FAST RESPONSE BUILDING ENERGY SIMULATION IN SUPPORT TO LOW CARBON DESIGN AND RETROFIT

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ABSTRACT

This paper investigates the benefits of applying building performance simulation throughout the design of new buildings and energy retrofit, with a major focus on low- and zero-carbon buildings. During the analysis, the state of the art on building simulation and the major drawbacks of the application of such advanced techniques are also highlighted, including a justification on why such tools are not commonly used in practice, especially when focusing on the first stages of building design. Eventually, the paper proposes a possible solution by introducing a fast response building performance simulation tool able to deliver dynamic energy simulation of buildings in limited time and with a limited number of inputs, nevertheless maintaining a reasonable level of accuracy. Although the tool itself is still a work in progress, the underlying simplified model and the input scheme have already been defined. Once complete, it is expected that such a tool could greatly help in the integration of advanced energy evaluation techniques in the design process of new buildings and feasibility analysis for building retrofits by greatly reducing time requirements and costs, while still being able to deliver useful results to the design process. Examples and case studies are presented to show the benefits obtainable by applying the tool compared to traditional more complex simulation tools. Hence, the main aim is not to present a software, but the method that enables the use of dynamic performance simulations in early stage building design.

INTRODUCTION

In recent years, zero carbon building (ZCB) has emerged as an innovative approach to reducing negative effects of CO2 emissions related to the building sector. Several countries have set regulatory targets for ZCB.

Although the definition of ZCB could sometimes leave space for interpretation, it is commonly referenced as a building in which the carbon emissions generated from on-site or off-site fossil fuel use are balanced by the amount of on-site renewable energy production, also referred to Zero Energy Buildings (ZEB) or Net Zero Energy Buildings (NZEB).

As those terms increasingly become of common use during daily practice in the building sector, an increasing number of such buildings are starting to rise as demonstration projects (Marszal et al., 2011).

Meanwhile, national and international regulation are pushing for those concepts to become mandatory in an attempt to reach energy and emissions reduction targets (IEA, 2008; European Parliament, 2010; ASHRAE, 2008). Most relevant to the discussion is the recast of the European Performance of Buildings Directive (EPBD) requiring all new buildings to be “nearly zero energy” buildings (nZEB) by 2020, including existing buildings undergoing major renovations.

As those regulations slowly comes into place and the building sector moves toward a more common definition and application of ZEB and nZEB concepts (Sartori et al., 2012), buildings will become more complex, pushing their performances to the limit both by reducing the energy needs of the envelope to the minimum and integrating innovative technologies for energy generation (Athienitis et al., 2010).

The necessity of optimising the performances of the building is leading to a change in the way buildings are designed, from a traditional multi-step design, to an integrated design (IDP), also known as whole building design (Attia et al., 2012). With this approach, every aspect of the design is handled concurrently and is considered interrelated, applying the concept of holism. Experts in different fields are therefore involved equally in the design of the building and both intuition and traditional tools are not sufficient anymore to achieve the required performances (AIA, 2012).

At the base of a successful design process is the need from the design team to have all the required information available, and this becomes increasingly important when considering integrated design and the need to achieve high level of performances such as in ZCBs or nZEBs. When evaluating the energy performances of highly efficient buildings it is not possible anymore to evaluate the single components in isolation and traditional tools becomes inadequate, leading to the need for new advanced tools, such as the application of Building Performance Simulation (BPS).

Building performance simulations can help in reducing emission of greenhouse gasses and in providing substantial improvements in fuel consumption and comfort levels, by treating buildings and their thermal systems as complete optimised entities and not as the sum of a number of separately designed and optimised subsystems or components (Hensen et al., 2004).

SIMULATION DURING DESIGN

When working on simple and conventional buildings, there is often no need to rely on advanced analysis to guess the behaviour of the structure, and traditional methods and experience can provide enough information to the design process. Nonetheless, when moving toward less simple situations, where complex building physics or complex installations are involved, a proper design cannot be achieved without the help of simulations (Hensen et al., 1993). This becomes increasingly relevant when moving toward ZEBs and nZEBS. The nature of the aggressive goals of nZEBs requires the creation of energy models during early design phases (Utzinger et al., 2009).

During the design process, a great number of decisions are taken based on various assessment criteria. It is self-evident that decisions taken at earlier stages of the design have bigger impact on building performances than measures taken during the later stages. This also helps the shift toward integrated design, with the idea of making decisions earlier in the design process, maximising the ability to influence the capabilities of the building while minimising the cost of design changes, as also shown by the "MacLeamy Curve" (Aziz Z., 2011).

A more efficient use of Building Performance Simulations during the early design stage could be very beneficial for the end result of a project, providing useful information on the energy performances of the building to the design process from the first phases and allowing informed decisions to be taken to ensure the achievement of ZEB/nZEB standards (Ferrero et al., 2015).

This could not only have a significant impact in term of architectural design of the building, but also in term of system design and sizing. Knowing energy needs, peak loads and thermal power curves of the building from the beginning stages of the design could greatly help the system engineers correctly identify the size of plants and optimize them based on the building's foreseen performances. Not only this, but it can also help in correctly evaluating the evaluation of innovative low carbon technologies, such as CHP (combined heat and power) machines. Those technologies can have a significant impact on CO2 emissions, but need to be correctly studied and designed from the beginning of the project to properly work as expected during the operation of the building (Gelegenis et al., 2015). An example of this is shown later in the paper where the results of the tools are used to properly size a CHP machine based on the thermal demand of the building.

Although BPS tools have great potential in helping the design process, they largely remain confined to be used as a verification tool and are yet to emerge in common industry practice (Attia et al., 2013).

Many existing energy simulation tools for buildings are very sophisticated and promise a high level of accuracy (Witte et al., 2001), such as Energy Plus and DOE-2, however, despite the proliferation of many BPS tools in the last ten years, architects and designers are still finding difficult to integrate them in the design process.

The two major obstacles to the wider implementation of BPS analysis during early stage building design and feasibility analysis can be identified in the lack of appropriate tools and the lack of resources (Attia et al., 2013; Ostergard et al., 2016).

Those two aspects are strongly related as the lack of resources is represented by the lack of required time and expertise needed to perform a building energy simulation with the level of detail typically required by the available tools to ensure a useful result. The amount of available information to input in the model is also to be taken into account. The problem is therefore to reduce the resource requirement while at the same time ensure an adequate level of accuracy in the results of the analysis.

Previous research efforts in this field can be roughly categorised in three different directions: simplification of the simulation code, defaulting of the input data or simplification of the description model (Picco, 2015).

The here presented tool focuses on the application of a simplified description model to a complex simulation code, with a clever use of defaulting the input data through the development of specific user interfaces.

Although other projects exist, working on tools with similar objectives, they normally focus on addressing specific issues and lack the kind of testing performed for the presented one. Following, Table I, is a non-exhaustive list of the simulation tools taken into consideration by the authors to come to this conclusion.

More sophisticated tools like EnergyPlus, Esp-R, TRNSYS or IES VE, although considered during the development of the research, are not included in this paper as considered too complex and outside of the range of application foreseen for the proposed tool.

In addition, each of the tools considered, although validated in term of simulation code, is missing a validation of obtained results when simulating a complex building through the implementation of a simplified model.

Additional details on each of the tools and conclusions derived by the authors on available tools can be found in previously published research (Picco, 2014).

Table I
List of simulation tools taken into account

MIT Design Advisor	• Focused on a specific aspect, • Limited on inputs, • Strong model hypotheses, • Partially validated
ZEBO b1	• Focused on a specific type of building, • Not web-based
Opt-E Plus	• Focused on optimization, • Not available to public, • High time requirements due to the number of simulations, • Not web-based
H.E.N.K.	• Limits in the simulation code, • Lack of information, • Not available to public, • Not web-based

SIMPLIFIED SIMULATION TOOL

To overtake the barriers that are currently preventing the diffuse application of building performance analysis during the first steps of the integrated building design process or feasibility study of renovations, the authors propose the use of a simplified simulation tool. Such tool is able to deliver dynamic simulation in a timeframe compatible with the needs of the design process while at the same time achieving an acceptable level of accuracy.

Although parts of the tool are still currently under development, as subsequently discussed, the envisioned structure of such tool can be seen in Figure 1. The user will be able to input all the required information on the building through a web app from a generic internet enabled device.

The data will be sent to a central server where a post processor will create the simulation model and perform the simulation without requiring the user to install any specific software locally. After this, the outputs of the simulation are post-processed to obtain meaningful results on the performance of the building and sent back to the user device.

Finally, the results are visualised through the results interface of the web app on the user device.

Based on this configuration, the final user will not need to licence any software or install and manage it on his device. Instead, he will gain access to the web interface and obtain the results as a service, in what could be considered as an automated consultancy delivery. Various business models behind the service are currently under discussion, although it is the intention of the authors to provide a basic service free of charge.

The proposed simulation tool, currently in development, is based on the use of the well-known EnergyPlus simulation engine (Crawley et al., 2004; Henninger et al., 2010), as the use of a complex, versatile and strongly validated engine does not have a significant impact on the time requirements for the building energy analysis. This choice enables to focus on the other aspects of the simulation, knowing the continuous updating and improve in features of the engine.

Not only this, but relying on an already existing calculation code will allow the final user to export the simulation model to EnergyPlus at any point if needed to extend the range of accessible features, if necessary.

The focus of the work is instead addressed on reducing time and information requirement through the use of a simplified building description model, able to simulate the building performances starting from a limited number of inputs, all easily available in early stage design or in feasibility study, and requiring a limited amount of time to perform the analysis.

Previously published papers by the authors (Picco et al., 2014) details the definition of the simplified description model through the implementation of a

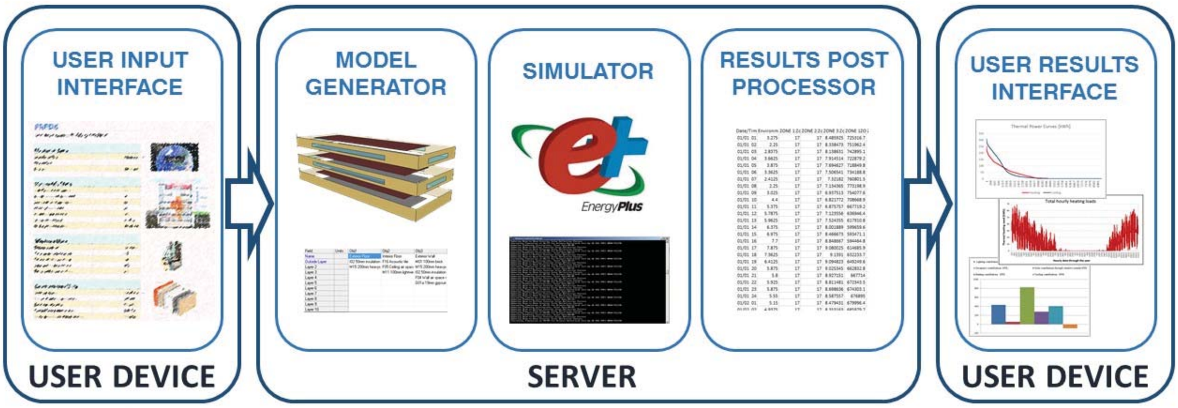

Figure 1: Structure of the final tool

simplified protocol and the methodology applied to both the creation of the simplified model and the validation of its results. The protocol was developed in eight consecutive simplification steps talking each aspect of the model definition resulting in the simplified model implemented in the tool and is now complete.

To further reduce the time required to perform the analysis, and enable professionals with limited expertise in the use of simulation software, the simplified tool also includes an automated model generator able to create the model and run the simulations starting only from a limited number of inputs on the most important characteristics of the building. This part of the tool is currently under development and testing and will enable performing energy simulation without the final user directly interacting with the EnergyPlus software and interfaces.

Work is still undergoing on the design and definition of the user interface. Although the design is not yet finalised, the various inputs and how they will be presented to the user is already defined.

The interface is separated in five different input groups defined as follow:

- **General Data**: Contains information on location, orientation and end use of the building.
  - *The location* input is connected to a database of available weather files and geographic coordinates;
  - *The orientation* represent the rotation between the relative north of the building and the true north;
  - *The end use* selection characterises all parameters of the building related to internal gains, occupancy, and occupant behaviour and is selectable through a database of different typical end uses (e.g. Residential, hospital, office, etc.).

- **Geometric Data**: Contains information related to the shape and size of the building, the user will be able to select from a number of different common floor shapes or a generic shape, tested and validated during the definition of the model, (the following discussion will focus on the generic shape option).
  - *Number of above ground floors*, to define the size of the building and placement of thermal zones in the model.
  - *Dimensions of floorplans* are required through the minimum number of input possible, for the generic shape, the length of the two fronts (north/south and east/west) are required. In addition, the floor area is required as, for a generic shape; it could be significantly different from the area obtained by multiplying the length of the two fronts.
  - *The Underground floor* fields define the presence of an underground floor and its eventual end use, as it could be different from the rest of the building, through a similar database selection to the one of the entire building.

- **Windows Data**: contains all the information required to model the transparent surfaces. Horizontal windows are currently not implemented in the model. Window shadings are considered for future updates.
  - *The Window Type* determines the thermal and solar properties of the transparent surface. The Window type can be selected by a database including the various properties of each glass.
  - *The Window surfaces* field will determine the vertical area of each transparent surfaces for each cardinal direction. No additional information is currently required by the tool to correctly model windows.

- **Construction Data**: In this group, the user inputs all the information related to the building materials and opaque surface thermal properties.
  - *Construction type*: A database of various construction types (e.g. masonry, timber frame, heavyweight concrete frame, etc.) complete with description and graphical aid for each entry, lets the user identify the right construction type, deciding the materials and structure of the building.
  - *The Construction Transmittance* fields lets the user further characterise the building by inputting the thermal transmittance value of each surface type. This information coupled with the previous selection will determine the characteristics of each construction by modifying the insulation thickness.

- **HVAC Data**: This section contains basic information on the HVAC plant and how it is controlled. The system section is particularly simplified as the current focus of the tool is on the envelope, nonetheless future updates will consider including more system options.
  - *System temperatures*: The zone air temperatures controlled by the HVAC system for both heating and cooling, for both set points and setbacks, the exact schedule of both determined by the end use of the building.
  - *Heat Recovery (HR) efficiency*: Determines the presence of a heat recovery system and its efficiency. As heat recovery is assumed as a standard solution, the default value will set the HR as present, but can be deactivated by the user.

For each required input, when appropriate, the tool will give a default value and a set of values inspired by good practice and current regulation will be given through the interface to inform the user and guide him in the selection of the right value. Each input field will also have a graphical explanation of the input to guide the user in the implementation of a correct model.

Similarly to the input interface, the output post-processor and result interface is currently loosely implemented through the use of spreadsheets and still require a case-by-case user input to work, this part of the tool will be designed and finalised once the automatic model generator is complete, in parallel with the design of the input interface.

Currently, the displayed results for the simulation are the thermal energy needs from the building, both in term of heating and cooling and displayed as monthly/annual total, hourly variation throughout the year, and thermal power curve for plant sizing. Electrical loads are also displayed for lightings and equipment. Mean Comfort charts can be displayed for the entire building, although it is still under discussion by the team if those results can be easily generalised for each possible simulated building with good level of accuracy.

In its first version, the tool will be limited to describing the energy performances of the envelope, additional sections of the interface are already planned to include the integration of innovative HVAC systems, renewable energies and specific design solutions that can be simulated with the simplified model.

CASE STUDIES AND RESULTS

During the past years of research, the simplified description model has been applied to a series of case studies with successful results. Although, as the automated model generator and user interfaces are not yet finalised, the different steps of modelling and post processing of outputs have been performed directly by the user.

First relevant case studies are the three different buildings modelled during the initial validation of the simplified description model. Those three case studies where developed during PhD work of the main author for the definition of the simplified model and helped in its validation. All three buildings have been modelled with a high level of detail and gradually simplified applying the simplification protocol previously cited in this paper to evaluate the differences in results. The final step of the protocol results in the creation of the simplified model that would be generated by the proposed tool. Both models, detailed and simplified, are implemented in the EnergyPlus simulation code, as will the tool proposed, therefore results of each of the simplified models is compared to an highly detailed and calibrated simulation performed in EnergyPlus with differences in energy needs of less than 5% compared to the monitored data. Comparisons with different simulation code have been performed, in both TRNSYS and Esp-R, to ensure results are unrelated to the simulation code used; giving positive results, but a detailed discussion of such result is outside the scope of the present paper.

As a reference, Figure 2 shows a graphical comparison between the detailed and simplified model of the first case study (CS1). As mentioned previously, additional details on the simplified model and protocol can be found in previously published papers (Picco et al., 2014).

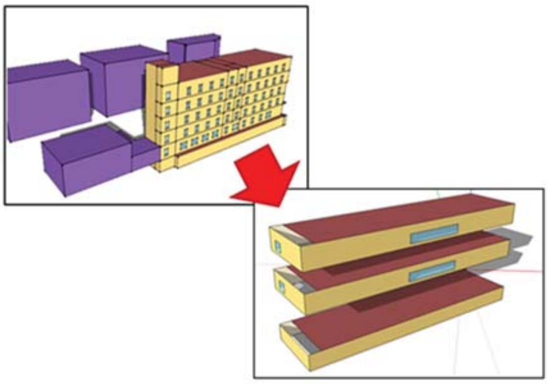

Figure 2: Example of CS1 detailed and simplified models

Table II and Table III below shows a summary of the results obtained by those three case studies, as shown differences in results between the simplified model used by the tool and a detailed model are always below an acceptable margin of 20%. This threshold, although not directly related, can be compared to the recommended acceptable value of mean bias error for detailed and calibrated simulation models as presented in the Measurement and Verification guidelines from DOE (DOE, 2008) equal to 10%.

Table II
Total energy needs difference on case studies

		Total Diff. [%]	
		Heating	**Cooling**
CS1	Ideal	-2.2	12.9
	Unitary	-12.8	-5.1
	VAV	-15.6	-14.6
CS2	Ideal	-2.1	-1.0
	Unitary	11.0	-8.6
	Fancoil	10.0	-1.8
CS3	Ideal	-7.6	-7.9
	Unitary	-10.4	-16.2
	Fancoil	-15.3	-5.4

Values are reported in term of % difference between the detailed and calibrated model and the simplified model that would be generated by the tool, to show the comparison of obtainable results. More information on this, including the results of each simulation in absolute values, can be found in previously published papers by the authors (Picco et al. 2015). As shown, all performed tests results in differences below the 20% threshold.

Table III
Peak loads difference on case studies

		Peak load diff. [%]	
		Heating	**Cooling**
CS1	Ideal	4.4	9.9
	Unitary	-3.3	0.1
	VAV	-3.7	9.8
CS2	Ideal	-13.9	6.5
	Unitary	-2.6	2.2
	Fancoil	-15.1	1.4
CS3	Ideal	0.9	1.2
	Unitary	-0.1	-0.1
	Fancoil	-14.5	-0.5

Following the initial validation, the simplified model was applied to a number of other buildings in the intent of evaluating their energy performances. When suitable, for validation and research purposes, those buildings have also been simulated using a detailed model to further compare the results. For each case the difference in results between detailed and simplified model on Energy needs and peak load outputs has always been under the aforementioned acceptable margin of 20%, further confirming the qualities of the proposed tool and its potential usefulness during the initial stages of the design process.

Two examples of application of the proposed tool to answer specific questions are discussed below and illustrated with the help of figures.

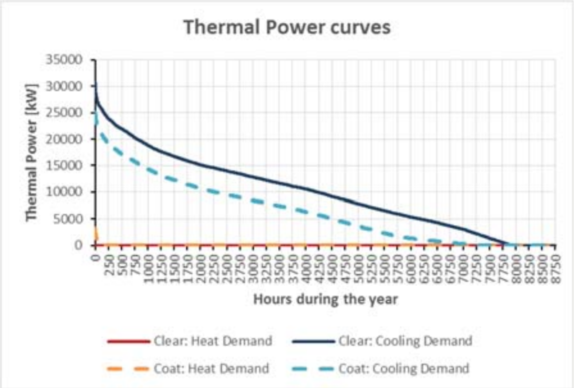

Figure 3: Example - Evaluation of window coating

Figure 3 shows the results in term of thermal power curves of the application of the simplified model to a large multi-use building located in the Middle East. Focus of the analysis was to evaluate the usefulness of application of solar coating to the transparent surfaces of the building. The figure shows the heating and cooling demand of the building under two different assumptions: clear windows, SHGC of 0.86, and coated windows, SHGC of 0.20.

Thanks to the use of the simplified model, the team was able to quickly estimate a reduction of 20% in the peak cooling demand and of 35% of the annual cooling needs. As expected heating loads for the building are negligible in both hypotheses.

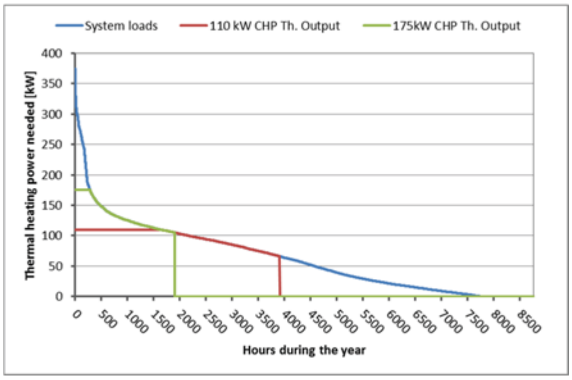

Figure 4: Example - Sizing of CHP machine

Another example application of the simplified model can be seen in Figure 4; in this case the interest from the team was to obtain the thermal power curve for the heating loads of the building to evaluate the optimal size of a CHP machine for a financial feasibility analysis. Thanks to the use of the simplified model the results was obtained despite the limited resources and time available. Alternatively traditional methods of sizing would need to be used, limiting the quality of the end result.

CONCLUSIONS

Buildings are becoming increasingly complex while our society is moving toward a sustainable future, asking for always increasing energy performances and integration of new systems and renewable energy technology. Consequently, the design of such buildings is becoming an increasingly complex process, requiring different expertise and attention to the energy aspects. A commonly accepted solution to this problem is the move toward integrated design, with the idea of optimising the building by talking all of its aspects from the initial stages of design. Nonetheless, there is still a gap to cover in term of lack of tools and resources before being able to fully integrate analysis related to the energy performance of the building during early stage building design.

This paper shows how it is possible to apply simplified simulation tools to perform building energy and performance simulation during early stage building design, significantly reducing the resource need, in term of time and data, compared to the current use of dynamic energy simulations.

This possibility comes, as expected, with a reduction in the accuracy of the simulation model, although as proved by previous research and validations, this reduction is limited and can be considered acceptable. During the initial stages of design, when uncertainty is still high, a 20% margin of error in the energy performance of building is still able to give useful information to the process to guide it toward the design of energy efficient buildings.

This is particularly relevant considering the design and regulation shift toward ZEB and nZEB buildings, due to their increased performance and energy need reduction, pushing the design of those buildings to its limit and requiring the knowledge and investigation of such performance from the initial stages of design.

Although the application of the simplified model already shows good results in this direction, further work is needed before a diffuse application, particularly for the completion of the automated model generator and user interfaces, currently in development and available in the near future. Additional development currently under consideration for a future stage of the tool is the integration of optimisation techniques, to automatically optimise the design of specific aspect of the building against different possible criteria. Nonetheless, it is the belief of the authors, the envisioned first version of the tool will prove extremely useful in the integration of energy aspects during the initial stages of building design as already confirmed by initial direct application of the simplified description model.

NOMENCLATURE

ZCB,	Zero Carbon Buildings;
ZEB,	Zero Energy Buildings;
$NZEB$,	Net Zero Energy Buildings;
$nZEB$,	Nearly Zero Energy Buildings;
$EPBD$,	European Performance of Buildings Directive;
IDP,	Integrated Design Process;
BPS,	Building Performance Simulation;
HR,	Heat Recovery;
$SGHC$,	Solar Heat Gain Coefficient

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