

Applying Energy Performance-Based Design in Early Design Stages

A methodological framework for integrating multiple BPS tools

Manuela Ianni¹, Michelle Sánchez de León²

ARC, La Salle Engineering and Architecture, Ramon Llull University, Barcelona, Spain

<http://www.salleurl.edu/arc/>

¹mianni@salle.url.edu, ²michelles@salle.url.edu

Abstract. *In current architectural practice some important changes are taking place because of the development of numerous Building Performance Simulations (BPS) tools to support design decisions during early phases of the design process. Many difficulties still persist, however, not necessarily due to the limitations of the available technology, but to the lack of appropriate methodologies to use the existing tools to improve the decision making process, particularly at the early design stages. In this work we present an application of performance-based design in early design phases, with the purpose to take better-informed decisions which would ultimately contribute to improve the energy performance of buildings.*

Keywords. *Energy performance-based design; design methodology; design decision-making process; building energy efficiency; building performance simulation tools.*

INTRODUCTION

In the 1960s, a way of design thinking known as performance-based design (PBD) began to be developed in the fields of engineering and operations research. Through the use of simulation, PBD aims at facilitating a methodology that anticipates the impact of different design solutions in order to improve the effectiveness of the decision-making process. The key feature of PBD is the explicit formulation of performance requirements that will guide design decisions, and the subsequent management of a process that guarantees their fulfilment.

When this idea was introduced in the field of architecture, it was expected that it would help to improve the predictability of outcomes and, there-

fore, more rational design decision-making. In particular, it was expected that 'better' buildings would be designed (Markus, 1969). Essentially, PBD consists of translating user requirements into quantitative criteria and performance indicators (PIs) which control the trade-off between various design objectives. Thus, assessing the performance of a building becomes a multicriteria evaluation process wherein the predictable effects of each design solution must be considered from multiple perspectives. Energy efficiency is one of the fundamental issues in terms of evaluating the performance of a building.

Energy performance-based design (EPBD) can be considered a methodological framework in

which energy efficiency acquires the utmost importance in the trade-off between the diverse design variables. From an operative perspective, EPBD provides a systematic procedure which includes the application of building performance simulation (BPS) tools during the design process with the purpose of optimising the building's energy efficiency. Several problems arise however when EPBD is implemented in design practice and, in the absence of appropriate solutions, crucial design decisions are still made intuitively or by rule of thumb.

Despite the vast knowledge accumulated over the years in the field of energy efficiency, EPBD is still not applied systematically during the building design process. This research is concerned with the application of performance-based design methods to support the decision-making process with the ultimate purpose of improving the energy performance of buildings.

ENERGY PERFORMANCE-BASED DESIGN: BARRIERS AND LIMITATIONS

EPBD fosters a methodological framework in which a building's energy efficiency can be formulated as an explicit target in the various phases of the building design process. It has been contended that the implementation of a PBD environment may help to improve the general performance-in-use of buildings, and supply new opportunities for organisational and technological innovation within the building process (Becker, 1999). A discrepancy exists, however, between theory and practice.

When EPBD is implemented in the design practice, there are no BPS tools which can provide full support of the decision sequences of the design process. For about a quarter of a century, BPS tools were intended for non-trivial building analysis, thus they were used only later in the design process (Clarke, 1985); even though several tools have been recently developed to perform early energy analysis, they are unable to provide appropriate feedback. Some of these tools can only deal with certain performance aspects or specific building and system components in one simulation environment, as well

as most of the output results are difficult to interpret in relation to design decisions (Weytjens et al., 2010; Attia, 2011). Therefore, an architect needs to use different BPS tools to deal separately with specific design issues as the design process progresses.

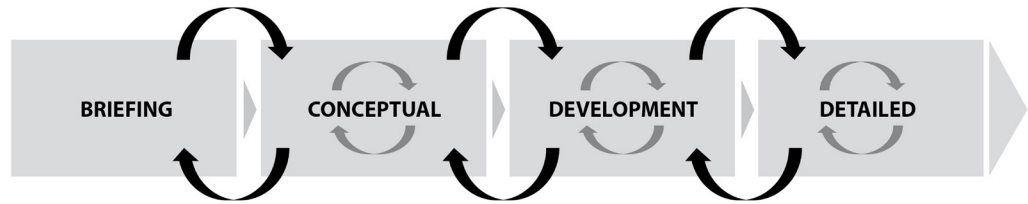
As a result, the implementation of EPBD requires the use of many different tools, thus making performance-based design a time-consuming and costly process. Because of this, architects tend to use BPS tools only at the end of the design process. Indeed, in practice performance simulation is primarily used to verify decisions already made rather than to support decision-making during the design process (Hopfe and Hensen, 2009), and early design decisions regarding energy efficiency are often based only on reference projects and the experience of the designer (Altavilla et al., 2004).

This research suggests that an appropriate methodology can be defined to overcome the problem of integrating BPS tools in performance-based design. The proposed methodology is based on creating a strong interrelation between defining a conceptual framework of the architectural design process and choosing the proper BPS tools. This methodology has been developed in conjunction with an application case in order to show how BPS tools can actually be used by architects to improve the energy performance of buildings.

METHODOLOGY AND STRATEGIES FOR IMPLEMENTING EPBD

In contrast to the traditional hierarchical and sequential nature of the decision-making process (Asimov, 1962; Archer, 1969), which suggests that design decisions are made one after the other, the stand adopted in this research is that lower-level decisions can help designers to reconsider decisions previously made at a higher level by linking the information generated throughout the various phases of the design process. In this way, the outputs of the decision processes in the early design phase can be compared with information on the building in operation.

Figure 1
The conceptual framework is represented as a linear process with two main feedback levels.



Accordingly, in this research the design process is understood as an information flow in which the outputs, evaluation results, of a stage become inputs, constraints, for the next one, and vice versa (Figure 1). Essentially, this informational flow relies on two main feedback levels: the first one allows better informed decisions to be made by looking back and reconsidering decisions previously made in the earlier phases; the second one means design decisions are made at each design phase with the support of energy simulation. In this way, a bidirectional propagation of the outputs of the decision-making processes increases knowledge about the project at stake, especially at the beginning of the design process, when consistent data about the project are not available.

In order to implement EPBD within this view of the design process, it is necessary to select the BPS tools. Thus, considering the two feedback levels of the informational flow (Figure 1), BPS tools are selected on the basis of their interoperability (interoperability of building modelling). The first feedback loop implies that the diverse BPS tools communicate through different design stages by using the same language. Then, the selected tools are organised and mapped into the different design phases according to their capabilities (usability and appropriateness). Thus, the second feedback loop has to be supported by different BPS tools appropriate for each design phase. The appropriateness of the different BPS tools for the diverse design phases is judged on the basis of the complexity and sophistication of the physical model (i.e. flexibility and responsiveness to the design problem), input required (i.e. customisation template and understandability of interface) and output provided (i.e. output under-

standability, calculation time, accuracy). In this way, different BPS tools can be strategically mapped and integrated within the design process.

The strategy adopted in this research focuses on the building of a unique model which can be exported and detailed as the design process progresses with the aid of other software. In this way, information produced in the early design phases can be compared and verified by the calculation results produced by more specific building simulation tools. Also, the possibility of building a unique model, which is subsequently upgraded, moving from one stage to the next, from one tool to another, from one design objective to another, can overcome wasted time and costs in terms of separate repeated models, which represents one of the major barriers to the integration of BPS tools within the design process.

CASE STUDY: A SOCIAL HOUSING BUILDING DESIGN PROCESS

The proposed methodology has been developed in conjunction with an application study. The design of social housing recently built in Cerdanyola del Vallès, Barcelona, has been used to explore the application of energy performance-based design to facilitate informed decisions in the design process. Specifically, the decision-making process followed by the design team has been analysed and alternative processes based on the application of performance-based design methodology proposed. Finally, a comparison has been made between the processes that led to the building construction and an alternative design process proposed in this research to draw conclusions about the improvement, benefits or limitations of the proposed PBD methodology.

The design process that led to the building construction

The existing residential building is a rectangular block that occupies the maximum area allowed by local building regulations (64x12m). Its main façades are oriented to south and north. It is a five-storey building served by two vertical cores (stairs and lift) and the basement is allocated for parking, the ground floor for commercial use, and the three upper floors for residential use (24 apartments). The building was designed to achieve high energy efficiency standards, and for this reason was chosen for the case study. Its design process has been recreated through information provided by the design team through documents and interviews.

It became clear in the interviews that the building was the result of a process in which design decisions, including those concerning energy, had been guided only by the experience and knowledge of the design team: many decisions were made by rule of thumb, or were based on experience with components, materials and constructive systems which the architects had used in previous projects, such as a solar wall. Although the design team acknowledged that designing is a dynamic process in which decisions change with the information generated throughout the design process, they opted for a specific building component (solar wall) from the beginning, and never changed their opinion. Making decisions gradually, which develop increasing complexity as the design process progresses, or deciding a priori, seem to be two irreconcilable approaches towards the design process.

It also emerged from the interviews that energy simulation had been used later in the project (EnergyPlus) merely to check compliance with building regulations. The design team was somehow 'forced' to use simulation to justify and guarantee compliance with the client's objectives (a public client), but they did not apply it during the design process because the professional fee did not include it, and also because time for simulations could not be included in the project schedule ('no time to experiment', in the architects' words). In fact, time and

costs were the main limitations which hampered the integration of building simulation tools within the design process.

The alternative design process applying energy performance-based design

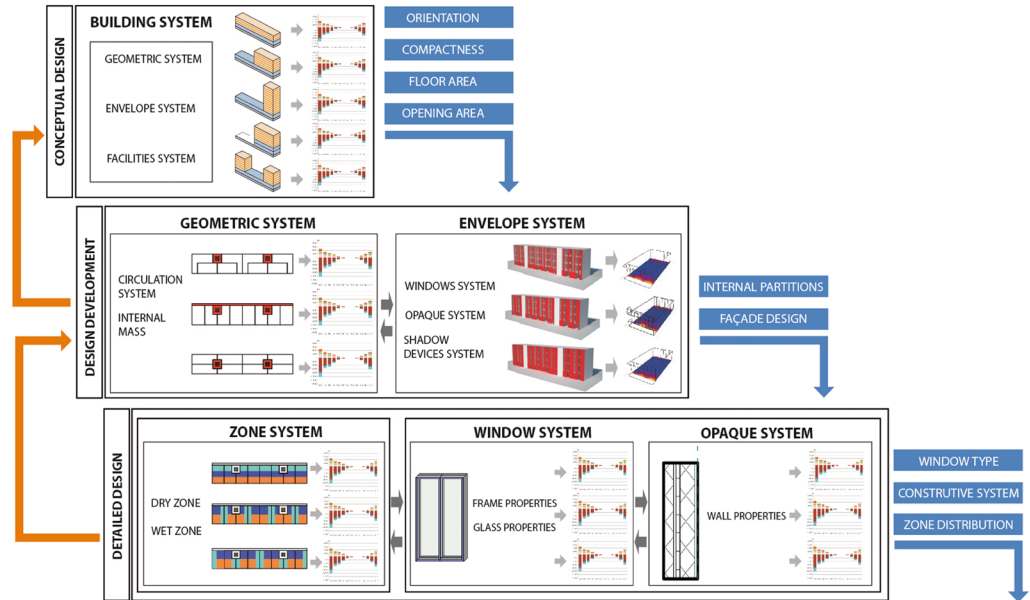
The design process of the building was reproduced by applying the performance-based design methodology proposed in this research, which aims at interlinking the information generated by BPS tools throughout the diverse design phases. In this way, an alternative design process to the one followed by the architects of the building was produced. This process focused on the early design phases of the process, conceptual, development and detailed/technical phases, which are when the most significant problems occur with regard to the application of BPS tools.

In accordance with the vision of the design process as an information system, the building was seen as a system composed of discrete manageable 'chunks' structured on the basis of an abstract hierarchy (system, subsystems and components) also known as top-down partitioning. Thus, the design process and the design object, i.e. the results of the process, were intended as congruent systems, the one complementing the other. Each building level defined the boundary of the different subsystems making the overall building system. Through the different levels of this abstract structure, the building was approached on different scales, from general (building overall system) to detailed level (components), from detailed to general level (Figure 2). Diverse design objectives were pursued to improve the overall building energy efficiency. Thus, performance indicators (PIs) were taken into consideration at each level (comfort, energy use intensity or consumption, heating/cooling demand and environmental impact) in order to evaluate different design alternatives.

In accordance with this systemic approach, certain BPS tools were selected on the basis of their interoperability. The selected tools were successively combined in the design process, taking

Figure 2

The design process comprises a progression of various stages, i.e. design, development, detail, in which the building has been considered on different scales, from general to detailed, and vice versa.



into account the objectives pursued in each design phase. After analysis of the available BPS tools, three were selected because of their high interoperability: Vasari (Autodesk), ECOTECT (Autodesk), and DesignBuilder with EnergyPlus. All of these tools provide bidirectional interoperability with BIM models through gbXML import/export capabilities. The tools present many differences in terms of modelling, calculation and results, however. Thus, they were differently applied in each design level or stage of the design process, on the basis of their capabilities (usability and appropriateness).

Conceptual design phase: building main subsystems. During the initial design phase, a wide range of design alternatives was considered in order to take decisions about building orientation, volume or compactness. Performance simulations were used to compare design alternatives without overemphasis on quantitative results. Thus, Vasari (DOE 2.2 simulation engine) was chosen because it enabled us to create a conceptual energy model flexible and consistent with the initial limited information of the

project, and can be employed for testing, evaluating and generating design hypotheses in a 'what if' life-cycle scenario. In this stage, the building was considered as a system composed of various subsystems (geometry, envelope, HVAC equipment) whose interaction significantly influences the building's energy performance. Then, by varying the parameters of the subsystems that make up the building (height, length, envelope area, glazing area, etc.), we generated various design alternatives. Energy simulations were performed for each parametric variation and the optimal energy performance analysed by gradual adjustment of the design parameters.

In order to explore the effect of form on performance, the HVAC system was considered as fixed, whereas other design factors were systematically varied to arrive at a final proposal. Through simulation of the different design alternatives and comparison of the results obtained from Vasari (Figure 3), several rules of thumb were confirmed in the specific context of the project. For example, increasing the compactness of the building energy use inten-

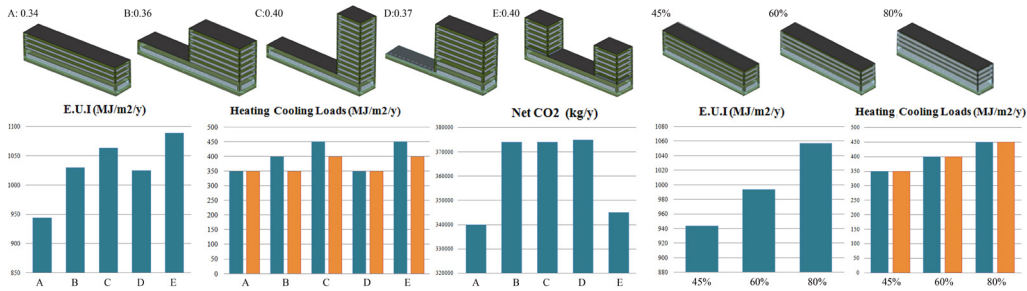


Figure 3 Analysis of the results obtained from Vasari (Autodesk) of different design alternatives obtained by varying the compactness and opening ratio. The option (A) is similar to that of the existing building.

sity (EUI) meant CO₂ production and, consequently, consumption increased, too. A thermal imbalance was also produced (i.e. heat losses were not already compensated for by heat gains, and vice versa), which contributed to the increase in the heating/cooling demand. Thus, the option with a lower value of compactness appeared to be the most convenient.

The same process was reproduced by changing the orientation of the building and the opening ratio (i.e. percentage of glazed surface compared with opaque surfaces), which are strictly interdependent parameters. A study of window size was made in relation to the orientation of the building, which consistently influences its energy consumption. Also, the choice of a particular orientation and window size in this early phase could determine the choice of thermal mass, which is typically determined in much later phases.

After the best orientation was established on the basis of previous calculations, different window areas of the south façade were considered (Figure 3). The analysis of the Vasari simulation confirmed that the building consumption could be reduced by minimising the opening ratios. Finally, a candidate solution was selected through a trade-off between design variables. The chosen solution has characteristics similar to those of the existing building (Option A: Compactness: 0.34; Orientation North-South; Opening ratio: 45%), which have been considered as constraints in the successive steps of the design process (feed-forward).

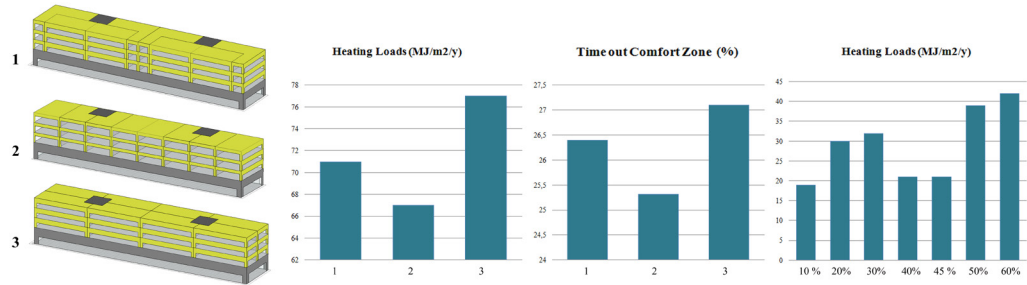
Autodesk Vasari was appropriate for this con-

ceptual phase, as it enabled us to analyse different design alternatives through a flexible parametric model with a real-time feedback on building energy behaviour. Vasari could not completely customise the model, however (input template of construction, schedules and HVAC is very limited, and the generic default settings cannot be changed). Also, Vasari did not provide information about some fundamental building performance aspects, like internal comfort, and it did not represent heating/cooling loads caused by ventilation air, which can have a significant impact in densely occupied buildings. Therefore, there was no consistent counterpart in the trade-off between conflicting design goals. In fact, the other performance parameters, which also depended on HVAC equipment, were directly proportional: the increase in the energy use led automatically to higher consumption and CO₂ emissions. This limitation in the outputs did not improve the decision-making process by facilitating provision of qualitative information to the designer, as evidenced by the fact that the chosen design solution coincided with the solution adopted by the architects in the actual design process. Thus, in order to improve the energy information about the project the model built in Vasari was exported to ECOTECT.

Development design phase: aggregation of building's components. The model built in Vasari was exported to ECOTECT (gbXML) to increase the energy information about the project with data about building internal comfort. After analysis of the results obtained from ECOTECT, the design chosen in the previous conceptual phase was confirmed. In

Figure 4

Analysis of the results obtained from ECOTECT of the different design alternatives obtained by varying the internal partition of the building and the opening ratio. The option (1) is similar to that of the existing building.



fact, the heating and cooling demand trend of the different design alternatives calculated with Vasari coincided with the quantitative data obtained from ECOTECT. In terms of comfort, there were no significant differences after we varied the compactness of the building, although a substantial difference between the time above and below comfort zone (18-26°C) was noted. Thanks to this information, the subsequent performance calculation and analysis could be refined by focusing on minimising heating demand, thus saving time on the project schedule.

Once the general design characteristics of the building were defined, a new sequence of decisions focused on the arrangement of the building interior's space. Different floor layouts were explored, analysed and evaluated with ECOTECT (Figure 4). Usually the area of internal mass does not significantly contribute to the building energy demand, however, the results of the energy simulations showed that there was an appreciable reduction of heating demand after a change in partitions. Thus, a design solution different from that employed for the existing building was chosen (Option 2).

Once the floor layout was defined, the same model was used for a subsequent analysis, in which different percentages of area of the southern windows were considered in order to improve the previous qualitative calculation made in Vasari. The calculations done with ECOTECT revealed a consistent reduction of heating demand when the ratio of glazed and opaque surfaces ranged from 40 to 45%, probably because of a balance between solar gains and heat loss through the envelope (Figure 4). This

means that the window area should not necessarily be minimised, as the results from Vasari seemed to suggest. This information was used to refine the south façade of the building: the relation between the design alternatives for the windows (window size and proportions) and the use of shadow devices (balconies and railings), was considered for maximising solar radiation during winter and minimising it during summer (overheating control). This thermal study took advantage of the generative modelling capacities of Grasshopper and the energy calculation tool EnergyPlus, connecting them with Ladybug plug-in. The optimised trade-offs between the sometimes conflicting objectives were calculated with Octopus, a SPEA-2 multi-objective evolutionary algorithm, whose results have been evenly distributed along its approximation to the Pareto-front (Figure 5). This study presented two design alternatives: the first, a vertical window (envelope opening ratio of 45%), with railings and a balcony reduced by 10% in relation to the maximum dimension allowed by local building regulations; the second, the reconsideration of the decision taken in the conceptual phase about the building's compactness in relation to the setback of the window from the wall.

In this phase, a unique model was used for diverse purposes. ECOTECT can export or import files in gbXML format, and export a model to other design tools using the DXF 3D format. Despite the advantages of interoperability and the flexibility of the modelling, ECOTECT simulation results are not fully representative of reality because of the lack of accuracy of the admittance method, which does not con-

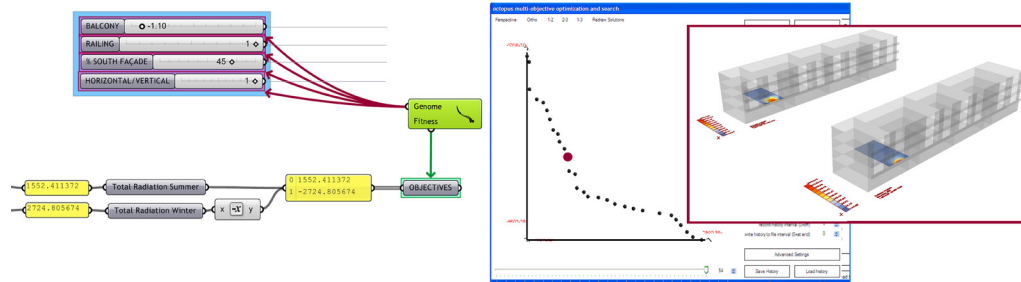


Figure 5
Partial Grasshopper script
and results of the trade-off
between conflicting design
objectives (Pareto-front).

sider the effects of ventilation; also ECOTECT does not provide performance indicators like energy consumption or CO₂ production. Because of the limited outputs, the model was exported and analysed in DesignBuilder in order to increase the energy information and to verify the decisions previously made.

Detailed design phase: building components. The model initially built in Vasari, imported and detailed in ECOTECT, was exported to Design Builder by means of the gbXML format. The different design alternatives previously obtained by varying the partitions of the building were reanalysed. The results obtained from DesignBuilder confirmed that the solution previously chosen (Option 2) was the more convenient, probably thanks to the improvement in natural cross-ventilation.

In order to compare the outcomes obtained in the two parallel processes, that followed by the architects of the building and that based on our methodology, a solution similar to that used for the existing building was considered and analysed. By varying the characteristics of the building's components or materials, like windows transfer coefficient (U-value) or wall thermal resistance (R-value), we found that consistent improvements could be obtained by reducing the average U-value of the building's envelope (Figure 6). The second option (U-value: 1.75 W/m²K) was selected through the trade-off between consumption, heating demand, CO₂ emissions and comfort issues.

DesignBuilder is the most comprehensive user interface for the EnergyPlus dynamic thermal simulation engine whose calculation results are similar to

the real energy behaviour of the building. DesignBuilder does not however have the necessary flexibility to develop or change a model of the building and its feedback is not immediate. For these reasons, it was not used in the initial design phases, in which many design alternatives need to be considered.

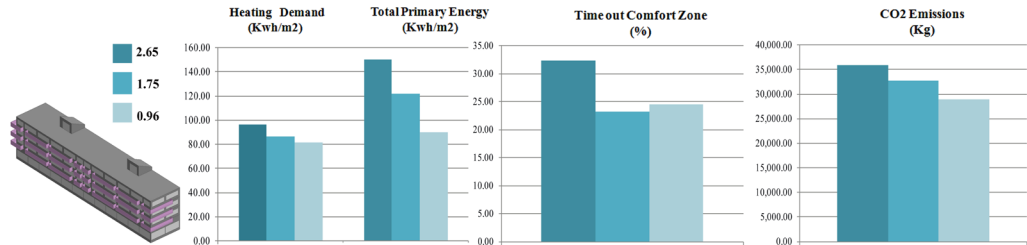
Comparing the outcomes of the two design processes

By comparing the process that led to the building construction through a traditional approach (linear design process in which BPS tools were used only later in the design process), with the alternative design process proposed in this work (energy performance-based design methodology), we can draw some conclusions.

At the beginning of the design process, both processes converged to the same design solution. Divergences which led to different paths started to occur in the development phase. This demonstrates that the designer's knowledge and experience was sufficient for some basic decisions at the beginning of the design process. As the complexity of the design object increased, however, in the development or detailed phases, better-informed decisions could have been made through the application of BPS tools. Unlike other design issues, decisions leading to improved energy efficiency cannot be made intuitively because of the complex interactions between the different building components and subsystems. Also, the detailed information about the performance of the components of the building used in the PBD methodology would have been particularly

Figure 6

Analysis of the results obtained from DesignBuilder of the different design alternatives obtained by varying the characteristics of the component of the building (average U-value of the envelope).



useful in the early design phases in terms of changing preconceived ideas about the alleged effectiveness of some building systems, as was the case in the actual design process of the building. Even though the 'traditional' design process adopted by the architects led to a design solution that complies with the goal of energy efficiency, it did not increase the architects' knowledge. Indeed, the solar wall was used in several earlier projects of the design team as if it was the only possible solution.

CONCLUSIONS AND FUTURE DEVELOPMENTS

Over the past few years, numerous BPS tools have been developed to help architects to perform energy analysis, but none can completely support the entire design process. As a result, architects are confronted to a discontinuous design process, in which they need to use different BPS tools as the design process progresses or, in most cases, only later in the design process. A design process based on energy performance-based design, in which different BPS tools are used to guide the decision-making process in the early phase, has been proposed, applied and tested in a case study.

The results of this research indicate that in some stages of the design process advanced simulation tools and quantitative data are needed, whereas simple calculations plus the designer's experience would be adequate for the early stages. Although the designer's experience could be sufficient in the decision-making process in early design stages, BPS tool simulation could be a valuable support in terms of reconsidering preconceived ideas, leading

to the innovation and evolution of the designer's knowledge during the same project. By linking the information produced in the diverse phases of the design process, the methodology proposed in this work could help to build knowledge that can be further applied in energy-conscious decision-making processes.

Future work will focus on the implementation of the proposed methodology in the whole design process, from early design to use. Thus, the predicted data obtained by the energy simulations performed during the design process could be compared with the data of the building in operation which can be obtained by measurements, bills or surveys.

ACKNOWLEDGMENTS

The work reported in this paper has been carried out as part of the research project "RÉPENER-Control and improvement of building energy efficiency by means of repositories," co-funded by the Spanish Ministry of Economy and Competitiveness through the National RDI plan (BIA2009-13365). The authors wish to thank Prof. Leandro Madrazo, coordinator of the project, for his continuing support during this research. The generative modelling with Grasshopper and the simulations with EnergyPlus have been done by Franc Bardera, student of the School of Architecture La Salle. The simulations with DesignBuilder have been done by Michelle Sánchez de León.

REFERENCES

Altavilla, F, Vicari, B, Hensen, JL and Filippi, M 2004, 'Simulation tools for building energy design' in J Hense and M

- Lain (eds), *Proceedings PhD symposium Modelling and Simulation for Environmental Engineering*, Prague, pp. 39-46.
- Archer, L 1969, 'The structure of the design process' in G Broadbent and A Ward (eds), *Design Methods in Architecture*, Wittenborn, New York, pp. 76-102.
- Asimov, M 1962, *Introduction to Design*, Prentice-Hall, Englewood Cliffs.
- Attia, S 2011, 'Early design simulation tools for Net Zero energy buildings: a comparison of ten tools', *Proceedings of the 12th IBPSA Conference*, Sydney, pp.94-101.
- Becker, R 1999, 'Research and Development Needs for Better Implementation of the Performance Concept in Building', *Automation in Construction*, 8, pp. 525-532.
- Clarke, JA 1985, *Energy Simulation in Building Design*, Butterworth-Heinemann, Oxford.
- Hopfe, CJ and Hensen, JLM 2009, 'Experiences testing enhanced building performance simulation prototypes in potential user group', *Proceedings of the 11th IBPSA Conference*, Glasgow, pp. 1976-1982.
- Markus, T 1969, 'The role of building performance measurement and appraisal in design method' in G Broadbent and A Ward (eds), *Design Methods in Architecture*, Wittenborn, New York, pp. 109-117.
- Weytjens, L, Attia, S, Verbeeck, G and de Herde, A 2010, 'A comparative study of the "architect-friendliness" of six building performance simulation tools', *Sustainable Buildings CIB 2010*, Maastricht, Netherlands.