BENIMPACT Suite: A Tool for ZEB Performance Assessment

Silvia Demattè¹, Maria Cristina Grillo², Angelo Messina¹ and Antonio Frattari²

1. EnginSoft SPA, Trento 38123, Italy

2. Department of Civil and Environmental Engineering, University of Trento, Trento 38123, Italy

Abstract: In the last years, there has been a big development of European policies and regulations on energy saving topics. This is due to the will to reach the targets of 20-20-20. Buildings consume a lot of energy, so the legal framework related to the reduction of energy consumption in this sector has had a huge evolution. The “NZEB (nearly zero energy building)” concept was introduced in 2010, eight years after the release of the original EPBD (energy performance of buildings directive). By 2020, all new buildings and buildings that are subject to renovation should have very low energy consumption, covered for the major part by renewable sources. Designing and realizing this kind of building is a very ambitious task, which needs to be supported by appropriate tools and software. This paper presents a new tool for assessing building performance, named BENIMPACT Suite (building’s environmental impact evaluator and optimizer), which is developed by EnginSoft (Italy). The suite is organized in different core modules that allow to verify how the building performance level is influenced by different design choices, such as envelope shape and materials, plant systems, renewable sources use, etc.. One of the test cases used to validate the BENIMPACT Suite energy performance is the evaluation of an interesting Italian ZEB, finished in 2010 and called CasaZeroEnergy. It is located in Felettano (Udine), a small town in northeastern Italy. This building is an experimental house designed and monitored by the Laboratory of Building Design of the University of Trento (Italy) and built by Polo Le Ville Plus Group (Cassacco-Italy). The energy performance of this building was modelled and evaluated using BENIMPACT Suite, and simulation results were compared with monitored data.

Key words: NZEB, suite, building performance, validation, monitoring.

1. Introduction

The authors want buildings in which people live to be safe and healthy, functional, comfortable, and also aesthetically integrated into the urban context. They also need to be properly designed to be energy efficient and environmentally friendly to contribute to primary energy consumption reduction, one of the key objectives in European policies as confirmed by the Kyoto Protocol and the targets of 20-20-20: 20% cut in emissions, 20% improvement in energy efficiency and 20% increase in renewable by 2020.

1.1 European Regulation: An Overview

Ten years ago, in 2002, the first EPBD (energy

performance of buildings directive) 2002/31/EC [1] was released in order “to promote the improvement of the energy performance of buildings within the community, taking into account outdoor climatic and local conditions, as well as indoor climate requirements and cost-effectiveness”. Minimum energy performance was required to new buildings and existing buildings subjected to major renovation.

Since then, sustainable design and green strategies applied to the building sector have become more and more popular among users, governments, designers and researchers.

Solar passive design and energy performance, insulation thickness increment, plant equipment improvement, renewable resources on site systems have become a trend.

Adopting a benchmark energy performance level made it possible to drastically reduce building energy

Corresponding author: Silvia Demattè, building engineer, research fields: development of concepts, methodologies and tools focused on buildings sustainability. E-mail: s.dematte@enginsoft.it.

consumption.

With the aim to reduce negative impacts from the building sector, and to help a faster diffusion of “smart” design strategies, the European Union has introduced quite a few policies and regulations. Some examples are the following directives: the 2005/32/EC on EUP (energy using products), the 2006/32/EC on energy end-use efficiency and energy services, and its new version, the 2009/125/CE on ERP (energy related products).

The Directive 2009/28/EC promotes the use of energy from renewable sources and requires that Member States should fix, by 2015, a minimum level of energy from renewable sources for new buildings and existing buildings subjected to major renovation.

The most important release of this general framework is the revision of the 2002 EPBD, the 2010/31/EC [2], known as Energy Performance of Buildings Directive (recast), which requires zero consumption as a long-term goal for our buildings.

The recast fixes 2020 as the deadline for all new buildings to be “Nearly Zero Energy” (for public buildings the deadline is the end of 2018): very high energy performance, and very low or almost zero energy demand, mostly covered by energy from renewable sources produced on-site or nearby.

1.2 Barriers in Achieving the NZEB (Nearly Zero Energy Building) Target

ZEB (zero energy building) could strongly help to reduce energy consumption, environmental loads and operational costs. Realizing sustainable buildings should be a best practice that every citizen should implement not only by reason of the presence of a strictly and mandatory regulation, but because this is a necessity for saving the world from high level of depletion, in order to allow the next generations to live in good conditions.

However, even if the development of energy efficient constructions is strongly stimulated by legislative requirements, there is still a wide range of

non-technological barriers that must be overcome in order to reach a wide diffusion of the zero energy building.

First of all, extra initial costs are far from the construction business mind. Usually, both contractors and clients are mainly driven by short-term profit-making and focus on the lowest price bidding and not on the long-term benefits and added value that can be achieved implementing environmental friendly measures [3].

Furthermore, ZEB are not usual constructions. They need a high level of knowledge and skills that are not always available in design and construction teams.

Several professionals are involved in the design process, and this might lead to problems if there are lacks in the communication among the different project team members. All stakeholders must fully understand issues and concerns of other parties and interact closely throughout all phases of the project. This is why an integrated design approach is needed to achieve multiple benefits such as higher efficiency and cost effective buildings.

Indeed every new building shall be designed since the preliminary phase for using in the best way all the chances given by the nature and by the current technologies in order to achieve the highest level of independence from traditional fossil fuel sources and the lowest environmental impact, in terms of materials use, energy consumption and pollutant emissions to the atmosphere. This necessity to design “environmental friendly” constructions must be compatible also with the amount of the investment, if the final aim is spreading the awareness of sustainable design in a spontaneous way.

The main problem now is the lack of tools needed by project teams to coordinate their work and to consider and evaluate different design alternatives [4].

In most mechanical industrial fields, ranging from aerospace to bio-mechanics, sophisticated 3D computer simulation tools have been used for years to predict machines response to specific forcing actions

in specific environments in order to integrate all the opportunities offered by different materials and technologies. The same kind of tools should be used in the construction sector.

Anyway, although many tries to develop a standard BIM (building information modeling), there is currently no software able to take into account all the features that a ZEB shall have. Thus, there is an evident need to develop software for the building simulation that can help designers to predict how the building will perform and enable them to model economic and environmental consequences of different design choices.

2. BENIMPACT Suite

BENIMPACT Suite wants to be a way to promote integrated design CAE (computer-aided engineering) and IDP (intelligent digital prototyping) in the housing field, because the authors believe that the opportunity to find “smart” solutions will lead to an increment of sustainable buildings (new or renewed ones), less natural sources depletion and green-house gas emission reduction [5].

BENIMPACT Suite analyses the whole life cycle of a building, with the aim to help designers in checking the quality of their solutions and in finding the “optimal” set of choices between different alternatives of building envelopes and energetic systems [6, 7].

2.1 Input Data and Databases

BENIMPACT Suite is connected to databases in order to speed-up the modeling process:

- (1) Materials and constructions;
- (2) Energy systems and sources;
- (3) Infiltration and ventilation rates;
- (4) User patterns and gains;
- (5) Weather data.

Databases for materials and constructions and energy systems and sources contain thermal, economic and environmental impact properties to be used for the life cycle analysis. Databases can be

updated by final users, developers, companies and in order to keep up with innovation.

Geometry models can be created and edited in a simple way using the OpenStudio (Fig. 1) or the Trnsys3d plug-in for Google SketchUp, which simplify the creation and modification of EnergyPlus and TRNSYS input files, respectively.

2.2 Evaluations and Functional Units

BENIMPACT Suite is organized in different modules/functional units (energy, LCA—life cycle assessment, cost) which can work both standalone or as an integrated system (global evaluation and multi-objective optimization) [8].

For each design, the energetic unit calculates annual energy consumption, and then the other functional units evaluate environmental impact (LCA) and costs for the entire life cycle of the building.

(1) Energetic unit

This module, which is based on EnergyPlus or TRNSYS, performs an annual energetic dynamic simulation with hourly step, verifies thermodynamic performances, and calculates annual energy consumption;

(2) LCA—life cycle assessment unit

The following environmental impact categories are considered:

- GPW—global warming potential (kgCO_2 eq.);
- AP—acidification potential (kgSO_2 eq.);
- PEI NE—primary energy intensity (not-renewable) (MJ).

Fig. 1 Geometry modeling using Google ScketchUp and the OpenStudio plug-in.

Specific routines implemented by EnginSoft “normalize” and “weight” the previous values in order to obtain a unique indicator of the environmental impact of the building to be used for optimizations. The implemented procedure is based on the IBO (Österreichisches Institut für Baubiologie und Bauökologie) workflow and both construction, use and maintenance of the building are considered [9];

(3) Cost unit

The following economic indicators are calculated:

- LCC (life cycle costing): “absolute” cost of a configuration [10];
- NS (net saving): delta LCC between different options;
- SIR (savings-to-investment ratio): expected saving over initial investments (a benchmark case is required);
- SPB, DPB (simple and discounted pay-back): time necessary to reach the break-even point of a configuration which requires a higher initial investment (a benchmark case is required).

The LCC method is used to drive the optimization process, while all the other indicators are really useful to compare different design options;

(4) Optimization and integration unit

The MOGA-II (multi-objective optimization is based on a genetic algorithm) searches for the “Pareto Frontier”, which collects the best solutions and represents the ideal limit beyond which every further implementation compromises the system [11, 12]. It is currently running on modeFRONTIER [13], a multidisciplinary and multi-objective software, where EnergyPlus or TRNSYS input files and databases have to be loaded since it is also used to integrate the different functional units and for the post-processing [14].

Results are plotted on a graph which can show up to four variables (Fig. 2), and users can select and analyze preferred configurations.

Fig. 2 BENIMPACT Suite graphical visualization of optimization results, an example.

3. Validation of BENIMPACT Suite: Case Study Selection

In order to test the validity of the project, BENIMPACT Suite was applied to different case studies, both new buildings and energy retrofitting. The validation test was made on two buildings where the monitoring data was available.

Since the use of monitored data is the most proper way of testing and understanding strength and weakness of a software/tool, the availability of such kind of data was the main criterion used for the case studies selection.

The first case study was Palazzo Kofler, built at the beginning of the 20th century, retrofitted three years ago with the KlimaHaus standard and subjected to monitoring for two years. KlimaHaus is a methodology of energy audit and certification, which aims to save energy and create a cultural change in the way people think. Since 2002, the KlimaHaus-CasaClima Agency promotes the adoption of building construction methods that meet energy saving and environmental protection criteria. Buildings designed according to the KlimaHaus standards can save up to 90% of the energy compared to traditionally built residences—thereby resulting in CO₂ reductions and financial savings [15].

Fig. 3 View of “CasaZeroEnergy” in Felettano, Udine, Italy.

The second case study was a new building, CasaZeroEnergy in Felettano (Udine, Italy) concluded in 2010 and currently under monitoring.

Following, the validation of the model performed on CasaZeroEnergy will be explained.

This methodology was divided into several steps:

- (1) Analysis of the local climate;
- (2) Analysis of the main building features;
- (3) Decision on which monitored data are important for the analysis and validation of thermal behavior prediction;
- (4) Analysis of the energetic behavior of the real building through chosen monitored data;
- (5) Building model construction;
- (6) Dynamic energy simulation;
- (7) Comparison of energy simulation results and

monitored values.

4. CasaZeroEnergy

One of the test cases used to verify and validate thermodynamic performance analysis is a northern Italian ZEB, known as “CasaZeroEnergy”. The building is a detached house, concluded in 2010 and located in the hills of Felettano (Udine, Italy) (Fig. 3).

This smart green building was designed according to the principles of the bio-climatic architecture, so local climate conditions were checked before the beginning of the design phase.

The site is characterized by a mild and humid continental climate with an average annual temperature of 13°C. There is no dry season, and summer months are quite hot. Prevalent wind runs from north to south and is useful for passive cooling (Figs. 4a and 4b).

This means that every building element and constructive solution was designed in order to minimize losses and to maximize free gains from the context, using passive design strategies, both for heating and cooling [16]. At first, the building has a compact shape, with a reduced ratio Surface/Volume of 0.78, in order to reduce heat loss in winter.

The main facade of the building is south-south-west oriented to benefit of the apparent sun path in winter.

Fig. 4 Prevalent wind runs from north to south and is useful for passive cooling: (a) bioclimatic concept of “CasaZeroEnergy” in Felettano, Udine, Italy; (b) natural ventilation in “CasaZeroEnergy” in Felettano, Udine, Italy.

On the south facade there is a great sunspace with a glazed surface of $3.60 \times 6.30 \text{ m}^2$. Openings on the east and west sides are protected from the summer sunshine with a system of shading achieved by moving louvers.

The building has two roofs: The biggest one, sloping, north facing, protects the house from cold winds in winter; The second one, on the south, is flat, lower than the other one, and arranged to support photovoltaic panels. The windows on the south facade, above the flat roof, have the function to allow air movement for summer passive cooling, letting out the air entered from the opposite northern side.

The building was built with renewable, recycled and recyclable materials for reducing the embodied energy content and the carbon dioxide emissions during the construction phase. For example, the kitchen furnishings are in recycled glass and the pavements are realized with bricks and stone slabs from the demolition of old buildings within 50 km, to limit pollution from transport. Also, the structure has a very low impact, because of the choice to use wood as main structural material.

The walls are light-weight structures, made by a timber-frame system with wooden pillars and beams. The gap insulation between the pillars is in wood fibers, while the external insulation layer, aimed to reduce thermal bridges, is in cork. In this way, the walls U-value was reduced to $0.218 \text{ W/m}^2\text{K}$. Also, the roof U-value is very low and equal to $0.205 \text{ W/m}^2\text{K}$. Inner walls are made with wood studs and plasterboard finishing. Windows and glazed parts have a U-value of $1.3 \text{ W/m}^2\text{K}$ and $1.1 \text{ W/m}^2\text{K}$, respectively.

One of the main features of this building is that it is not connected to the gas network, and it works only by using electricity, totally produced by a photovoltaic plant of 14.6 kW of peak power. Other passive alternative energy systems are installed in the building.

The first one is the sunspace on the south facade,

which allows the solar radiation entering the space and being conveniently stored.

The external glazes of this system can be fully open for regulating the temperature both in summer and winter.

In CasaZeroEnergy exhausted air is naturally replaced through the openings on the north and south facades. In this way, it is possible to ensure good indoor environmental quality, the day-time cooling of the living space and the night-time cooling of the building elements. Shading systems are very important for avoiding overheating during summer. For this reason, these systems were properly sized and selected, in order to control and adjust the incoming heating and lighting solar radiation.

Furthermore, on the building roof there is a solar collector plant for DHW (domestic hot water) production. An under-floor heating and cooling system is connected to a geothermal heat-pump that exploits the constant temperature of the earth at a depth of 2.5 m under the garden surface.

4.1 CasaZeroEnergy Monitoring

The building is currently monitored. Temperatures and electricity use are measured by thermometers and multi-meters in different spaces of the house with a data-logging interval of three minutes. Twelve rooms were selected due to their different exposition and final use (bedrooms, living room, kitchen, bathrooms, laundry, etc.).

The main scope of the monitoring is to understand the real building behavior and to validate the quality of the ZEB project, in light of the increasing necessity and demand for this type of houses [17].

Starting from monitored data, the typical day was calculated and plotted both for summer and winter periods, which correspond respectively to June 1 to July 31, 2011 and to the whole winter season of 2011-2012 (December 21 to March 21).

The typical winter day (Fig. 5) shows that 10 of the 12 monitored rooms display similar temperatures,

with a difference from the average temperature lower than 1.5 °C.

The two exceptions are: the laundry and the office.

Generally, these rooms have a constant set-point temperature of 18 °C and warmer hours depend on internal gains and solar heat gains.

Causes of the different behavior of the laundry are higher internal gains due to the presence of several equipment, which release sensible and latent heat contribution, and the windows opening during the first hours in the morning which reduces the room temperature.

Instead, the different temperature evolution in the

office is caused by a different set point and heating system. This space has a set point of 15 °C and is heated during the day by an electric heater [18].

There is another important space, which has not been monitored yet: the sunspace. It is very important for the passive heating of the building, because of its capacity to preheat the air and store the heat. Properly managed, the green house can be used for maximizing passive solar gains from October to March, reducing the energy demand.

Also during the typical summer day (Fig. 6), the same two rooms, the laundry and the office, show a non-homogeneous behavior.

Fig. 5 Monitored temperatures: typical winter day.

Fig. 6 Monitored temperatures: typical summer day.

The laundry is still warmer due to its higher internal gains except in the morning, when the windows are usually opened to allow the entire house to benefit from the passive cooling down effect of fresh winds from the north.

Like in winter, the office curve presents an odd behavior, different from every other room. This is due to the fact that this space is not conditioned. In particular, it becomes overheated during the afternoon because of its west window without sun protection.

From the comparison of the two graphs (Figs. 5 and 6), it is possible to understand that the summer and winter behavior of the office is really similar: the two curves have an identical shape and they are just shifted along the temperature axis. This difference in temperature depends on the higher amount of solar radiation entering in the room in the summer.

4.2 Validation of BENIMPACT Suite on CasaZeroEnergy

The first step required to prepare an energy analysis model for a building is to divide it into thermal zones. A higher number of thermal zones affects the time required to run an energy simulation. Thus, it is really important to individuate the lowest number of zones able to correctly reproduce the building behavior.

Basing on the previous analysis, the model was divided into four thermal zones: sunspace, laundry, office and the rest of the house (Fig. 7).

Fig. 7 Thermal zones of the building model.

Some hypothesis on set point temperatures, air change rates and internal heat gains were made. Set point temperature values were deduced from monitored data, while for internal gains the starting points were values given by Italian directives.

In summer, the sunspace is open and without a heating system it is possible to better appreciate the influence of internal gains. For this reason, a model without the sunspace was prepared and verified using summer monitored data. Summer thermal simulations were run and the building behavior was checked varying inputs until the model and the real building converged.

At first, the authors also ran simulations without turning on the cooling.

The living space was the easiest to adjust because it is used as a standard living space, according to the final use established in the regulation.

For the laundry, increasing internal heat gains were simulated in order to meet the real behavior of the room, strictly related to the presence of equipment.

The opening of the windows, scheduled as resulted from monitoring, was then added. The introduction of this ventilation ratio was necessary for the overlapping of the model to the real building.

After that, the sunspace was added. In modeling this element, the most difficult part was defining the air exchange rates between the living space and the sunspace and between the sunspace and the external environment. Furthermore, an appropriate schedule for the sunspace opening management had to be hypothesized due to the lack of real data.

When the whole building model with all the four thermal zones was ready, the winter thermal simulation was verified. For performing this analysis, it was necessary to complete the office thermal zone definition by the introduction of a standard electric heater. The schedule of the heater was supposed looking at the monitored data.

As shown in Figs. 8 and 9, the building model with four thermal zones simulates well the real temperature

Fig. 8 Monitored vs. simulated temperatures: typical winter day.

Fig. 9 Monitored vs. simulated temperatures: typical summer day.

evolution of the building. Small differences are due to the faster response of the model, which has less thermal mass: only the building envelope, all internal floors and ceilings and partitions which encase thermal zones are modeled, while other internal walls and the furniture are not simulated.

By means of the simulations, not only energy consumption and temperatures were verified, but also the time constant of the entire building, which depends on thermal capacity and thermal transmittance of constructions.

It is interesting to learn it is the real difference between the calculated time constant for the real building and for the model.

For performing this kind of calculation, it was necessary to use monitored data of a period in which the home was empty and every system inside was not

used (end of November—beginning of December 2011).

The time constant τ_0 was calculated using the following expression:

$$\tau_o = - \frac{\tau}{\ln \left(\frac{(t_f - t)}{(t_f - t_i)} \right)}$$

where,

- (1) τ is the time of calculation;
- (2) t_f is the final temperature of equilibrium between the building and the environment, and it was supposed to be equal to the average external temperature of the considered period;
- (3) t is the instantaneous temperature at the time τ ;
- (4) t_i is the initial temperature of the building, when the heating system of the building was switched off.

For the monitored data, the result of this equation was equal to 100 h and for the model the time constant resulted in nearly 70 h. This second value is more

similar to that one calculated during the design stage using the following expression:

$$\tau_o = \frac{C_m}{H_{tot}}$$

where, C_m is the total thermal capacity of the building, H_{tot} is the total thermal losses coefficient.

Indeed, in this way, the result was equal to 58 h with the same values of thermal capacity and thermal losses coefficient also used for the model.

There is an evident similarity between these two results, which are both calculated without taking into account the presence of all internal thermal masses, as explained above. This confirms the hypothesis made when comparing the real behavior of the home with its simulation (Figs. 8 and 9).

Once the model was validated with all the considerations above, it was possible to affirm that the calculated net heating and cooling needs of the building, which are respectively 20 kWh/m² year and 12 kWh/m² year, can be reasonable, and they could be even lower than expected thanks to the higher thermal mass contribution.

It is important to underline that this building is not equipped with a mechanical ventilation plant with heat recovery. Therefore, the calculated energy demand is very low and the possibility to implement such kind of a system would give greater energy results, but at the

same time it would affect the concept of the bioclimatic architecture of the building.

In any case, with this current configuration, all thermal loads can be totally covered by the renewable energy produced on-site by solar collectors and PV panels. Considering the energy efficiency of the geothermal heat pump in both heating and cooling mode, 14 MWh are still left and they can be used for domestic electric energy needs and the left over can be sold to the grid.

Another analysis was made to check the effective contribution of the sunspace to reduce net heating energy consumption. For this purpose, the average day net heating power for the living space, with and without sunspace, were compared (Fig. 10). Here, the green house contribution is truly welcomed as it reduces the net heating needs of the building by 4 kWh/m² year.

One last performed analysis was related to the possibility of further simplifying the energy model, by unifying the living space zone with the laundry and the office, in order to have a model composed of only two thermal zones: the house and the sunspace. In this model, standard ventilation rates and standard internal gains were used and the calculated net heating and cooling needs were respectively equal to 19 and 10 kWh/m² year. Due to the small dimensions of the

Fig. 10 Net heating power required by the living space without or with the sunspace (GH).

Table 1 Summary of the analyzed building models and their results.

Model	Thermal zones				Net energy needs (kWh/m ² year)			Simulation results
	Sunspace	Laundry	Office	Rest of the house	Heating	Cooling	Energy needs	Thermal behaviour of the rooms
Four thermal zones	√	√	√	√	20	12	Adequate	Adequate
Without sunspace		√	√	√	24	12	Adequate	Adequate
Two thermal zones (standard input values)	√				19	10	Adequate	Not adequate

office and the laundry, this model could be used to assess the building energy needs and for heating and cooling plant sizing, however, because of its lower level of detail, is not adequate to show the inhomogeneous behavior of these two rooms.

A summary of the analyzed building models and their results is reported in Table 1.

5. Conclusions

To effectively reduce the energy demand of a building, both winter heating and summer cooling loads have to be considered through an integrated design process based on consistent energy concepts.

There are many design choices that affect the building's energy demand, such as:

- (1) Building form (surface/volume) and orientation towards four cardinal points and prevailing winds;
- (2) Window size and orientation;
- (3) Shading systems.

All those variables mean that each building design is different, particular, and it can not be defined only through statistic and scientific research. In order to implement very good solutions, high energy performance constructions and systems can not be considered as stand-alone elements, because they have to work well together, as a unique organism and in that specific environment. This is why the designer has to strongly consider also the specific micro-climatic condition and users habits through a dynamic simulation model. Simulations allow determining the thermal behavior of the building under specific conditions, verifying potential and

constraints of different design choices and trying to find solutions to fix design errors.

The test case of CasaZeroEnergy demonstrated that BENIMPACT Suite is an effective tool to assess the building energy needs, for heating and cooling plant sizing, and to verify the thermal behavior of different rooms. It is also shown that it is really important to individuate parts of the house which might behave in an odd way, and separate them in the model.

Thermodynamic and environmental performances were analyzed, hour by hour and for the entire life of the building, using the software package EnergyPlus and some prototypes implemented by EnginSoft, showing that the specific micro-climatic condition and users habits can really affect the behavior of the building or some of its rooms (Figs. 5 and 6).

The energy model is the first step of a more complex process that analyses the whole life cycle of a building. It has been integrated in BENIMPACT Suite through specific utilities developed by EnginSoft which calculate also environmental impact and cost of each configuration and search for the "optimal" trade-off between environmental and economic sustainability. In fact, in order to spread the awareness of sustainable design, "environmental friendly" constructions must be characterized by "smart" investments, and the convenience for all has to be proved in a scientific way, as done in this work with the thermodynamic performances.

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