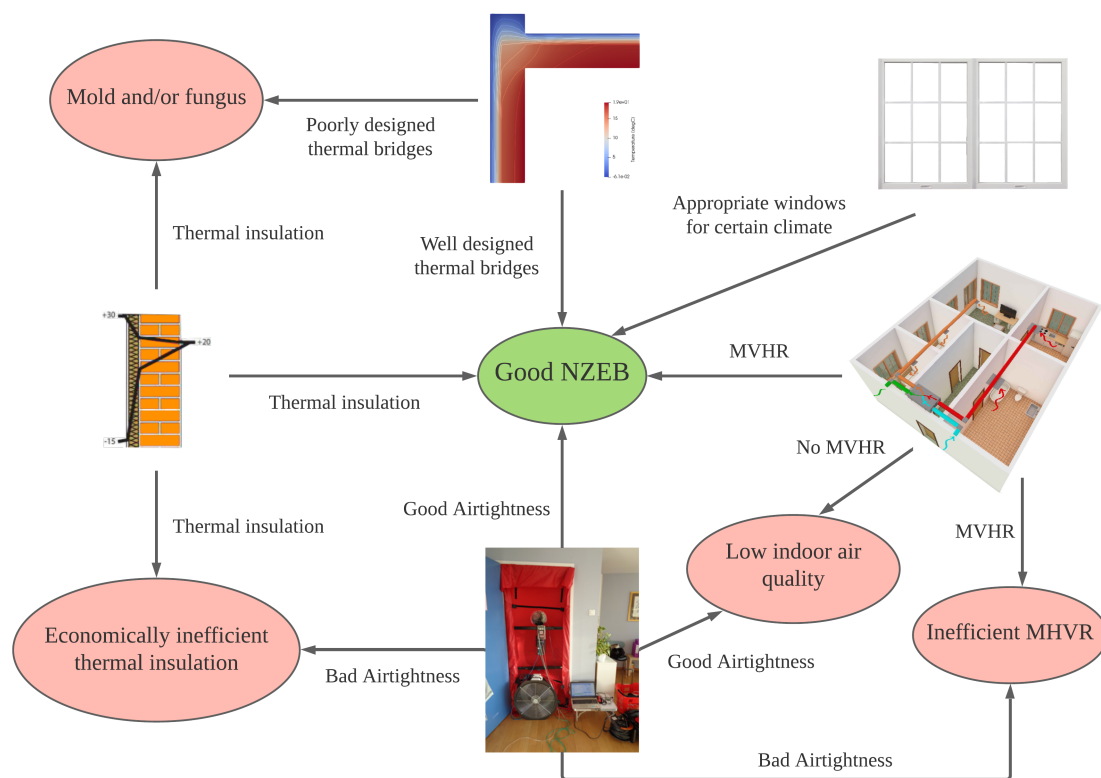

Figure 1. Schematic view of parameters that form good NZEB.

For the reasons stated in last paragraph, it is inevitable that the new kind of project control methodology must be defined. The methodology must preserve the project value on a sustainable level with incorporating the energy performance in it. For that reason, this article introduces the project control method that deals with NZEB related parameters in a way it does not interfere with conventional project control but rather it augments it from energy performance side of view. Performance evaluation is performed by checking the legislative conditions that define NZEB,

which are specific to each EU member state, and are based on EPBD. Outside the EU, NZEB usually has certain criteria for evaluation of building performance [12].

The paper is structured as follows. Section 1 provides general introduction to NZEB terms in the beginning, and NZEB project delivery, building energy simulation and the use of Building Information Modeling (BIM) for an energy simulation input in separate subsections (Sections 1.1–1.3 respectively). Section 2 outlines the methodology used for this research, as well as the need for proposed NZEB control method. Section 3 introduces the proposed method for control of NZEB delivering with all its steps. Section 4 provides the validation of a tool that is used in the proposed method in two ways—BESTEST (Building Energy Simulation test) validation in Section 4.1 and in compare with results published in [13] in Section 4.2. Section 5 offers conclusions and presents plans for future research.

1.1. Nearly Zero-Energy Building Project Delivery

Before the analysis of project delivery methods suitable for NZEB delivery, it is essential to define the project success for it. In conventional projects the project success is often determined by the "Iron triangle" (cost, time and quality parameters) following by subjective parameters concerning end-users and project stakeholders [14]. As NZEB is characterized by decrease of the energy use comparing it to conventional building, the building energy performance must be included while measuring the project success and it must be the one of key parameters that should be controlled during the project life-cycle. The increasing of the building energy performance must be conducted carefully, taking care of indoor environment quality.

The first thing to decide when delivering the NZEB is the project delivery method. Role model can be found in delivery of Green Buildings (GB) that are certified by one of many internationally recognized certificates. GB design and construction have longer history than NZEB design and construction, so there is much more research done on that subject. It mainly focuses on commercial building sector while the NZEB standard aims at both commercial and residential. Parameters that are controlled in GB project can be divided in two groups concerning objectives that must be fulfilled in order to declare project as successful. GB projects need to fulfill long-term objectives (relating sustainability) and short-term objectives (relating project management success) [15]. Project manager performance criteria consists of cost, quality and schedule performance, and sustainability criteria consists of environmental, economic and social sustainability (according to the paper [15]). The scope of their study is limited only to commercial office projects. The research is conducted by exploring the stakeholder's perception regarding project success by collecting the opinions from in-depth interviews with GB recognized experts. From the interviews, authors concluded that sustainability performance in GB will not influence schedule and cost performance in case they are properly controlled.

It is often stated in the literature that for successful NZEB delivery, an integrated approach is a requirement as it is important to include all professionals in NZEB delivery in all project phases. It is important to start a project with design phase which is optimized by applying one of many multi-criteria optimization methods [16,17]. In this case, energy goals are well defined and have greater potential to sustain on a satisfactory level throughout the project. If integration of all included professionals is done in all project phases, project delivery system is restricted to only two types—Construction Manager at risk (CM at-risk) with included integrated approach concepts and Integrated Project Delivery (IPD). To find the most suitable project delivery systems for NZEB projects, Kantola and Saari [18] used inductive reasoning while analyzing the literature alongside with testing their conclusions by several interviews. They concluded that IPD is most suitable project delivery system for NZEB delivery but it needs to be accompanied with competitive dialogue procurement method or the competitive procedure with negotiations. The second best method is CM at-risk but it is worthwhile to add some IPD elements so it is essentially hybrid system IPD CM at-risk. They also state that for standard housing construction project, the design-bid-build method is the best option because

it can operate well without any innovations, and cost assessments are way better when comparing it with other systems because of the required bidding process.

1.2. Building Energy Simulation

To make the right decisions in pre-design phases and design process, the important thing is to choose a tool for assessment of the building energy performance based on chosen materials, constructions, systems and orientation of the designed building. Designers mostly choose one of two different types of building energy performance assessment—based on calculation methods defined in standards which certain country accepted (ISO 52016-1:2017 [19] or ISO 13790:2008 [20]) or based on software for dynamic simulations (e.g., EnergyPlus, TRNSYS, ESP-r). The difference between these two ways to assess the building energy performance is in the type of calculation. Standards ISO 13790:2008 and ISO 52016-1:2017 use quasi-steady-state method for building energy assessment. ISO 52016-1:2017 is newly adopted standard and provides normative template for the choice between hourly and monthly method but still does not use dynamic impacts like heat accumulation (it uses simplified models). Software for dynamic calculation of building energy performance model the building as close to the reality as possible taking concern building materials, constructions, orientation and location, occupancy, and indoor and outdoor climate in time-steps ≤ 1 h. There is a standard (more specifically validation test called BESTEST) that is widely used for comparison of software and methods for the building energy performance assessment—ANSI/ASHRAE 140:2017 [21]. Alongside with BESTEST example cases, authors usually use additional validations when comparing the calculation methods as BESTEST gives simple test buildings and specified climate. Authors often use buildings from the BESTEST, and climate from location that is point of their interest, nationally standardized NZEBs, or building and location of their choice. The literature review from [13] shows that results for standard ISO 13790:2008 differ from those from BESTEST or reference buildings in a range 11–114%. The paper shows the validation of algorithm created by following the ISO 52016-1:2017 and when comparing the algorithm results and the results from ANSI/ASHRAE 140, the maximum differences between the result and mean value from BESTEST is 14% for heating and 10% for cooling. The paper also provides a comparison of ISO 52016-1:2017 results when calculating energy for heating and cooling of standardized NZEBs for Croatia comparing it with TRNSYS results. In this analysis, maximum differences of these two methods concerning the annual energy needs are 40% for heating and 18% for cooling.

The differences are also presented when comparing results from energy simulations and real energy use when building is constructed and used. There is no tool for assessment of this deviation because building energy use is strongly dependent on some uncertain variables like occupancy and weather. The differences are usually significantly big [22–24]—in a range of those when comparing standards and building energy simulation software. For renovations or systems operation and maintenance, usually, the model is calibrated so it is as close to reality as possible [22–24]. In that case the model is much more reliable for future decision making process.

It can be seen that results from building energy simulation tools can differ a lot when comparing the designed and constructed (used) building. No matter the differences, those tools are good for decision making process to observe the impact of certain decisions on building energy need.

1.3. Building Information Model as an Input for Energy Simulation

There are efforts in academia and industry in connecting the BIM and building energy simulation. For BIM-based energy simulation, the most important action is information transfer between BIM software and energy simulation software, with minimizing the information loss in this process as much as possible. Gao et al. [25] conducted research in the connection between BIM and building energy simulation models. They invented the information transfer classification process and named it BIM-based-BEM (Building Energy Modeling). The information transfer is usually conducted through Industry Foundation Classes (IFC) or green building XML (gbXML) and it is divided into six steps:

geometry (step 1), material (step 2), space type (step 3), thermal zone (step 4), space load (step 5) and HVAC (step 6). They analyzed the information transfer between various software and concluded that the IFC transfer is at step 1 (only geometry is transferred correctly) and the gbXML transfer is at step 3—materials and space types can also be transferred alongside with geometry information. They also conclude that correct information transfer is not user-friendly as there are many steps between BIM and BEM. Sanhudo et al. [26] conducted similar research and also concluded that the information loss in information transfer between BIM and building energy simulation is the main problem, so a lot of already stored information must be entered again in building energy model. They also concluded that even though there is a problem of information loss, there is huge benefit in using BIM in retrofit projects because of the ease of building information management. Kamal and Memari [27] also analyzed the connection between BIM and building energy simulation with information transfer process they called BIM-to-BEM interoperability process (BBIP). They found the main contribution of BIM in energy modeling is the ease of data handling. That ease of data handling can lead to automation in building energy modeling and simulation, clear simulation output presentation, capability of managing building data especially the real-time information in order to have an up-to-date energy model. They see that the lack of clear standards and the lack of easy solutions is the main problem in BBIP.

The other approach is to extract data that is useful from BIM model which is than used for energy calculation that is based on standard which certain country adopted. Following this approach Choi et al. [28] made a module in Python that extracts data from the IFC and they use this data for a calculation based on standard ISO 13790:2008. They declare this way more error-free when comparing it with manual input due to human error. Similar research [29] shows how the information can be extracted and transferred from IFC to basis of semantic model that is then upgraded so it can calculate all the needed outputs to satisfy GB certificate in Singapore. The advantage of the approaches from [28,29] is controlled information extraction, so the information loss has minimized impact on energy calculation.

2. Motivation and Methodology

Conventional project control must be expanded by introducing the building energy performance goals because if actions connected to them are properly controlled, achieving the NZEB performance will not negatively influence schedule and cost performance as stated in [15]. This project control expansion must be compatible with any project control method. Key thing is to firstly define control parameters connected to NZEB delivery process and then to define tools and procedure how to control them. This paper proposes which parameters are essential to control and describes procedure when to control them. Furthermore, the paper gives validation of one user-friendly building energy performance estimation tool that is implemented in BIM authoring software Archicad. More intuitively, the structure of the paper is shown in Figure 2.

The results from any building energy simulation tool for a building in a design phase differ a lot from actually measured energy parameters on constructed building because of many uncertain inputs like occupancy and climate data. Although these differences could be considerably big, those tools present building model that represents building's response to change of the input parameters characteristic to energy performance. For that reason, they show the impact of certain decision that is connected to building energy performance, so they are inevitable in decision making process for NZEB buildings. Those tools are mainly not user-friendly, and person who calculates building energy performance must be an expert in this engineering domain to produce and interpret reliable results. For the reason, of using this kind of tool in project control method, the key thing is to find some tools that give relatively good results for minimal input, so a person who is not expert in building energy engineering domain can notice some risks and discordance connected to NZEB delivery. Some BIM authoring tools enable preliminary energy calculation and they are more user-friendly than professional tools for building energy modeling. The problem occurs when exploring the back-end processes of calculation and information transfer, so this kind of energy modeling can be described

as black-box modeling. For some tools of this kind, the source of equations that are used for energy estimation is specified, but there is no in depth theory explanation. For that reason, this paper also shows a validation of one energy simulation solution called Energy Evaluation that is implemented in BIM authoring software Archicad.
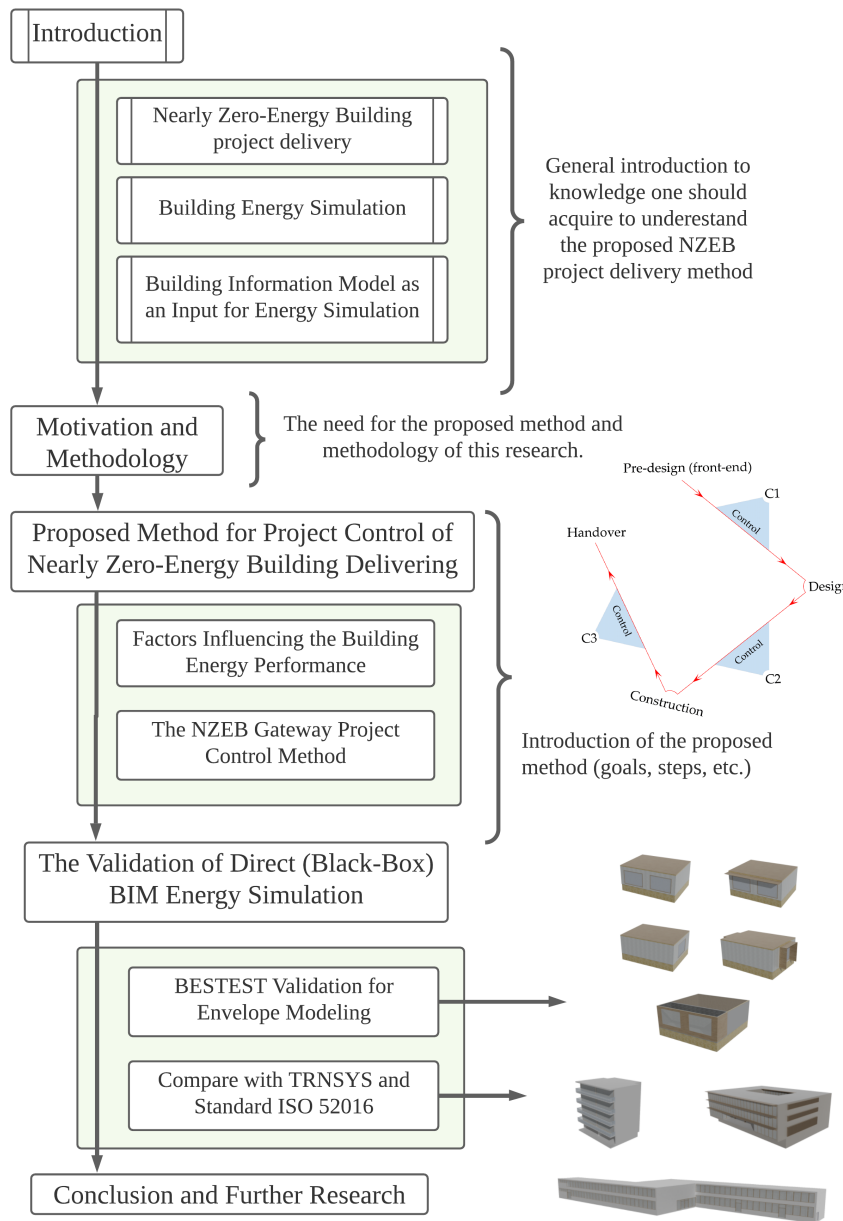

Figure 2. Framework of the paper—graphical methodology.

Firstly, the paper introduces the parameters that influence the building energy performance from four point of views (i.e., cooling and heating energies estimation methods): parameters used by machine learning, parameters that are controlled while performing the calibration of building energy model, parameters that the software for dynamic building energy simulation must include, and parameters used by the standards ISO 52016:2017 and ISO 13790:2008. After analysing the parameters, the project control method (the NZEB Gateway Project Control Method) is introduced with its three control phases and procedure. As the control method assumes that there is a tool that is easy to use but gives reliable results in a view of estimated building energy calculation, paper also gives validation of one tool that is implemented in BIM environment and directly translates information

model to energy model. Validation is performed in two ways—comparing the results following the standard ASHRAE 14:2014, and by modeling selected buildings described in more detail in the paper [13] by comparing the results for required annual heating and cooling energies from that paper with those from the Energy Evaluation tool for same inputs.

This paper proposes an NZEB delivery control method based on controlling the parameters that impact the energy need for heating and cooling because they are the basis of calculation of right sizing HAVC systems. The energy needs for heating and cooling are mostly analyzed factors of whole building energy needs (e.g., [13,30–34]) because they are recognized as the main characteristic of building envelope in protecting the building environment from the outside climatic conditions [29].

3. Proposed Method for Project Control of Nearly Zero-Energy Building Delivery

From Section 1, it can be concluded that the project control in NZEB delivery process must be put on a higher level. Furthermore, project success must include building energy performance. Taking concern that engineers use various tools and methods in assessing the building energy performance, and various project delivery methods are used while NZEB delivery, the NZEB project control methodology must be independent of tools used and project delivery methods. For that reason, this paper introduces a method for NZEB project control as additional procedure to conventional project control processes. To define the method, it is essential to define which outputs should be controlled. For that reason, this section firstly introduces the factors (parameters) that influence the building energy performance. After all the parameters are defined, section shows the principles of methodology, i.e., the concept of the method.

3.1. Factors Influencing the Building Energy Performance

The parameters that influence the building energy performance were analyzed from references that differ from one another when observing the methodology of estimating the energy performance. In firstly analyzed paper [30], the authors used artificial intelligence model (evolutionary multivariate adaptive regression splines) to predict the energy performance of the buildings. In the research, they used 8 input layers that were parameters with impact on building energy performance and two output layer that were heating load and cooling load. The input parameters were: relative compactness (ratio thermal envelope to conditioned volume), thermal envelope area, wall area, roof area, overall height, orientation, glazing area and glazing area distribution. The research did not use activity in the building as dynamic impact on building energy performance, as they analyzed models with occupancy set to be sedentary with the same operation set in all cases. They concluded that according to 10-fold cross-validation approach their method is the best model for predicting the heating and cooling loads.

When existing building is modeled for reliable prediction of energy use, there are standardized guidelines that specify when the building energy model is calibrated. The most often used guideline is ASHRAE 14:2014 guideline [35]. The guideline advises set of parameters on which modelers must take more care, those parameters are: zoning, schedules, HAVC systems, thermal mass and weather data. Some authors detect other parameters as more important and calibrate model on them alongside with advised by this standard, like Aparicio-Fernandez et al. in their paper took more concern on impact of infiltration [36]. Modeler must be very careful in calibration process when satisfying the criteria from [35] by creating engineering assumptions because errors occur frequently, even in papers from top rated scientific journals [37].

When observing engineering tools for dynamic simulation of building energy (e.g., EnergyPlus, TRNSYS, ESP-r), there is no recommendation on which parameters modeler must take more concern because all the parameters are equally important while developing a reliable model. These tools often use balance equations (heat, energy, moisture) that describe certain hygrothermal behavior and they are often coupled so one energy-related phenomenon impacts the other. These connections (couplings, like heat and moisture transfer) are described by differential

equation models and solved on a scale of whole building that is consisted of zones with strictly defined constructions (opaque or transparent, with strictly defined hygrothermal properties) and connections between the zones or connections to the outside environment. The schematic view of one of commonly used tool (EnergyPlus [38]) that is described in this paragraph is in Figure 3. The similar way is presented in standards for predicting the energy performance of building, ISO 52016-1:2017 [19] and ISO 13790:2008 [20]. The difference is mostly in the calculation methods as standards do not use dynamic methods but rather stationary ones.
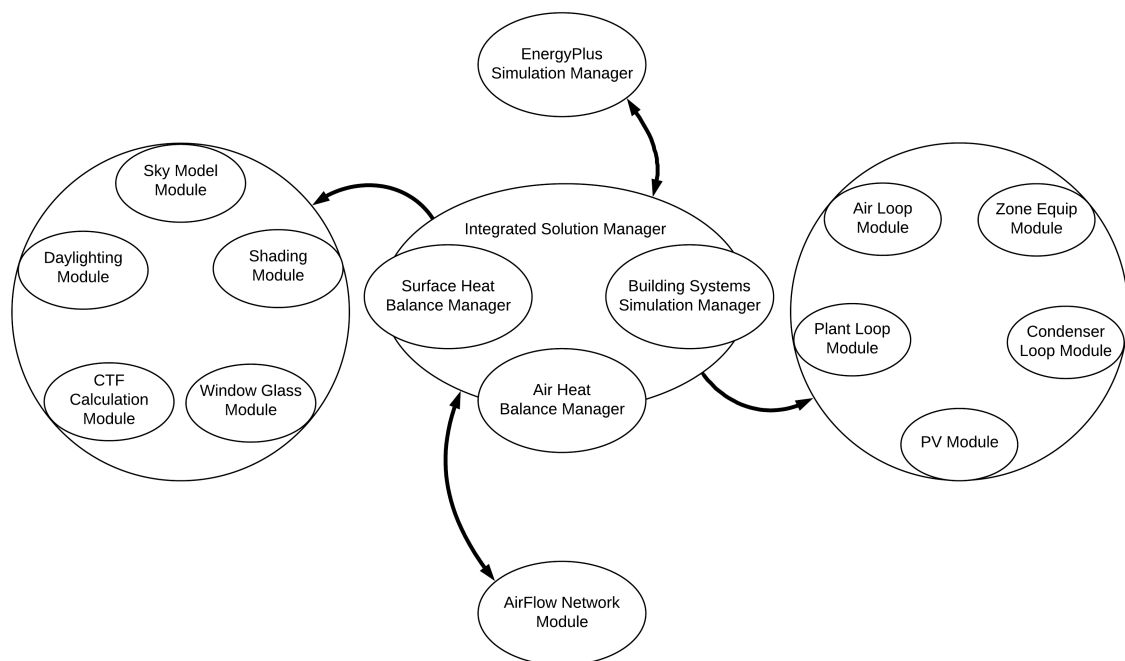
Figure 3. Example of schematic description of commonly used software for dynamic simulation of building energy (EnergyPlus).

When predicting the effect of energy retrofit in projected life-cycle, more complex procedure must be used, and costs of proposed variants must be included in the planning process. When following the Pučko et al. paper [39], this life-cycle planing process starts with first step that is selection of variants where the most important thing is good definition of goals and presumptions. They used BIM as a tool for managing information of selected variants, so the second step is modeling in 3D BIM authoring software. For each variant, two analysis must be observed—energy analysis in one of engineering tools for building energy performance assessment, and cost analysis. After these two analyses comes the final step—selection of cost-effective variant. The paper is a good representation that not only energy aspects in delivering the NZEB must be obsereved, but also the costs that come with each variant solution.

3.2. The Nearly Zero-Energy Building Gateway Project Control Method

In order to obtain project success containing the building energy performance goal, this section introduces project control method that should be used in NZEB delivery. Advantages of proposed control method are presented in the ease of control process, as it is not necessary that person who controls NZEB project delivery must be an expert in that specific expertise area to target and reduce the risks concerning energy goals. The control method is independent of a project delivery method, which could be another advantage because of its universality. One undoubted advantage is introduction of step that manage the responsibilities if NZEB does not satisfy legislative performance criteria. The control method that is proposed has three levels of delivery control (C1, C2 and C3)

based on the point in which part the project delivery is. For a clearer view of proposed set of control phases, they are presented on a diagram that represents the gateway points of most of project delivery phases (Figure 4). More generally, the control phases are checkpoints before main project delivery phases. Control C1 is first that comes and it is a checkpoint before the design process. The pre-design (front-end) phases are the most important phases in project delivery because the decisions in these phases make high impact on the project change with relatively low costs [40]. For that reason, the designers must be encouraged to collaborate with other professionals in these phases of NZEB delivery so the project is well defined from the beginning. After the design process, control C2 should be conducted in order to explore differences between pre-design phase idea and designed solution. Completing the design phase, project must not only be standard-compliant, but also completed in a way that it is as optimized for construction phase as possible with minimization of information loss between the phases. The last control is C3 and it is conducted before the handover so project manger can be sure that the building is fully functional and in accordance with design before they deliver the building to the client. Table 1 shows summarized view of proposed NZEB gateway project control method and each control is described in detail in the following paragraphs.
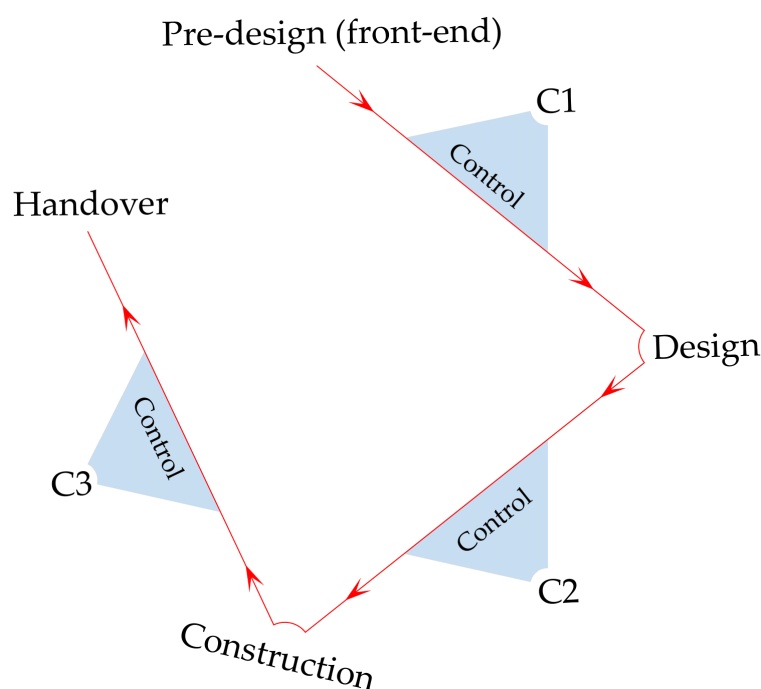

Figure 4. The NZEB gateway project control method with control gateways C1, C2, and C3.

Table 1. The proposed actions of the NZEB gateway project control method.

Control C1	Control C2	Control C3
construction (light, medium or heavy) *	U-values–opaque elements *	U-values–opaque elements •
relative compactness †	U-values–windows *	U-values–windows •
window-to-wall ratio †	glazing U-values *	glazing U-values •
shadings *	g-values *	g-values •
preliminary heating load *	heating load †	airtightness (n_{50})–blowerdoor •
preliminary cooling load *	cooling load †	heating load check ‡
	primary energy †	cooling load check ‡
	designed airtightness (n_{50}) †	primary energy check ‡

* BIM model and documentation check; † documentation check; • check compliance between constructed and designed (in BIM); ‡ demand new energy calculation if constructed parameters are significantly different.

As C1 is controlling the pre-design phases, it demands that the building in a schematic form (before the design process) must be developed in a way that it proves possibility it can be designed as NZEB. To do so, professionals in these phases must be encouraged to explore many variations concerning building orientation, relative compactness, window-to-wall ratio and positioning of windows, opaque elements construction (light, medium or heavy), preliminary U-values of opaque elements and windows, shadings, and g-value of windows. A professional who is controlling the NZEB project deployment should encourage the professionals in project delivery to use BIM in order to minimize information loss and errors as well as reducing the redundant tasks when observing designing/modeling the elements of building that impact the energy performance [28]. The other important reason for encouraging the BIM use is the possibility of using preliminary (black-box) building energy simulation tools that are implemented in BIM-authoring software (e.g., Archicad, Allplan, Revit). For exploring the reliability of these tools, this paper also analyses validation of one of these that is implemented in BIM-authoring software Archicad (Energy Evaluation) in Section 4. The parameters that are proposed to control before the design phase are: type of construction, relative compactness, window-to-wall ratio, shadings, and preliminary heating and cooling loads. Professionals in phases before this control must deliver a design that proves the possibility of designing their building idea as NZEB, so preliminary heating load and cooling load must satisfy maximum allowed values for the country and climate where the building is located. Heating and cooling loads are chosen because they are the most important characteristics of building envelope and an input for right-sizing HAVC systems. Furthermore, professionals do not need to specify HAVC systems in this phase as they depend on other not yet specified parameters. Thus, the primary energy (that is one of the most important parameters that describe NZEB) can not be calculated before design phase.

The design process must deliver all the necessary documentation for the standards compliance check so the control of this phase include the control if the design documentation is well developed and have all the necessary information before it is sent to mandatory checking by the public authority. The C2 demands a process of checking the parameters that influence the energy performance of building with more care. The important thing is to check if there are differences in documentation and BIM model for the next parameters: U-values of opaque elements, U-values of windows, glazing U-values, and g-values. These parameters will be used in the last phase when the differences control between constructed and designed envelope elements will be performed. It is also important to check the documentation for the heating and cooling load, and primary energy alongside with above-mentioned parameters. The primary energy includes impact of designed HAVC systems and RES (Renewable Energy Sources), so if primary energy satisfies values from country standard, HAVC systems and RES are well designed. The important thing is to document designed airtightness because it must be experimentally tested with air pressurization test (blowerdoor) within engineering commissioning. It is recommended by the C2 that a professional who is conducting the control, should run energy simulation in energy simulation tool implemented in BIM-authoring software to record the heating and cooling loads of this phase ($Q_{H,nd}^{e,d}$ and $Q_{C,nd}^{e,d}$ respectively). It will certainly differ from designed, but it will be used in C3 for comparison of energy performance of building if building will have significant differences after the construction phase.

The last control phase (C3) is conducted before handover. With this control, professional who leads the project delivery of NZEB building intends to prove that the building is in compliance with the design and regulations. Concerning the energy performance related parameters, here is proposed control procedure. Firstly, construction elements of the building must be checked. BIM is a good help for this phase because the professional who is providing control can dynamically go through every element simultaneously in the real building comparing it to its digital representation. For this actions, BIM viewer software can be used (e.g., Tekla BIMSight, Allplan Bimplus) because they can be used on smartphone or tablet so the control is much easier to carry out. The most important control in this phase is conducting the air pressurization test (blower door) in order to observe

true airtightness of the building envelope. Airtightness is important characteristic of the building thermal envelope as it is a value that is used in calculation of building energy balance that can be directly measured. A professional who is carrying out the control must document all the differences and change BIM model from the design phase to represent the real building. After documenting the differences, they must run the energy simulation with true airtightnes (n_{50}) and document the differences between heating and cooling energy loads in design phase and after building is constructed ($Q_{H,nd}^{e,c}$ and $Q_{C,nd}^{e,c}$ respectively). The difference between two values must be documented in a way shown in expression (1).

$$\Delta Q_{H,nd}^{e} = Q_{H,nd}^{e,c} - Q_{H,nd}^{e,d} \qquad \Delta Q_{C,nd}^{e} = Q_{C,nd}^{e,c} - Q_{C,nd}^{e,d} \tag{1}$$

When adding those differences on the designed values from the documentation ($Q_{H,nd}$ and $Q_{C,nd}$ respectively)—as in expression (2), professional that carries out the control must observe if the new values $Q_{H,nd}^{*}$ and $Q_{C,nd}^{*}$ comply with the national NZEB standard.

$$Q_{H,nd}^{*} = Q_{H,nd} + \Delta Q_{H,nd}^{e} \qquad Q_{C,nd}^{*} = Q_{C,nd} + \Delta Q_{C,nd}^{e} \tag{2}$$

If values $Q_{H,nd}^{*}$ and $Q_{C,nd}^{*}$ do not comply with the standard, professional who carries the control must contact consulting professional to provide more complex analysis of building energy simulation with true airtightness and construction elements, and give recommendation of building repair to satisfy necessary energy requirements. The cost of hiring the energy consultant, and repair costs bears the stakeholder who is responsible for the process where the deficiency occurred.

4. The Validation of Direct (Black-Box) Building Information Modeling Energy Simulation

As the proposed NZEB project delivery control assumes that building energy simulation tools implemented in BIM-authoring software give reliable results, this section provides a validation of one of these (tool Energy Evaluation) that is implemented in Graphisoft software Archicad. Tool Energy Evaluation is reduced version of Archicad Add-in software EcoDesigner Star and comes with every version of Archicad after the version 17. EcoDesigner Star, and therefore Energy Evaluation uses software VIP energy for building energy performance simulation. VIP energy uses expressions, models and balance equations from the technical report [41] that was basis for software development, but they are not well specified in the official manual [42]. For that reason, and with reduced functionality of the Energy Evaluation tool, the energy model created within the BIM-environment in Archicad can be characterized as black-box modeling. To explore reliability of the results, two sets of validation was performed. Firstly, this paper shows the BESTEST validation [21] that is popular when comparing the results of building energy modeling software to the results from similar software. The second validation is performed on three Croatian NZEB reference buildings–residential, school, and office building. The results from the models developed in Archicad were comapred with the results from published paper that explores differences between dynamic energy simulation in TRNSYS software and the standard for estimating the energy performance of building—ISO 52016-1:2017 [19].

4.1. Bestest Validation for Envelope Modeling

For the analysis of the reliability of Energy Evaluation tool, 13 energy models were created in accordance to BESTEST and compared with the results from other building energy simulation software described in [21]. Cases that were analyzed are shown on Figure 5. Here, cases from 600 to 650 represent low thermal mass tests, while cases from 900 to 950 represent high thermal mass tests. The construction materials and properties are presented in ASHRAE 140:2011. The geometry for cases 900–950 correspond to cases 600–650 with the difference in envelope construction type. Case 960 is a hybrid of base case (Case 600) with unconditioned high thermal mass solar zone connected to the low thermal mass observed one. The connection is a 20 cm thick concrete wall. The standard gives all

the necessary inputs for energy simulation of a certain case (e.g., wall construction, roof construction, floor construction, window properties, infiltration rate, etc.).
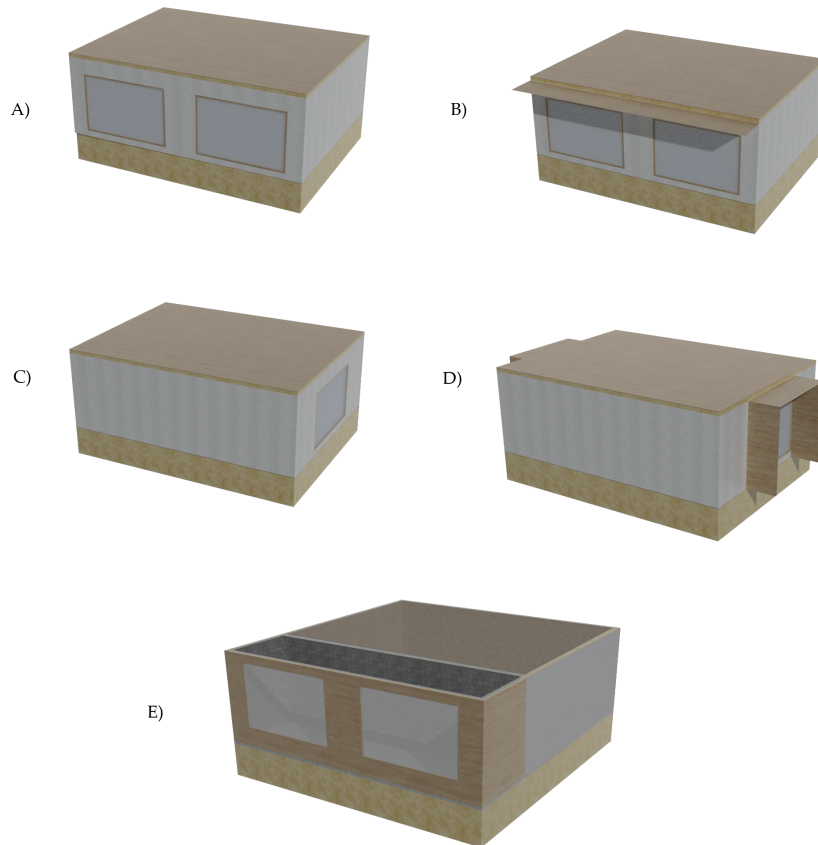

Figure 5. Analyzed BESTEST reference buildings: (**A**) Case 600, 640, 650/900, 940, 950; (**B**) Case 610/910; (**C**) Case 620/920; (**D**) Case 630/930; (**E**) Case 960.

First thing in process od modeling in Archicad was the definition of wall, roof and floor constructions with material characteristics defined in ASHRAE 140:2011. Zones are modeled with automatic filling of space that is covered by opaque and transparent elements. Each zone pulls the information of construction that covers it in Energy Evaluation tool. The tool has U-value calculator so it automatically calculates this energy parameter—from construction elements when observing opaque constructions and from defined catalog values for windows. U-values can be added manually (helpful if construction layers were not defined). HVAC for heating and cooling were set to be not yet specified (black-box modeling). The tool is not capable of setting the infiltration rate directly with certainty, but gives calculation of airtightness (n_{50}, air change rate at pressure difference of 50 Pa). For that reason, infiltration was modeled with rough estimation as it is defined in [20] with following connection: $n_{inf} = n_{50}/20$. Weather data is defined by the standard and it is in tmy format, that can be put as an input in the Energy Evaluation tool.

As it can be seen on Figure 6, all the results are within the range of BESTEST software comparison when observing annual energy need for heating. The cases 650 and 950 do not have result for heating load analysis because for those cases heating systems are disabled and not observed in energy models according to [21]. BESTEST results are presented with mean value of results from software that conducted the same energy simulation and with minimum and maximum result value, while Archicad results are presented with magenta squares. When observing energy need for cooling (Figure 7), the same thing can be seen.
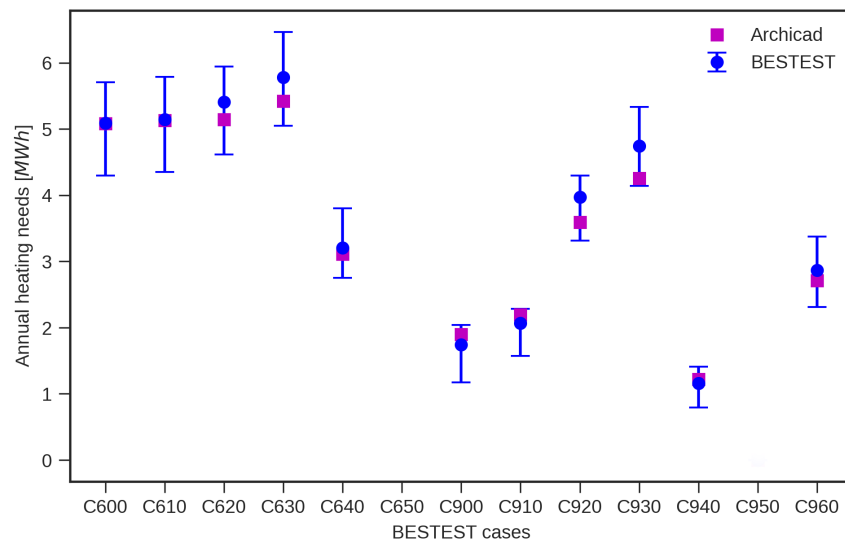
Figure 6. BESTEST results for Archicad Energy Evaluation tool for annual heating energy (MWh).
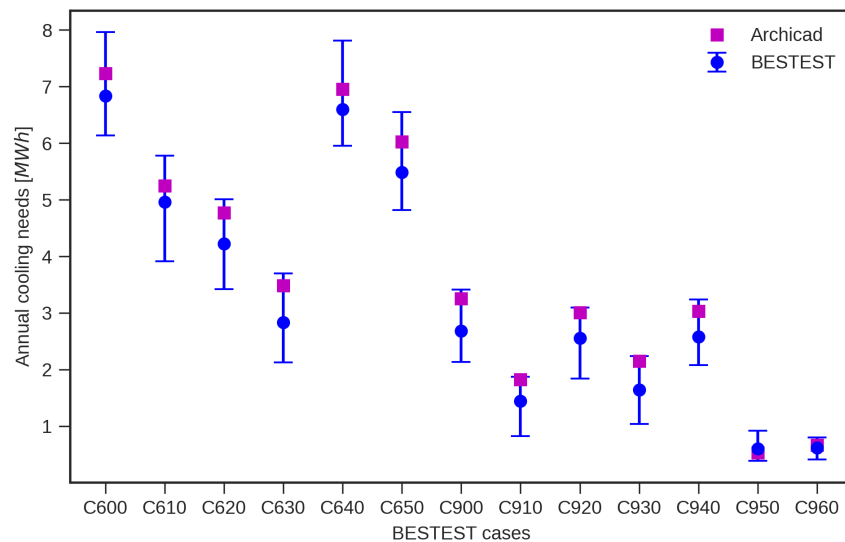

Figure 7. BESTEST results for Archicad Energy Evaluation tool for annual cooling energy (MWh).

Even though some resulting values are near the limiting extreme values, all the results are in range characterized by software conducted the same test. From Figures 6 and 7 it can be concluded that Energy Evaluation tool gives similar results as other building energy simulation software and are within the BESTEST limits. The largest relative difference from mean value is registered for Case 930 and it is 30.9%, but it is lower than the maximum value from the BESTEST that is 36.1% so it is in a range defined by the similar software.

4.2. Compare with Trnsys and Standard ISO 52016

In order to explore potential of energy simulation within BIM environment when observing more realistic buildings, this section presents a comparison between energy models developed in Archicad Energy Evaluation tool and the results published in [13]. The paper [13] provides comparison of five building models developed in software for dynamic building energy simulation—TRNSYS, and the results calculated according to the standard ISO 52016-1:2017 [19]. The buildings that were modeled in Archicad and compared with the results from [13] are shown in Figure 8.
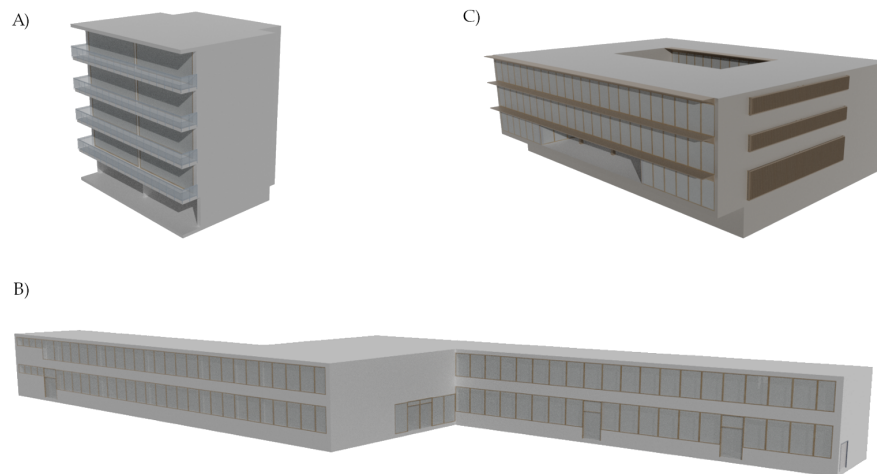
Figure 8. Analysed NZEB reference buildings: (**A**) Residential building (B1); (**B**) School (B2); (**C**) Office building (B3).

The authors decided to analyze the buildings on which the proposed control method could be applied: residential building (Figure 8A), school (Figure 8B), and office building (Figure 8C). The buildings are Croatian reference NZEB buildings and they are modeled with inputs like in [13]. The main characteristics of analyzed buildings are given in Table 2.

Table 2. Main characteristics of analyzed buildings.

ID	Type of Use	Heating/Cooling Hours	$A_{floor}[m^2]$	$V[m^3]$	Thermal Mass
B1	NZEB residential building	6 am–11 pm (7 days a week)	607	1638	Very heavy
B2	NZEB school	6 am–8 pm (5 days a week)	2068	8278	Very heavy
B3	NZEB office building	5 am–6 pm (5 days a week)	2745	8231	Very heavy

The overall heat transfer coefficient for walls and windows (U_{wall} and U_{window}) are set to be identical as in [13], as well as the total solar energy transmittance of glazing (g_{window}). The list of inputs of predominant building elements for energy modeling that was taken from the same reference are shown in Table 3, while basic thicknesses and materials are as follows:

- External walls: reinforced concrete (20 cm) + thermal insulation on the external side (20 cm).
- Roof: flat roof made of reinforced concrete (20 cm) + thermal insulation on external side (24 cm).
- Ground floor: concrete floor slab (10 cm) + thermal insulation (10 cm).
- Floor to an open garage—B1 and B3: reinforced concrete floor (20 cm) + thermal insulation on external side (20 cm).
- Walls to staircase (unconditioned)–B1: reinforced concrete (20 cm) + thermal insulation on the side adjacent to staircase (20 cm).

Table 3. Inputs for building energy modeling.

ID	U_{wall} [W/(m²K)]	U_{window} [W/(m²K)]	g_{window} [−]	Infiltration Rates [ACH]	Internal Heat Gains [W/m²]	Heating/Cooling Setpoint [°C]
B1	0.17	0.86	0.6	0.5	5	20/22
B2	0.17	0.86/0.68	0.60/0.40	0.7	6	20/22
B3	0.17	0.68	0.40	0.7	6	20/22

The analysis and results comparison were done concerning two types of climate that are used as a standard input for the building energy estimation in Croatia, continental climate defined for the city of Zagreb, and littoral climate defined for the city of Split. Raw data are defined by the Croatian Ministry of Physical Planning, Construction and State Assets, and for the purpose of this paper it was transformed in a way it can be readable in Archicad Energy Evaluation tool. The format in which raw data was transformed is .tm2 and transformation was done using the Python 3 programming language with additional packages pandas and numpy. All the graphs in the paper were created using package matplotlib. Temperature, relative humidity and solar irradiance on a horizontal surface for continental climate are shown on Figure 9 and for littoral on Figure 10.
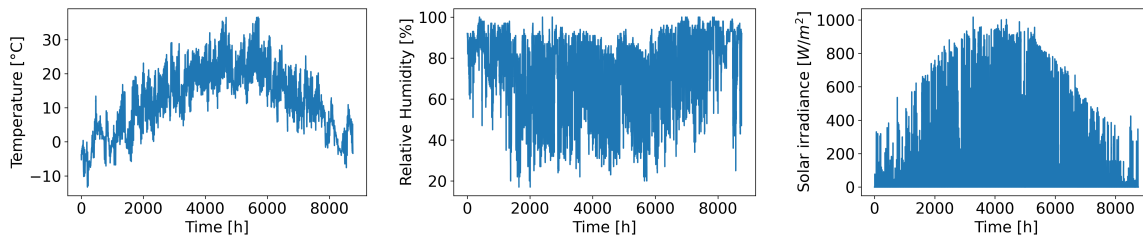
Figure 9. Ambient temperature, relative humidity and solar irradiance on a horizontal surface for standard Croatian continental climate (typical meteorological year).
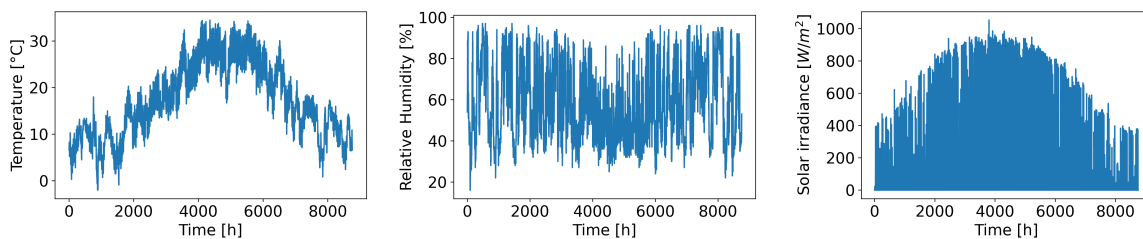

Figure 10. Ambient temperature, relative humidity and solar irradiance on a horizontal surface for standard Croatian littoral climate (typical meteorological year).

4.2.1. Results and Comparison between Trnsys, ISO 52016, and Energy Evaluation Tool

Energy needs for heating and cooling were calculated in the Energy Evaluation tool based on all the presented inputs and compared with results from [13]. The observed values were net heating energy and net cooling energy in $kWh/(m^2a)$, i.e., specific annual energy needs per useful floor area. Figure 11 shows the results from Archicad Energy Evaluation tool for analyzed buildings (residential-B1, school-B2, and office-B3) compared to those from TRNSYS and by ISO 52016-1:2017. Concerning the continental climate, energy model for residential building B1 in Energy Evaluation tool gives 15.65 kWh/m^2 for annual heating and 86.55 kWh/m^2 for cooling. These results are very close to results from TRNSYS as the difference with respect to TRNSYS result for heating is 1.1% and for cooling is 2.4%. If we compare the Archicad results to those acquired from the calculation according to the standard ISO 52016, the differences are larger. In the paper [13] the differences between TRNSYS and standard ISO 52016 are observed with respect to TRNSYS result. This paper presents the differences with the respect to the standard ISO 52016 which lead to different values of differences when comparing two papers (even though results from Archicad and TRNSYS are very close in some cases). While comparing the results from Archicad to those from standard ISO 52016 we get relative difference of 60.0% for heating and 12.6% for cooling.

When observing the NZEB school (B2) for the same climate input we get 38.69 kWh/m^2 for annual heating and 43.93 kWh/m^2 for cooling. The annual energy need for heating is (again) very close to the result from TRNSYS (difference 5.6%), and the difference when comparing the result with the standard ISO 52016 is 25.7%. Annual cooling need gives larger differences comparing both to

TRNSYS (29.6%) and the standard ISO 52016 (39.7%). The last energy model for continental climate is for office building B3. The annual energy need for heating is 34.44 kWh/m^2 and for cooling is 40.47 kWh/m^2. The difference to the result from TRNSYS for annual heating need is 33.7 % and for annual cooling need is 25.2%. When comparing these differences with the standard ISO 52016 we get for annual heating need 47.2% and for annual cooling need 36.4%.
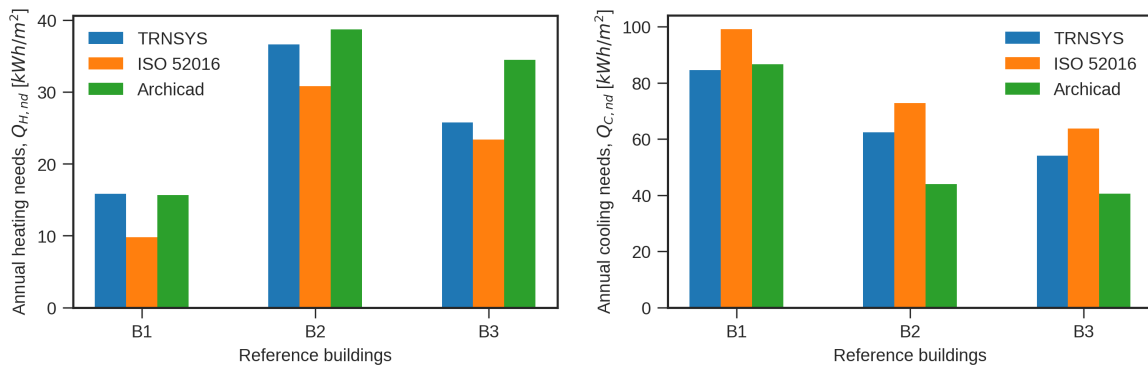

Figure 11. Annual heating and cooling needs for analyzed buildings in continental climate for three types of energy simulation: TRNSYS (**blue**), ISO 52016-1:2017 (ISO 52016, **orange**), and Archicad Energy Evaluation tool (Archicad, **green**).

If we observe littoral climate (Figure 12), similar differences occur. Energy need for B1 is 0.25 kWh/m^2 (approximately 0 kWh/m^2) for heating and 123.93 kWh/m^2 for cooling. The differences to the results for cooling from TRNSYS and the standard ISO 52016 are 9.3% and 4.4% respectively. For the case of B2, annual energy loads are 6.16 kWh/m^2 for heating and 68.24 kWh/m^2 for cooling, with differences to TRNSYS results 15.7 % and 20.0% respectively. When observing the differences to the results from the standard ISO 52016 we get 12.6% for heating and 30.0% for cooling. The last building that is analyzed gives 6.48 kWh/m^2 for annual heating need and 60.44 kWh/m^2 for annual cooling need. The differences to TRNSYS results are 1.5% and 17.7% for heating and cooling respectively, while comparing them with the results from the standard ISO 52016, they are 54.7% for heating need and 41.0% for cooling need.
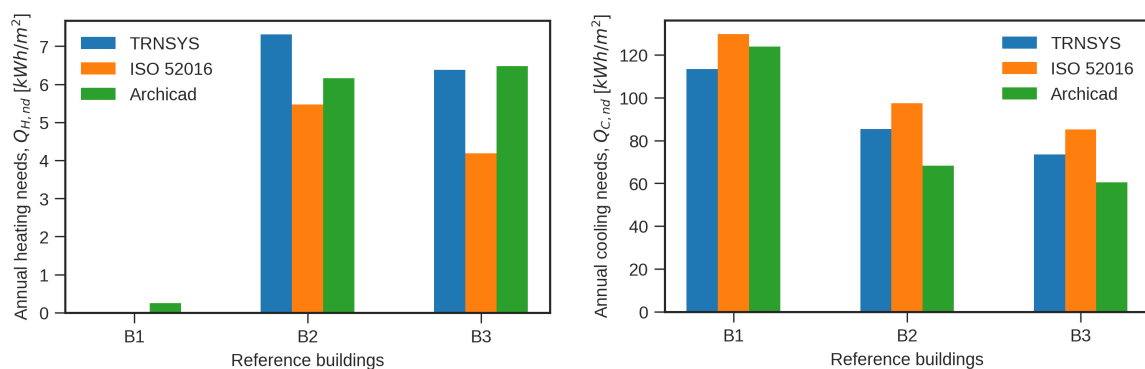

Figure 12. Annual heating and cooling needs for analyzed buildings in littoral climate for three types of energy simulation: TRNSYS (**blue**), ISO 52016-1:2017 (ISO 52016, **orange**), and Archicad Energy Evaluation tool (Archicad, **green**).

From the results, it can be seen that differences vary a lot, but in general it can be seen that the results from Archicad Energy Evaluation tool are relatively close to the results from TRNSYS as the largest difference is 33.7%, which is detected for annual energy load for heating in continental climate for building B3. This is in the range of relative difference errors of BESTEST as the largest relative difference from the mean value for the test is observed for annual energy for cooling for Case 950 with

a value of 52.2%. When comparing the results with the standard ISO 52016-1:2017, the differences are relatively large, but they are smaller than those from the paper that compare TRNSYS and the standard. The maximum relative difference is detected for building B1 for annual heating load in continental climate and it is 60.0% compared to 62.1% from [13] when the difference is observed with a respect to the standard.

4.2.2. The Impact of Assumptions Concerning Climate and Lower LOD Modeling on Energy Results

Two additional analyses were conducted on the same set of buildings. First one is the comparison between the climate data that is defined as Croatian reference climates for continental and littoral parts (**A1** in Figures 13 and 14) with the climate data that is downloaded directly within Energy Evaluation environment for the same location (**A2** in Figures 13 and 14). The largest relative difference is documented for the annual heating load for building B1 in continental climate with the value of 51.7%. The second additional analysis (**A3** in Figures 13 and 14) observes the possibility of defining the envelope elements with lower Level of Development (LOD), i.e., just with specific thickness, U-value and construction type as light, medium or heavy (describing the thermal mass effect). This analysis is chosen due to possibility of using this tool for pre-design phases because in them professionals usually do not define building elements in detail, but rather give just as an idea for the design phase. The thermal envelope elements for these models are defined as heavy with thickness and U-values as defined in the reference **A1** models. The largest relative difference for this analysis is 27.7% (B3 for annual cooling needs for continental climate) but in a way that the result is closer to the TRNSYS result. This kind of black-box modeling is good in a way that modelers do not need to specify all the construction layers, but bad side is that they can not experience impact of thermal insulation positioning (due to the impact of thermal mass).
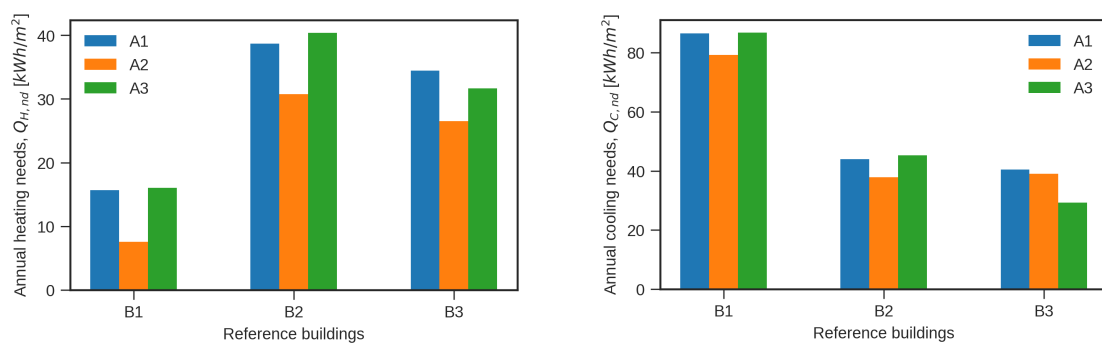

Figure 13. Comparison of the results described in Section 4.2.1—**A1** with the results for directly downloaded weather data—**A2**, and the results for constructions with lower LOD—**A3**. The results are for continental climate and Energy Evaluation tool.
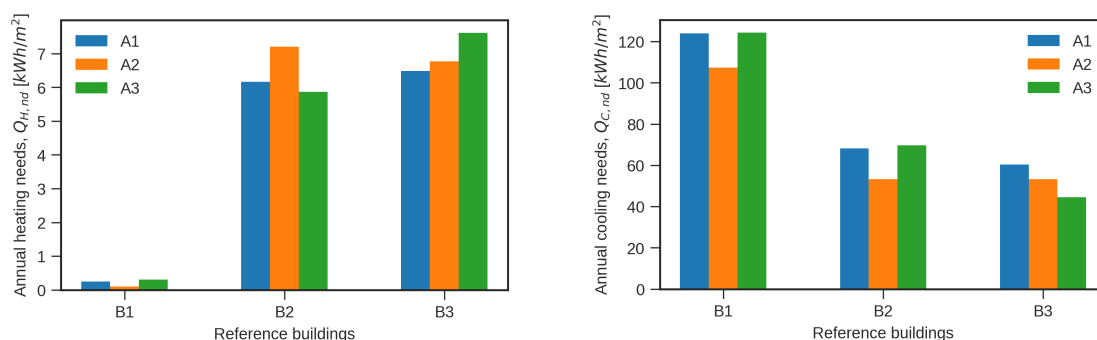

Figure 14. Comparison of the results described in Section 4.2.1—**A1** with the results for directly downloaded weather data—**A2**, and the results for constructions with lower LOD—**A3**. The results are for littoral climate and Energy Evaluation tool.

5. Conclusions and Further Research

The paper presents the method for the nearly zero-energy building project delivery control with use of building information modeling. The procedure that is proposed consists of three levels of project control introduced before three main project delivery phases—design phase, construction phase and handover. This procedure is independent from any project delivery method, but construction manager at-risk delivery method should benefit the most because with this three-level project control, many risks could be eliminated. The proposed project control depends on reliable results from direct building energy simulation in BIM environment. For that reason, the paper provides two types of validation testing of the building energy simulation tool within the environment of BIM-authoring software Archicad.

The first validation is popular BESTEST and the results from energy model in Archicad satisfy all the analyzed cases (Cases 600–650 and 900–960). The second validation considered modeling of more realistic buildings: residential building, school and office building in two types of climate–continental and littoral. The results were compared with those from TRNSYS–software that is usually used by the building energy and systems modeling and designing professionals, and with standard ISO 52016-1:2017. When comparing the results from Archicad environment with TRNSYS, the largest relative difference is for annual heating need of office building in continental climate. As this difference is lower than maximal relative difference detected in ASHRAE 140 BESTEST, the tool Energy Evaluation within Archicad environment is considered reliable for the use defined by the control method. When comparing the results with the standard, worse results are documented, but they are in range of those detected in comparison between TRNSYS and the standard ISO 52016 for the same set of buildings. The additional analysis showed that standardized climate data should be used when estimating the building energy performance, because two identical building energy models may differ a lot when comparing the results for standardized reference climate and climate downloaded directly to Energy Evaluation software from sources that assess the climate parameters. Another additional analysis showed that it is possible to model the envelope elements just with the information of thickness, U-value and construction type (thermal mass assessment without defining true layers of construction), but when using this way, the impact of positioning of thermal insulation is neglected (as well as the impact of other thermal mass phenomena).

This paper presents the theoretical aspect of project control procedure for controlling the NZEB project delivery, so further research should be conducted in a view of implementing the parts of the method or the whole method in order to document its feasibility. The method should increase the quality of new NZEBs, and reduce the risks through all the project delivery phases. The method also could be used for deep energy renovations up to NZEB standard. This paper shows validation of only one direct building energy modeling tool that is implemented in the BIM environment. It should be explored if the other tools implemented in other BIM environments (e.g., Revit, Allplan) will also satisfy the validation presented in this paper (mainly considering the BESTEST validation) so the method could be independent of BIM-authoring software.

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