HOW TO APPLY BUILDING ENERGY PERFOMANCE SIMULATION AT THE VARIOUS DESIGN STAGES: A RECIPES APPROACH

Andrea Ferrero[1], Emanuele Lenta[1], Valentina Monetti[1], Enrico Fabrizio[2], Marco Filippi[1]

[1]DENERG, Politecnico di Torino, Torino, Italia
[2]DISAFA, University of Torino, Grugliasco (TO), Italia

ABSTRACT

Designing high-performing buildings has led the design process towards a multidisciplinary and integrated design approach, with energy design emerging as new expertise. Energy design is usually assisted by building simulation, which does not represent an absorbed knowledge. To this regard, this study aims to provide guidelines for the use of building simulation at the various stages of design process, by means of a recipes approach. Different steps for each design stages were defined. A case study modeled in EnergyPlus is also depicted as practical experience to extrapolate this approach. A building simulation recipe was created for each main stage of the design process.

INTRODUCTION

According to the European Directive 2010/31/UE, from December 2020, all new buildings will have to be "nearly Zero Energy Building" (nZEB) (UE, 2010): that means high energy performance buildings, whose very low energy demand can be supplied with energy from renewable energy sources produced on site.

For designing nZEBs architects have to lead the project towards a high levels of energy performance (Attia, 2012). Compared to the traditional design, nowadays in an integrated approach, intuition and traditional tools are not more sufficient (AIA, 2012).

The American Institute of Architects supports the importance of integrating computerized energy simulation tools in the Design process, since the very preliminary phase (AIA, 2012), in which the design decisions taken so far subsequently have an influence on the majority of the further ones (Hemsath T.L., 2013). Many authors (Donn, 2009, Bambardekar, 2009, Bazjanac, 2011, Hensen, 2011) agree that building performance simulation is becoming an unavoidable means to guarantee the full achievement of the chosen targets. The implementation of an energy model makes possible to manage project ideas, materials, and details in a dynamical and interactive way, in order to have an optimal control on internal comfort levels, passive strategies, energy efficiency, renewable sources and innovative solutions.

The level of application and research has increased, due to the development of detailed and free software tools (Crawley, 2008). However, some critical issues, such as the time for modelling and running the simulation, limit the application of building simulation that is thus not always able to follow the evolution of the project. Moreover the average cost of some of these software (not open source); the skills required to master these programs (Hobbs, 2003); and the need for large quantity of input data from the very first stages of the simulation (Attia, 2009) (Hemsath, 2013) can impact on the simulation use.

Quasi-steady calculations are used for the energy assessment but they don't allow to analyze the behavior of the building and the plant in a dynamic state. Indeed the quasi-steady calculations method is thus based on a simplified and standardized procedure that does not consider the positive and negative effects of the hourly variation of climatic variables, whereas dynamic buildings simulation software tools are based on algorithms considering the hourly trend of physical phenomena that govern the building-plant system. This thus allows to obtain a more realistic picture of the building behavior, and more detailed outputs (with hour-steps of output, rather than monthly). It also makes possible to carry on studies, such as the evaluation of the thermal masses distribution or the comparison between different types of cooling plants, which require the simulation of the dynamic behavior of the building-plant system (Fabrizio et al. 2012) or the coupling between demand side and supply side measures (Bayraktar et al, 2012).

Furthermore, some sustainability protocols encourage the use of dynamic building simulation for the design of green buildings, such as the LEED rating system (USGBC, 2009).

A new professional figure, referred as energy modeler, has been developing, devoted to the creation and simulation of building energy models, which requires specialized skills (Hayter, 2000).

The energy modeler is a professional figure of growing interest (Anderson, 2014) that provides support to the design process through feedback and numerical data guiding the design team towards low energy choices. His activity is not limited to the verification of the building energy performance in pre-construction phases, but can regard each design phase with specific simulations.

METHODOLOGY

The authors took part to the 2014 Solar Decathlon Europe competition within the project Sunslice of the Polito team. In order to achieve the sustainability goals, the Sunslice project required the creation of different building energy models for each project stage and consequently the running of a great number of simulations.

After completing the project, the data and materials relating to the simulations performed, were analyzed aiming to define a sort of "building simulation guidelines" to be used during the design process. In particular, the relationship between the energy simulation and integrative design process was investigated trying to identify common stages. Later the outcomes of this analysis were applied to a case study. A set of recipes were defined addressing to the use of building simulation during the design process. The recipes aim to collect all relevant information to perform simulations in different stages of design. The goal is to provide, for each type of simulation, a complete chart of the input data and the steps needed to the construction of the energy model and the use of output data obtained.

A similar approach can be found in the literature (Hand, 2011). With special reference to the building simulation program Esp-r, Hand developed an Esp-r cookbook to provide general guidance for deploying virtual representations of the built environment.

ENERGY SIMULATION AND INTEGRATIVE DESIGN

Integrated design process

According to (Brunsgaard, 2014), the Traditional Project Delivery (TPD) is a form of more traditional design (typical of contexts such as North America and Europe), which is linear and composed of independent stages. The actors involved in the early stages of the project are the customer and the architect, who defines the proposal at the conceptual level. In the following stages, the implementation of the building functional performances is generally conducted by engineers. This type of design does not take into account the energy performance requirements since late stages of the design process: it is thus more difficult to apply changes to the building design without increasing cost. Bioclimatic aspects and building energy performance is usually not adequately considered.

In recent years several research projects have focused on the integrated design process, in order to better manage the complexity of the high energy performance projects (AIA e AIA CC, 2007) (IISBE, 2009) (IEE, 2014). The breakdown of the process at different stages and the schematic identification of the activities in each of them unite the different projects. An iterative process, where the team members work together in a collaborative way, characterizes this approach. The process stages are defined by milestones that represent decision-making moments. A multidisciplinary team, composed by professionals with different expertise and skills, drives the design process.

The analysis of the case studies shows a possible classification of the phases that compose them. As shown in Figure 1, overall six stages can be listed: the pre-design stage, three design stages, and two post-design stages. The integrated design process focuses on the first four stages (Concept Design, Schematic Design, Development Design, and Construction Document).

Within the integrated design process, energy simulation can give more quality to the process. Compared to traditional design practices (where the stages occur only in sequence), in the integrated design an iterative approach is adopted to study different design solutions. Only later – during the design development stage– one of these solutions is chosen and optimized. The energy simulation is the tool that allows to compare the design alternatives and to optimize the final solution.

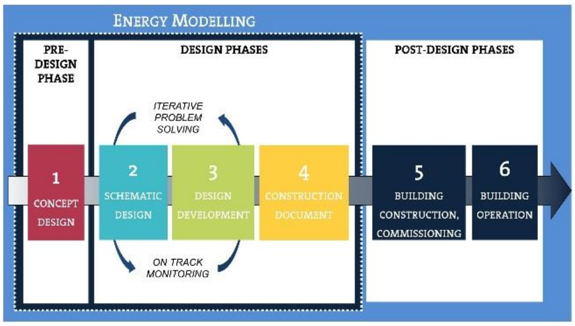

Figure 1 Integrated design process.

The integrated building simulation–aided design process

For each stage of the integrated design process, specific steps of the energy simulation process are defined.

As depicted in Figure 2, step 1 involves the identification of the energy goals and strategies that will guide the future design decisions. At this stage, it is very important to collect all the necessary information about the site, local weather conditions, available energy sources and functional requirements of the building. The simulation of the building performed at this stage is not a whole building simulation. Only climate studies are performed by using programs which allow "to read" weather files of the studied location (e.g. Climate Consultant 5.4 and Autodesk Weather Tool) and to study the relative climatic conditions (profiles of temperature, humidity, days of project etc.). For instance Iwecfiles (International Weather for Energy Calculations), developed by the research project ASHRAE (ASHRAE Research Project 1015, 2003) are text files available in various formats (epw, stat ..), containing all the climatic variables of a reference year in a given location (8760 hourly values of dry bulb temperature of the air, wet bulb temperature of the air, specific humidity, etc.., which are then interpolated by the software on the time step of calculation). The definition of the energy goals, within the concept design phase, allows the design team to integrate into the work strategies for energy saving.

In step 2 it may be useful to employ "reference building models", (i.e. standard models of reference with features similar to the project building for solving the problem of the lack of input data in the early stages of design. Even at this stage, no simulation are performed, but works of research and input data collection from reference buildings are carried out. From this point of view, the commercial building reference models, developed by the US DOE and available on-line (DOE, 2009), may represent a valuable source.

In step 3, the guidelines of the design (the shape, the orientation, the volume and the distribution of the interior of the building) provide the first input data for the energy performance simulations. At this stage, particular attention is placed on the aspects related to the geometry of the building, which will not be modified later in the design process (Morrissey, 2010). The goal is to combine energy strategies with the architectural choices. The first studies on the building systems are usually developed at this stage and lead to the identification of the type of thermal generating unit (based on the availability of the energy sources identified in step 1), and the concept related to production of DHW and Photovoltaic. In this phase, the creation of the first energy model allows to perform simulations devoted to the study of the building orientation, the form and volume, and the definition of the conditioned zones. Since this represents a preliminary design stage, the use of input data taken from standard reference models allows to speed up the modeling, in order to evaluate different design solutions.

After working on the geometry of the building, in step 4 the focus is brought to the building envelope design. In this case, the studied solutions do not affect the overall shape of the building but only the formal aspect. Simulations mainly concern window to wall ratio for different orientation, type and geometry of solar shading systems, optical and thermal properties of transparent components, natural ventilation strategies, the layers of the building envelope opaque components and the internal thermal mass.

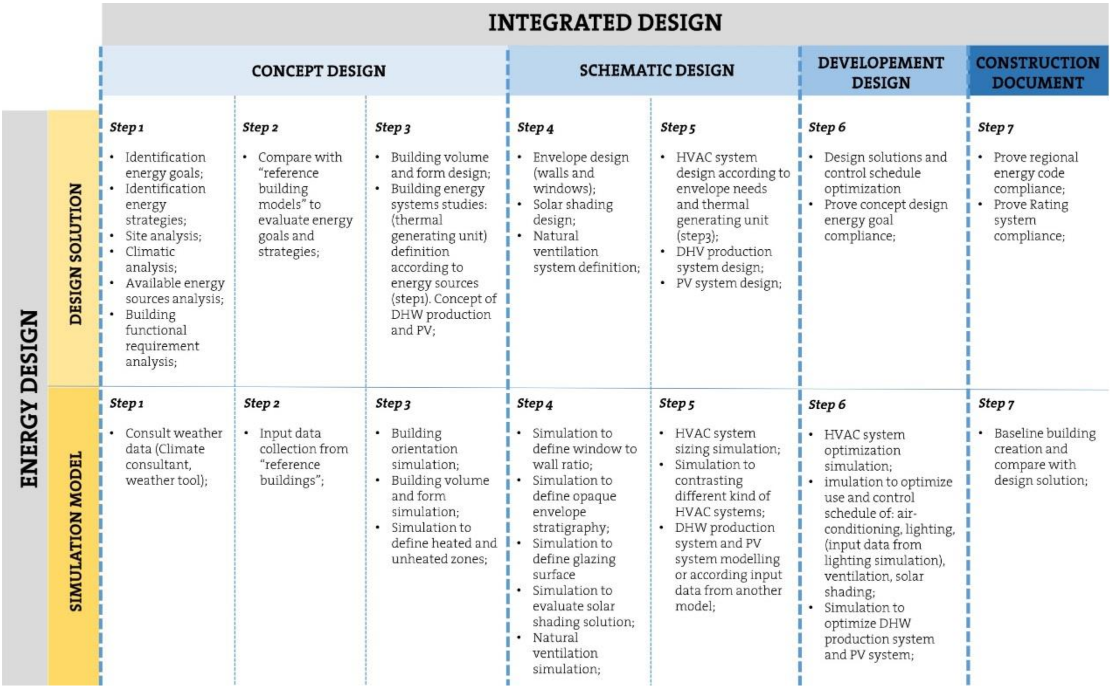

Figure 2 Energy design steps during the four main stages of the integrated design process.

In step 5, the HVAC system in accordance with the envelope needs and the thermal generating unit type, is defined. The DHW production and PV system generation are also investigated. At this stage, the energy model is updated with the design choices related to the building envelope. Simulations are performed during the design days for the sizing of the HVAC, which is subsequently modelled. Similarly, the DHW production system and the photovoltaic system are modelled (according of data if they were designed on another model).

Step 6 regards by the optimization of the project: detailed solutions and control schedules are thus investigated to be optimized. With regard to the energy modelling steps, simulations related to the optimization of the systems, of use and control schedules, and of thermal and visual comfort are developed. At this stage, the energy model is completed with a high level of detail. It is possible to get annual results on all the building energy uses to be compared with the reference values set.

Step 7 (during construction) concerns the regional code compliance and classification according to the rating system of building sustainability used in the project(e.g. LEED protocol). In this last design stage, the baseline building is created and compared with the proposed building. The score obtained by the rating is based on the percentage improvement of the proposed building energy performance compared to the estimate primary energy consumption of the baseline building.

THE CASE STUDY

The Sunslice project

The case study is set into the Solar Decathlon Europe 2014 architectural contest, to which the Politecnico of Turin participated by the elaboration of the Sunslice project: a vertical building conceived with the purpose to solve urban density.

The energy model

The building was modelled within the EnergyPlus program v.7.2. The three-dimensional geometric building model was created in the SketchUp program, with the Openstudio plug-in for generating and exporting idf file (EnergyPlus input files). The building was simulated in Turin. The building was divided into five heating zones, four of which were conditioned (living zone, first bedroom zone, second bedroom zone and bathroom zone) and one was not (technical zone). The heating temperature set points was set to 19°C in the living zone and bedrooms zone and to 21°C in the bathroom. Solar shadow were also studied in SketchUp, to obtain monthly schedules of the sun shading for the south exposed windows.

The occupation rate in the rooms is set to 0.04 pers/m^2 (UNI 10339, 1995 (table 8)) with an occupant activity level equal to 120W per person. The occupancy schedules were distinguished for different time periods, days of the week and thermal zone of the building. About lighting and internal gains, the values of the installed power in the various rooms have been sized through simulations on artificial lighting. The lighting power density varied according to the room typology: 3.57 W/m^2 for the bedroom zone, 3.5 W/m^2 for the bathroom zone, 3.72 W/m^2 for the living zone and 3.94 W/m^2 for the second bedroom. The appliance internal gains were calculated by setting an installed power of 5.38 W/m^2 (DOE Reference Commercial Building, Midrise Apartment building, new construction 90.1-2004).

As for the ventilation, in simulations where the system was off, the rate of natural ventilation was set to 0.3 vol/h (with a factor of heat recovery efficiency in winter period equal to 75%). In the simulations of the HVAC system the value was set to 0.7 ric/h (referring to the UNI EN_15251 Table B5: In-door Environment Criteria) for the supply of the mechanical ventilation system. Unlike real systems, the return rate was imposed (by the program) as equal to supply rate, in order to balance the system.

With regard to the system modeling, one of the EnergyPlus HVAC templates was employed. In particular, the "Unitary heat Pump: air to air", constant flow with a direct expansion heating / cooling, was used. The simplification adopted by this template, considers a single terminal unit that serves the various zones, rather than more terminals as in the real case. Quadratic and biquadratic functions of COP and EER curves were calculated to determine the performance of the system , starting from climatic data of Turin (wet bulb temperature, dry bulb temperature of the air).

Results

The Solar Decathlon Europe 2014 organizing committee set specific design stages by means of different deliverables. Based on this, the Solar Decathlon design stages were reformulated according to the integrated design process stages depicted previously.

In the concept design stage, the analyses related to the climatic context, guided the definition of bioclimatic strategies in relation to the context. In particular, studies exploring which features of the climate in Turin could be exploited (Te <Ti during the summer night can be used for free cooling, maximizing solar gain in the winter) and which mitigated or controlled (excessive direct sunlight in summer, cold weather in winter), were carried out.

Initial simulations were also performed on highly simplified geometric models in order to investigate the design of the building form and orientation by evaluating their influence over the building energy demand.

During the schematic design stage, simulations related to passive design, were performed as follows:

- Comparison of different solutions for exterior walls, roof floor, internal floor and ground floor;
- Optimization of the windows sizing.

South exposed windows were designed to maximize gains in winter, while North windows were designed aimed at finding a good compromise between small heat loss in winter and quality of natural lighting (e.g. a first study of the south exposed windows shading (with the choice of a exterior mobile curtain) and a first study of the natural ventilation strategies).

The energy demand trend and the level of thermal comfort were investigated at this stage. With regard to the thermal comfort, additional simulations were performed to study the trend of internal operative temperature, determining the percentages of values that fell within predetermined comfort conditions. At this stage, the systems for the indoor climate control were not modelled as only the building passive behaviour with respect to climatic condition was investigated. For the sizing of the system, the winter heating and cooling loads were calculated with ad hoc simulations in the winter and summer design days (January 21), resulting in 4981 W and 3570 W respectively. The yearly building energy need for heating and cooling are reported in Table 1.

Table 1
Case study simulations results

ENERGY NEEDS	
Heating	13.23 $kWh/(m^2y)$
Cooling	16.30 $kWh/(m^2y)$
ELECTRICITY DEMAND	
Heating	9.29 $kWh/(m^2y)$
Cooling	4.27 $kWh/(m^2y)$
Mechanical ventilation	3.22 $kWh/(m^2y)$
PRIMARY ENERGY	
Exported energy	42.63 $kWh/(m^2y)$
Delivered energy	20.69 $kWh/(m^2y)$

Simulations were also performed during design days for the HVAC system sizing. At this stage, the system was modelled. Initially it was initially set as a VRV system with a heat pump, but after simulations showed that thermal loads were too low for this type of system, a multi split heat pump air-air was thus adopted.

The Development Design stage (Step 3) concerned the optimization of the various building components. For instance, with regard to the HVAC system, the COP and EER curves, were calculated and then used in the simulations.

Moreover, specific use and control schedules for the HVAC system were defined based on assumptions on the building management and occupancy. A similar approach was adopted for the lighting use shading control.

Furthermore, for each month of the cooling period in a conventionally day, the curtain length required in the different hours of the day up to a completely shield the window from direct solar radiation, was investigated.

The simulations results concerning the electricity demand for heating and cooling and for the mechanical ventilation system are presented in Table 1. The Italian conversion factor 2.17 was used for converting electrical energy into primary energy.

Finally during the Construction Document stage simulations were carried out as in compliance with the LEED rating system.

All the simulations carried out in the project are summarized in Figure 3.

SIMULATION RECIPES

Building simulation represents a topic of growing interest, especially with a view of achieving low energy and sustainable goal during the design procress. Even if some references for the use of building simulation during the design procress are already available (e.g. Hand, 2011), the integration of building simulation for a better building design, is still problematic.

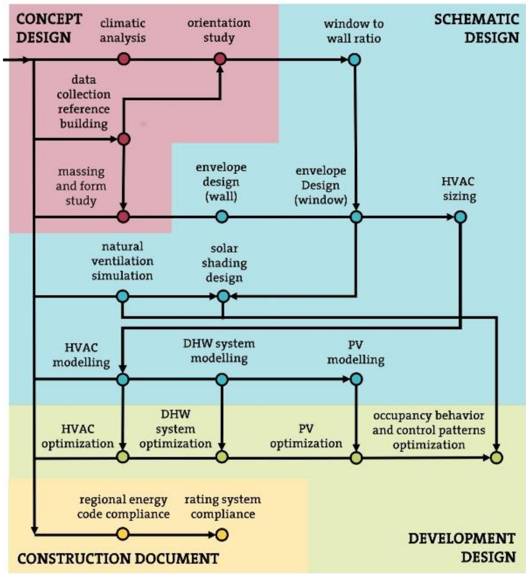

Figure 3 Energy modelling flow in Sunslice project.

To this regard, the authors developped an handbook for building simulation which was not meant to be regarded as an exhaustive reference for the building simulation applications, but it is rather a guideline for building simulation beginners to fill in the above mentioned gap especially in the application of building simulation from early stages of the design process. In particular, it starts from the basics, "the creation of a building energy model" and follows up on how simulation can be used to direct design choices.

With the application of the authors' approach to the case study, as depicted in the previous section, several remarks about the use of energy modelling during architectural design were made.

First, in early stages the need to define a building geometric model and to enter a large number of data about the building (many of which are unknown) makes difficult to support the evolution of the project. It also requires a deep knowledge of the building thermo physical features, climate, technologies and systems to manage the complex set of data input and output. Especially in the later stages of the simulation, the energy model becomes more complex and plant systems play an important role with its settings.

As for the output data, they often must be correctly treated in order to verify the results and/or to find forms of communication of the results easy to understand for the other designers and consultants. Whether possible, the energy performance assessment results should be presented in a graphic and easy to read format, based on results comparisons between different solutions, when necessary.

The above highlighted aspects led to a critical review of the simulations carried out in the Sunslice project, through an analysis of the different types of simulation. The intent is to track the design data of the simulations (using input data and specific outcomes) trying at the same time to outline generic steps that can

be applied in other projects for each type of simulation.
By analysing the process and the elements that characterize each steps of simulation, different types of simulation were identified by means of a recipe-based approach. In fact, similarly to the preparation of a recipe also in energy modelling, everything starts with some ingredients (the input data of the energy model to be simulated), based on a preparation process (the energy modelling process) and it is completed by a final result/product (the output data of the simulation). This "cookbook" of energy modelling is therefore a practical guide to the use of energy modelling during the design process. Eight representative simulations were selected from the case study to create exemplar recipes. The "cookbook" is organized in four sections, according to the logic used to categorize the stages of the simulation process (schematic design, concept design, development design, construction document), as also depicted in Table 2.
If opposed to the Esp-r cookbook, the set of recipes proposed by the Authors is characterized by a more practical approach. In his Cookbook Hand included a first generic introduction to building simulation, highlighting the tactical approaches usually employed and the corresponding design and simulation questions to answer to when dealing with a client's requirements during a building project definition. Practical examples of the various modelling tasks (e.g. geometry modelling, building schedules, climate data, etc) with direct reference to the Esp-r platform are included in the Cookbook, which is also completed by a companion Exercises book.

Table 2 Simulation recipes

DESIGN/ENERGY MODELLING PHASE	CONCEPT DESIGN	SCHEMATIC DESIGN	DEVELOPEMENT DESIGN	CONSTRUCTION DOCUMENT
RECEIPTS	• Orientation study • Massing and shape study	• Envelope design: wall • Envelope design: window • Solar shading design • HVAC sizing and design	• HVAC optimization	• Rating system compliance

Each simulation recipe proposed by the authors is composed of four main sections. The first section corresponds to a "Recipe at glance" which allows the user to identify the main features of the recipe, by providing information regarding the level of difficulty and the time of preparation (divided in geometric modeling, numerical modeling and graphical restitution of results) and the time of "cooking" (i.e. the time that the PC run the simulation). The second section (Ingredients) collects the list of all the inputs necessary for defining the building energy model, as reported in Table 3. This section also provides a picture of the building model level of detail, which corresponds to the level of simplification or complexity required for the pursued task to be accomplished.

Table 3 List of input categories

INPUT CATEGORIES
Profile of Occupation;
Profile Lighting;
Profile of Electrical Equipment;
Profile Ventilation;
Profile of the temperature set point;
Profile of Shading;
Housing Opaque;
Housing Transparent;
Geometric Modelling;
Thermal Zone;
Plant.

For each of these categories three different levels of detail were defined.
The third section (Preparation) focuses on how to finalize the "recipe", describing the necessary steps to create the geometric model, set the numerical model and obtain the correct output of the simulation.
The concluding section (Presentation) collects in a graphical form the simulations outputs and presents some proposal of graphical representations (e.g. exemplary charts). It also contains the explanation of the operations and the features necessary to compare and illustrate the results. Figure 4 depictes the recipe for the building envelope design.
The preparation time reported in each recipe was quantified based on the energy models developed for the case study and expressed in hours, while the partial time (geometric modeling, numerical modeling and processing and graphic rendering of the results) as a percentage of the total value.
All the ingredients (input data) necessary for the building envelope design are flagged in the corresponding input categories. The number of checkmarks (one to three) indicates the level of detail used. In the example, there are three checkmarks for the opaque envelope because this simulation use detailed project constructions and a single check for the ventilation because there is a simplified and constant rate. Even though the section concerning the preparation of the simulation, organized in steps, is made as general as possible, it makes reference to the simulations carried out in the case study through the use of Openstudio for geometric modeling and EnergyPlus for the numerical modeling.
The section concerning the presentation of the results, following the directions on the organization and representation of the outputs obtained, shows the graphs relating to hour energy requirements. The graphics are accompanied by a summary table containing the annual values of total energy requirements that allow comparing the two project ideas to them.

Impact

The audience of the recipes proposed by the authors is that of professionals and designers, aiming to have a direct impact on the design process of sustainable buildings. The recipes were gathered into different typologies to help users, in particular the project team, handle the energy modelling during the design process and apply the right recipe to the corresponding design stage. The set of recipes were also published in their Italian version to spread the use of building simulation among the professional community.

Another major application of these recipes is that of the academic context. One of the main aim pursued with the creation of this set of recipes was to promote the use of building simulation during lectures. The recipes can hence be used by students in engineering and architecture classes for the implementation of the energy modelling in an integrated design process. Prospectively, the impact of these recipes can be verified by evaluating how students with and without recipes accomplish the assigned task and comparing thus the recipe real influence in the design process.

CONCLUSIONS

A set of recipes for the use of building simulation and the energy modelling during the different stages of the design process were presented. In contrast to the common use of manual and guides for the use of specific building simulation programs, which are more frequently available, these recipes are conceived as generic guideline for the use of building simulation during the design process. However in order to give some practical examples, they also include some building simulation applications with the EnergyPlus software.

Further implementations to this set of recipes could concern the inclusion of recipes with examples referring to other simulation software.

A possible future prospect may be a larger set of recipes to be available online open source as a reference for students and designers who approach building simulation for the first and for those who need to use the building performance simulation in both the academic and the professional field.

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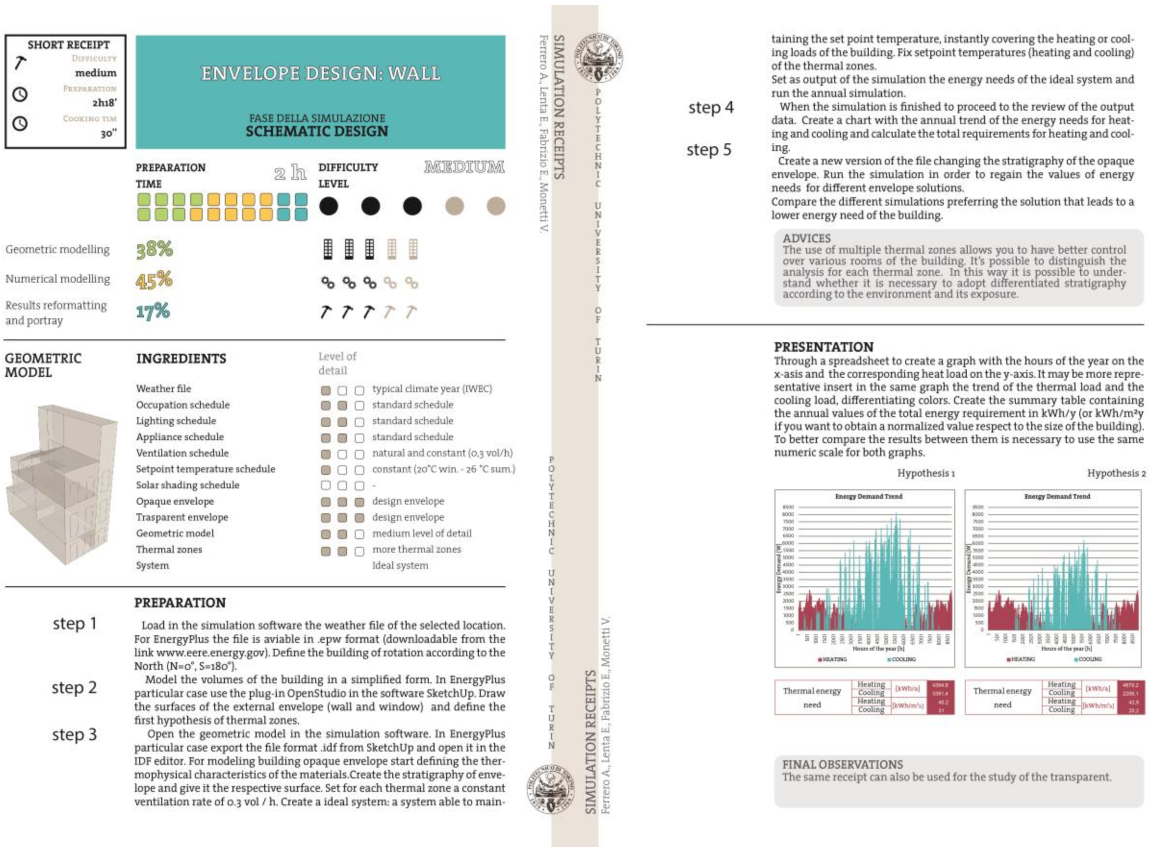

Figure 4 Recipe example: Building envelope design