Universitat Ramon Llull

PhD THESIS

Title

The Application of the Energy Calculation in the Building Design Process

Investigation into the Effectiveness of Existing Methods in the Ordinary Design Practice

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Abstract

Buildings, from the construction to the use until the disposal, are responsible for a considerable impact on the environment. Much of the environmental impact of the building sector is related to energy use. In the whole building life-cycle, the largest amount of energy is employed for the building operation. When the sector impact is considered, it is necessary to take into account that new construction is still predominant at a global scale. In projects of new construction it is essential to make energy conscious decisions from the design phases to limit the negative impact of new buildings. In this context the use of existing energy modelling tools to predict building performance is seen as a promising way to improve the energy performance of buildings.

Despite the existence of a great variety of tools, which implement from simplified calculation methods to advanced simulation methods, their use in current design practise is limited at present. Often energy calculations are confined to final design stages and conventional verifications, as it frequently occurs in the application of energy certification procedures. While deeper analyses are circumscribed to a few engineering firms in a few countries and they regard exceptional buildings in size and typology. Existing exceptions are not relevant for the global impact of the building sector. In most projects energy modelling is not deeply integrated throughout the whole process and its effective penetration in routine work of practitioners is very restricted. The paradox is that energy modelling has more application in exceptional projects than in the great majority of projects that really determine the sector impact.

In this thesis, **the use of energy calculation methods in routine design is investigated**. The aim is to better understand the application barriers and the potential of existing modelling approaches, in order to improve their exploitation. Our concern is the integration of energy assessment in the activity of common practitioners behind exceptional cases. With this study we intend to contribute to filling a gap that is recognised in literature: the need for more research on the integration of energy modelling into the design process. Most studies have been carried out in the fields of engineering and building physics. This thesis instead is approached from the design perspective, paying attention to the process by which the design solution is generated. Then **the focus is not on energy analysis, but on its integration in the design process.**

The work carried out includes a theoretical research and two case studies. The theoretical research encompasses disciplines that tend to be separated in literature, as building design and energy performance assessment. This interdisciplinary approach is the base to examine the use of existing modelling methods within the context of building design. The theoretical research is complemented with the two case studies, each one concerning the reconstruction and the analysis of the design process of a multifamily building for social housing. In both cases we have examined how the calculation methods applied by the design team have been integrated into the process.

The theoretical research is based on the review of the literature following two parallel lines of inquiry. One line deals with the building design process, spanning from previous studies on design to methodologies for the integration of performance assessment in building design. The work reveals the complexity of design, evidencing the dynamic and holistic nature of the design process. The other line of inquiry deals with energy performance assessment, and in particular, with existing methods for the calculation of the energy performance of buildings. The study gives evidence of the considerable diversity existing in the range of the available methods.

These two lines of inquiry set the base for the next step of the research, which focuses on the use of existing modelling methods within the context of building design. The theoretical analysis of the author is complemented by observation of the real design practice. The study shows that a part of the obstacles that hinder an effective application of energy modelling are inherent to the design process. In fact, the stages of the design process differ from each other, the evolution of the process is largely unpredictable, and the energy aspect must be conciliated with other aspects that rise through the process. So it is not trivial to coordinate the energy assessment with other design tasks. The challenge for design teams is complicated further by the intrinsic complexity of building energy analysis.

In this context the selection of an appropriate tool becomes crucial. Precedent studies highlighted the need for research on the identification of suitable modelling methods. For this reason, a central part in the work deals with the identification of appropriate tools to be used at different stages of the design process. Precedent studies have made a screening of individual tools to scrutinize their features. In the thesis instead we focus on how tools features match with design needs, stressing the differences between design stages and the singularity of each project. In particular we identify and discuss ten key factors for the suitability of energy modelling tools (such as feedback immediacy, responsiveness to design decisions, flexibility to design modification, accuracy and so on). This framework provides a systematic way of analysing how tools features match with design needs.

The work presented in this thesis highlights that the selection of suitable calculation methods entails a difficult trade-off. In fact, the effective application of existing calculation methods requires the capacity to cope with conflicting needs in order to find a proper balance for each project. For instance, the detail and the accuracy of the model have to adapt to the information available at each design stage. At the same time, the creation of a detailed model must be compatible with the time limitations of the project and the synchronization of design tasks. Likewise, the model complexity must be congruous with the competences of the design team. All these factors, which are determinant for the choice of the energy calculation methods, are not self-evident. They are comprehensible only if the design process, the context of application, is well understood.

The conflicting needs that we have identified provide an explanation for the limited use of energy calculation tools. At the same time, the systematic analysis on the suitability of calculation methods constitutes a conceptual framework that may improve the application of tools. In fact, this systematization is necessary to facilitate the identification of suitable tools for routine design. The proper selection of the calculation methods is essential to extend their use and exploit them in a more fruitful way.

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Structure of the document

The document is structured in the following chapters.

In **Chapter 1**, we introduce the context of this research explaining the necessity to investigate on the application of energy calculation methods in routine design. The initial hypothesis and the objectives of the research are defined and the methodology is outlined.

In **Chapter 2**, we deal with the design process through a critical overview of literature precedents in two subject-matters: design process and energy calculation methods. The analysis of literature proceeds from general to specialist disciplinary perspectives: we consider texts on building design, then sustainable design, and finally, energy assessment in design. Based on the panorama outlined in the literature overview, the discussion focuses, at first, on the dynamic nature of the design process, and then, on its holistic nature. Finally, the uniqueness of each design process is stressed.

In **Chapter 3**, we present a broad view on building energy calculation based on the existing literature. Some fundamental concepts are introduced. Generic calculation flow charts are outlined, and calculation inputs and outputs are presented. The boundaries of analysis are considered and main common characteristics of energy calculation method are highlighted. All these concepts are accompanied by critical considerations from the design perspective. The aim is to identify the implications derived by applying energy calculation in design. Finally, real design practice is observed: the current application of energy calculation in ordinary design practice is addressed, contrasting different opinions of experts. From the study a great diversity of energy calculation methods emerges. Given the singularity of each design process, matching particular project needs with a calculation tool is nothing obvious.

In **Chapter 4**, we address the suitability of calculation methods to design needs. In particular we investigate the factors that condition the applicability of the calculation method, taking into account the uniqueness of each project and the existence of different design needs at each design stage. For instance it is recognized that the consistency and detail of the project information is changing. First we analyse the contribution of precedent literature highlighting the necessity of further research rooted in design studies. Then, to fill in this gap, we identify a set of key factors and we systematically analyse each one examining the correspondence between design needs and features of calculation methods.

In **Chapter 5**, the case study of the design process of a residential building in the Barcelona metropolitan area is presented (Case A). A hypothetical process is reconstructed. The two design stages of the project are analysed: conceptual design and design development. At each stage a specific calculation tool is used to support design decisions. In the case study, we exemplify some of the concepts exposed in theoretical terms in earlier chapters. Hence, we take into account the dynamic and holistic nature of the design process; we consider two energy modelling tools that reflect the diversity of existing calculation methods; and we illustrate some implications that energy analysis has in this design process. Finally, the key factors for the choice of the calculation method in the project are analysed.

In **Chapter 6**, the case study of the design process of a residential building in Vienna is considered (Case B). This second case complements the first one by presenting a real design process. The design phase is examined. The methodology of the analysis reported in this chapter is similar to the precedent case study.

In **Chapter 7**, we draw the general conclusions of the research. In particular, we highlight the results achieved approaching the application of energy calculation methods from the design perspective. We make some reflections on the use on energy calculation including some explanations for their limited application in current design practice. Beyond the direct research outcomes some additional considerations are provided to set the base for future research.

The chapters are complemented by the following annexes.

Annex 1 is a report of a survey conducted among different practitioners about the calculation tools being used at each stage of the design process. The survey results are used for the reconstruction of Case A in order to determine the calculation tools used at each stage of the project.

Annex 2 contains a description of the three energy calculation tools and the underlying calculation methods that appear in the case studies.

Annex 3 includes a detailed documentation of the models generated with the energy calculation tools that are analysed in the case studies.

Annex 4 reports the list of the publications of the author.

Chapter

1

Introduction

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In this chapter our main goal is to introduce the reader to the research work conducted in this thesis, and explain its scope and methodology. In Section 1.1, the context of the research is presented in order to define the object being investigated and explain the importance of the study. In Section 1.2, the scope of the research is specified whereas in Section 1.3, the methodology of the research is outlined. In Section 1.4, we mention two research projects on which the author has been working, and their relationship to the thesis.

1.1 CONTEXT AND IMPORTANCE OF THE RESEARCH

The context of this research deals with the need to face a concrete problem that has become increasingly relevant in the last few years: the environmental degradation. Hereafter, we focus on the responsibility of the building sector and we consider the role of energy performance prediction in design as a means to reduce the environmental impact of buildings.

1.1.1 The accelerated degeneration of the environment

The consequences of human activity on the environment are reaching alarming proportions[1], and urgent solutions are needed. Studies that contribute to stopping the accelerated degradation of the environment and to foster the sustainable use of resources - energy in particular - are still very necessary. Research can contribute to finding short term solutions to these problems, and also to setting long term strategies that are essential for sustainable societies.

One of the main challenges, both in the short and long term, has to do with the use of energy. The fact is energy resources are limited. In addition to this, the processes involved from the extraction to the final use of energy produce multiple impacts on the environment, such as the production of CO_2 emissions that increase the climate change.

[1] The acceleration of environment alteration is alarming according to several experts. A number of reports have been repeatedly produced during the last years, including those provided by WWF (2012) and IPCC (2007). The state of the planet presented by WWF is dramatic, especially taking into account that the study underestimates substantial impacts, like those associated to waste production (WWF, 2012, p. 38). The most evident facet of the environmental problem, and certainly not the only one, is the climate change. This is well documented by the Intergovernmental Panel on Climate Change, in the Fourth Assessment Report (IPCC, 2007) and more recent reports. Roaf (2007) provides an overview of the main figures, including the prediction of future scenarios.

1.1.2 The energy and the impact of the building sector

The building sector is one of the main sectors responsible for energy use (IEA, 2012), especially in the industrialized regions such as Europe[2]. The sector is expected to increase its impact in fast growing BRIICS[3] economies (WWF, 2012, p. 50). Bill Dunster clearly shows the extent of the problem, with the example of the emission generated by the energy use of a residential building:

> *"It is now likely that a typical 4 person UK household, each responsible for 12 tonnes CO_2 / year over 4 generations, will be directly responsible for the deaths of the same number of people in a climate change hot spot. This figure will increase exponentially as climate change accelerates.*" (Summary of Dunster intervention, in Bath and North East Somerset Council, 2009)

The energy used in a building is the consequence of the decisions made throughout the project life cycle, from the design to the construction, to the use of the building. Therefore, it can be largely reduced by making appropriate choices at the right moment[4]. Typically the most relevant decisions affecting the energy use of the building are taken during the building design stages. In particular, a great opportunity to save energy is determined definitively at initial design stages, and less may be achieved at the final design stages (Baker, 1999, pp. 6, 92; Kwok, 2007, p. 1; Heiselberg, 2009). Modifying the building during the construction, or even later, is difficult and sometimes impossible. Because of this, no substantial reduction of energy use may be achieved with late interventions on the building. These arguments highlight the need to study the influence of building design on the building performance, from the initial stages to the final design stages.

The energy resources spent on the building sector includes the energy embodied into the building[5] and the one consumed in the building use. Considering that more than half of the energy resources are usually spent on the building use, the quantification of this portion is particularly important. For

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[2] According to the IPCC (2007) the building sector has the highest mitigation potentials on global temperature change.

[3] BRIICS refers to Brazil, Russia, India, Indonesia, China and South Africa.

[4] According to Clarke (2001, p. XI), "*the better design of new buildings would result in a 50-70% reduction in their energy consumption relative to 2000 levels, and* […] *appropriate intervention on the existing stock would readily yield a 30% reduction"*.

[5] The embodied energy is quantified by taking into account the production and the disposal of the building.

this reason we consider it relevant to focus on the energy required for the building use.

1.1.3 The prediction of energy use within building design practice

Currently the use of calculation in order to predict the energy use of a building and guide the design process is very limited in design practice[6]. Worldwide, and in Europe especially, the commitment of the institutions to improve energy efficiency through the building design is growing. The new regulations are simply imposing the verification of performance requirements according to a given certification procedure. This may require the use of standard calculation methods, but it does not mean that energy calculation is integrated from the beginning of the design process to inform design decisions.

Several calculation methods and tools already exist, as documented by several reviews (ASHRAE, 2005, pp. 32.1-32.3; Crowley, 2008; Waltz, 2000, pp. 15-26; Clarke, 2001; ISO13790:2008, pp. 15-16; Massetti, 2010, pp. 23-56). Although they might be exploited as design tools, design teams are not yet used to their integration in design practice. In addition, finding the most appropriate energy calculation tool for the design task at stake might not be straightforward (Waltz, 2000, p. 17).

In conclusion, in the routine of ordinary building design, energy calculation is still unlikely to be integrated into the design process. The current situation justifies the interest of the thesis on the applicability of energy calculation within the context of building design.

1.1.4 The separation of disciplines and the perspective of this research

Understanding the problems that hinder the integration of energy calculations into the design process is a fundamental purpose of this research work. Some of the difficulties have to do with the fact that energy analysis and architectural design are treated by separated disciplines (Massetti, 2010). In this regard, one of the aims of this thesis is to contribute to changing this segregated disciplinary approach.

In the last few decades, there have been calls to adopt an interdisciplinary approach in order to incorporate all dimensions of design, including the energy performance, into the architectural profession. However, most of the

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[6] Clarke (2001, pp. IX, 281) recognizes the limited application of advanced energy calculation tools within the design process and indicates some of its reasons.

research related to the building sector still takes a specialised approach instead of merging different disciplines (Klotz, 2009). Accordingly, design studies and research in engineering and building physics tend to develop separately. Following this trend, most studies on the use of energy calculations in design have been carried out by research groups specialised in engineering and building physics. For instance, McElroy (2009), which investigated the integration of energy simulation among practitioners in Scotland, belongs to an engineering research group specialized on energy systems.

This thesis is proposed within a PhD in architecture and not within a PhD in engineering. The aim is to approach the use of energy analysis from the point of view of building design. This shift from the prevalent research perspective of precedent studies derives from the necessity to cross traditional boundaries of disciplines in order to enrich existing knowledge.

1.2 DEFINING THE SCOPE OF THE RESEARCH

We have concluded Section 1.1 by defining the object of the study and highlighting its relevance. Throughout this section we explain the scope of the research.

1.2.1 Initial considerations

We extrapolate from the context that we have analysed so far some considerations that are fundamental in investigating the application of energy calculation in the building design. From the outset, we identify three generally accepted statements:

- The energy spent in building operation may be reduced by taking appropriate design decisions, especially at initial design stages.

- A large variety of calculation methods to evaluate energy spent in building operation already exist.

In the light of these considerations, the exploitation of energy calculation tools in design would be expected.

- Nevertheless, energy calculation has scarce exploitation within the design process of ordinary buildings.

1.2.2 Research issues

The reasons for the scarce exploitation of energy calculation in building design are not completely clear. At this point several questions arise. The first fundamental question being:

- In ordinary design practice, is it possible to take advantage of energy calculations within the design process to improve the energy performance of buildings?

The possibility of an effective integration of energy analysis in design is not obvious, especially with the limited resources available in ordinary projects. There is the problem of integrating energy calculation in design practice with appropriate design methodologies, and at the same time, it is necessary to adopt suitable tools. Considering that existing tools respond to a large variety of calculation approaches, a second question arises:

- What kind of calculation methods may be adopted in design?

We have observed the necessity to take action at all design stages in order to reduce the energy use of a building, from the initial to the final design stages. Therefore a third question arises:

- What kind of calculation methods may be adopted in each stage of the design process?

These are the questions that this research attempts to answer.

1.2.3 Limiting the scope of the research

For a more precise definition of the purpose of the thesis, we introduce some remarks hereafter.

The purpose of our research is not to evaluate and compare specific calculation methods but to understand which characteristics make them suitable (or not) in design, from the initial to the advanced stages.

We intend to study existing potentials for a widespread application of energy calculation among practitioners in ordinary design practice. Our concern is with routine projects that are representative of a large part of design activity within the building sector. This is because the priority is to deal with the part of the sector that has more impact on the environment, instead of focusing on exceptional design practices.

Our analysis regards the calculation methods that already exist. It is not our concern to consider their evolution towards new calculation methods that could exist someday in the future. Taking into account the urgency of the environmental problem, the issue is how the already existing tools may be exploited.

We consider the application of energy calculation throughout the whole design process. In our study we pay special attention to the initial design stage because it is then when the most effective decisions on energy use are taken. It is also at this stage when strategic decisions, such as the building orientation, are made by the architect, while specialized technical details may be decided later with the support of a specialist.

1.3 OUTLINE OF THE RESEARCH METHODOLOGY

In our research we follow a theoretical approach based on the analysis of **literature**, and we complement the theoretical research with some **direct observations** of the design practice focusing on two case studies.

1.3.1 Theoretical research

The theoretical research involves a critical analysis of literature references which encompass different disciplines, namely design, engineering and building physics. As a first approximation to the object of research, we have developed the literature review following two lines of inquiry: the design process and the existing energy calculation methods.

It is assumed that a deep insight on the design process is a prior condition to understand how energy calculation might be effectively deployed in building design. Hence, part of the study focuses on design activity and, in particular, on the whole process that design teams follow to reach a complete proposal.

Another part of the research involves a critical overview of consolidated calculation procedures for the quantification of energy use in buildings. The overview provides a broad picture that encompasses the variety of existing calculation methods.

Once these two lines have been investigated, we consider how energy calculation is, or might be, effectively deployed in design. In particular, we have analysed precedent studies on the use of energy calculation tools in design; identified and examined several implications of the use of existing calculation methods in design; and, finally, detected and systematically analysed ten key factors to identify suitable calculation methods for design.

The results of the theoretical research are illustrated and tested with two case studies of two building projects in Barcelona and Vienna.

1.3.2 Case studies

In the theoretical research, the study is approached in a broad perspective, whereas each case study deals with a circumscribed design context defined by the building use, the climate and social-technical setting of each project. Likewise the study is limited to three energy calculation tools.

In the two case studies the design process has been analysed. In both projects, the buildings are destined for residential use, and they are located in a European country. However, each case is differentiated by specific climate and technical-social conditions of each location. In Case A, we deal with a multifamily residential building for social housing in the Barcelona metropolitan area, and in Case B, we consider a building with same use in a peripheral neighbourhood in Vienna.

Each case study deals with the reconstruction and analysis of a design process in which energy modelling tools have been used. Case A is a hypothetical design process, in which we assume a different energy modelling tool has been used at each design stage. The reconstruction of the design process is based on the theoretical research developed in the thesis combined with our direct observation of real design practice. Case B is a real design process. Its reconstruction is made a posteriori, based on our direct observation of the information we have gathered about the project. In the case studies, our aim is not to present a best practice, but to reproduce the working methods of current design practice. In the analysis of Case A, the specific goal is to investigate how energy calculation could be exploited in a hypothetical design process which reproduces realistic settings. Whereas in the analysis of Case B, the purpose is to observe how energy calculation had actually been used in a real design process. In this way, the two cases studies are complementary.

1.4 RELATIONSHIPS WITH RESEARCH PROJECTS

In parallel with the work carried out in this thesis the author has participated in two research projects: IntUBE, co-financed by the 7th Framework Programme (FP7-ICT-2-2.3ICT 2008-2011) and RÉPENER, co-funded by the Spanish National RDI plan (BIA 2009-13365 2009-2012). Both projects belong to a line of research developed by the research group ARC from the School of Engineering and Architecture La Salle.

The goal of this line of research is to create an integrated energy information system, which enables different stakeholders to model, store and analyse energy information through the entire building lifecycle (conceptual design, design development, operation and retrofitting). The purpose is to improve the energy efficiency of buildings. Through these projects, alternative designs for the information system architecture have been developed and a prototype has been implemented (Madrazo, 2013)[7]. The underlying assumption is that having a system which provides qualitative energy information to different stakeholders (designers, occupants, owners, and building managers), generated at the different stages of the building lifecycle, would help to take better informed decisions, which in turn would result in a significant reduction in energy use.

For these research projects it was necessary to develop a comprehensive vision of the building sector to capture the problems of all stakeholders, the interactions among them and the relations between all phases of the project lifecycle. On the other hand, the work carried out in the thesis focuses on the activity of design teams throughout all design stages and the integration of suitable calculation tools for each project and stage. Furthermore, in the research projects the design teams are regarded as users of the information system, whereas in the thesis they are contemplated as the main agents of the design process and as users of energy calculation tools.

In the thesis, we address some questions that arose in the IntUBE project concerning the application of energy calculation tools in the design process. In particular, in the research project we were dealing with the selection of appropriate calculation tools for each design stage. We realized that there were no shared visions among the different researchers involved in IntUBE concerning the selection of the adequate tools for each stage of the design process. In the thesis the underlying difficulties have been investigated.

Conversely, the research work of the thesis has contributed to the IntUBE and REPENER projects, by identifying the knowledge required by design teams to integrate energy calculation in design. In particular, it helped to identify which qualified information is needed by practitioners at each stage of the design process. For example, they have to compare calculation results with reference values. Then, practitioners must be able to define reliable performance benchmarks, which have to respond to the precision required for each design stage. Within the research project, it was essential to know the designers' demands of qualified information. Based on this, it was possible to develop suitable services, which have access to the information system to inform and support design teams.

In addition, the research conducted in the thesis has contributed to the IntUBE and REPENER projects by highlighting the complex and dynamic workflow in which design teams are involved. Based on this, we detected the need for a

[7] SEIS, an energy information system based on the application of semantic technologies, available at: www.seis-system.org [2014-06-26].

flexible front-end for the information system, which would enable practitioners to reformulate design goals and adapt them throughout a project.

The research projects and the thesis complement each other. This is facilitated by the selection of the same case study, dealing with the design process of a residential building in Spain (described in Chapter 5). The information obtained by this case study was used for the different purposes in the thesis and the research projects. The information on the original building and design process was obtained through interviews with the designers, and the original documentation of the building project.

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Chapter

2

Building design process

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The calculation of building energy performance may be used in very diverse contexts, such as research in building physics, building design and building operation. Since the aim of this thesis is to evaluate the applicability of energy calculation in design, through all stages of the design process, it is necessary to first get an understanding of the design process. In this chapter, a literature review is presented, crossing references from various disciplines related to building design. In that way, we intend to observe and analyse how the design process has been intended and conceptualized in previous literature. As a result of this analysis, we form our critical vision of the design process which will help us to discuss the subsequent integration of the energy calculation methods. The scope of the study is circumscribed to a limited number of references and it is far from providing a comprehensive review on building design process – widely debated in the specific literature.

In Figure 2.1, the structure of this chapter is visualized. Section 2.1 provides a review of specialized literature on building design, sustainable building design and energy assessment in building design. Section 2.2 is dedicated to a critical analysis of the identified literature, divided in two parts: Section 2.2.1, which deals with the dynamic nature of the design process, and Section 2.2.2 which focuses on its holistic nature.

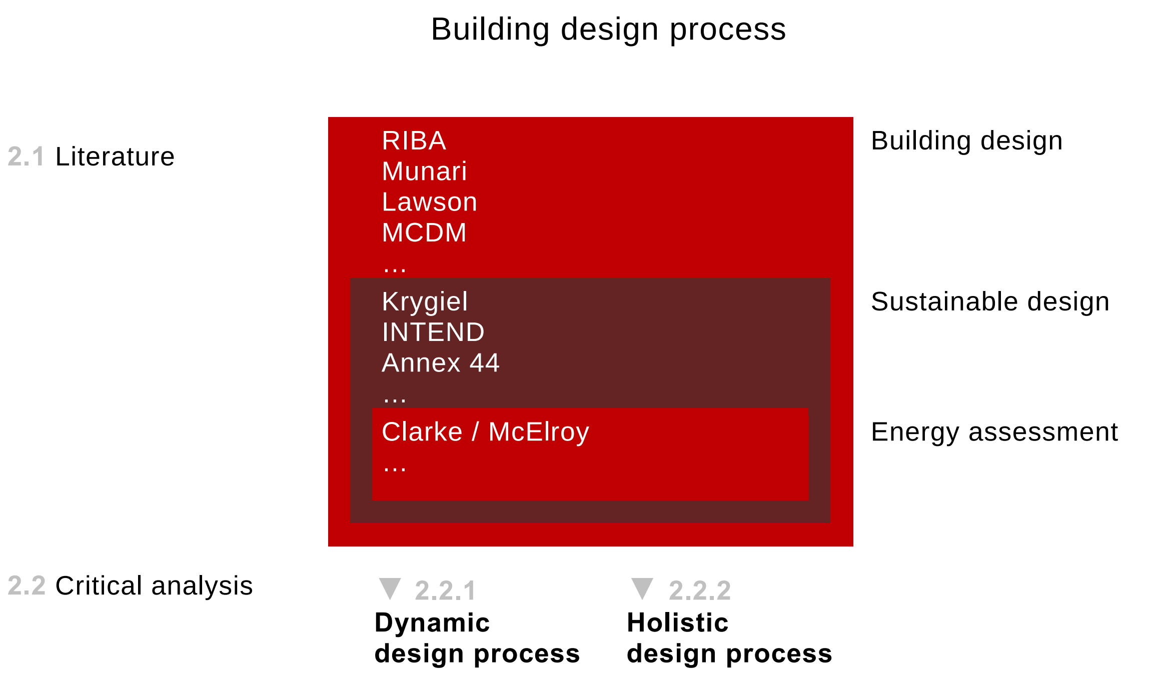

Figure 2.1. Diagram of the structure of the chapter.

2.1 LITERATURE OVERVIEW ON BUILDING DESIGN PROCESS

In this section, theoretical models of the design process are considered, and also design methodologies that establish more or less explicit models of the process of design. Precedent literature is treated with the intention of getting an insight into the design process.

In the following subsections, we present and discuss various views on the design process. The references are taken from three fields:

1. **Building design** - which deals with the structure of the design process and design methodologies applicable in architecture;

2. **Sustainable building design** - a particular area of building design which is oriented to the reduction of environmental and social impacts of buildings;

3. **Energy assessment in building design** - a particular area of sustainable building design, focused on building energy use.

We decided to narrow down the field of study, following these three steps, for the following reason. Starting from literature on building design, we may observe the design process in a broad perspective, which captures its complexity. Then, we progressively restrict the analysis to sustainable building design, and finally, to energy assessment. In that way, we may observe specialized literature on energy assessment having in mind the complex nature of the design process. With this approach, we intend to overcome conventional boundaries among disciplines, which might be a significant obstacle for this research.

2.1.1 Building design

Cross (2007, pp. 17-20, 95-97) has provided an overview on design methods' history that can help give insight into the design process, as it is understood by current studies in the field. In the 1920s, the idea of the design product as a *"scientific design product"* rose. Further on, in the 1960s, the formulation of design methods emerged. Their authors defended a scientific approach to the design process. However, Cross remarks that in the 1970s some of the pioneers of design methodologies, like Alexander and Jones, hardly questioned the value of this scientific approach to the design. Around the same time, authors such as Alexander and Lawson stressed the distinction between science and design. Even so, new design methodologies continued to develop during the following decades, especially in engineering. Recently, there has been an increasing regard of performance analysis methods as drivers of the design process (Augenbroe, 2011, pp. 16-18). The methods based on the building performance have been progressively enforced by technical regulations in the engineering and construction sector.

Besides the evolution of design methods, it is significant to consider how a field of research focused on the study of design has been developing. Pioneer studies on engineering design appeared in the 1960s, but design studies started consolidating as an autonomous research field only in the last few decades. A consolidated and shared understanding of the design process is still missing between existing studies (Cross, 2007, pp. 17-30, 99-103). That is because most of the research done in this area is relatively recent. In addition, the design activity is not a trivial subject to be studied, being the design process largely implicit for researchers (id. p. 9). Even the practitioners involved in a project are not fully aware of the design process and are unable to reconstruct it.

Even so, Cross identifies features of design that have been recognized by several experts, including Eastman, Lawson and Simon, and have become consolidated today in the field of design studies. According to Simon, the design activity can be seen as the process of solving a particular kind of problem. Hence, the design activity involves identifying and analysing a design problem and developing a solution. However, the peculiarity of design is that the design problem is ill-defined. As Cross (2007, pp. 99-100) explains, often a client does not provide a precise description of the design problem, that is, the constraints and goals of the project. Practitioners' experience shows that also after the constraints and goals have been stated, it may be necessary to reformulate them during the design process. Since the design problem cannot be precisely formulated at the beginning of the process the exploration of tentative solutions becomes necessary and it helps designers to better understand the design problem (id. p. 78). Design studies have also revealed that the designer approach is solution-focused: a designer is more oriented to generating a solution, which is the ultimate goal, rather than defining the problem (Cross, 2007, pp. 7, 19, 79). In fact, what is demanded from the designer at the end of design process is not to recognize the patterns of the problem, but to impose the pattern to the solution (ib.). The designer looks for a satisfactory solution and not for the optimum one, because it is imperative to produce a solution within the time and resources available for the project (Cross, 2007, p. 7).

After this introduction on design methodologies and the present understanding of the design process, we consider some models of the process that has been proposed in literature. In order to gain a deeper insight into building design process, we will review the specific models proposed by RIBA (2007), Munari (1983), Lawson (2005) and Spekkink (2005).

The Royal Institute of British Architects (RIBA) has outlined a plan of work that is conceived to coordinate the activity of stakeholders through all stages of a building project. The plan of work has been updated several times from the

1960s (RIBA, 2014), but its underlying philosophy remains. In the plan of work, RIBA (2007) maps an explicit sequence of work stages through the building life cycle including the *“design”* stage (Figure 2.2). In turn, the *“design”* stage is structured as a design process being subdivided in more detailed stages: *“concept”, “design development”,* and *“technical design”*. As Lawson (2005, p. 160) observes, RIBA admits some unpredictable jumping between stages out of the sequence stated. The plan of work gives an example of design process structured by phases. This structure provides a frame in which to develop a design methodology.

Figure 2.2. The structure of the RIBA plan of work, which indicates the stages of the design process (adapted from RIBA, 2007).

Munari (1983) has developed a design method applicable to several design problems. The focus of this methodology is on the solution of a generic design problem. In fact, *“problem”* and *“solution”* are the two opposite ends of the design process, represented by Munari as a linear and unidirectional series of steps (Figure 2.3). To reach the solution of a design problem several steps are necessary: the problem definition (DP); the identification of sub-problems (CP); the collection of data (RD); the analysis of data (AD); the creative phase (C); the documentation of materials and technologies (MT); the experimentation (SP); the construction of models (M); the verification (V); and finally, the technical drawings necessary for the construction. The method involves the decomposition of the problem in several sub-problems that can be solved one by one to achieve the final solution.

Figure 2.3. Munari represents a linear design process which leads through a sequence of phases from the design problem to the solution (figure adapted from Munari, 1983).

Lawson (2005, pp. 38, 47) proposes a representation of the design process for the solution of a generic design problem. This model of the design process is not based on the identification of separated chronological phases or a fixed route along the whole process. It is based instead on the continual *“negotiation”* between design *“problem”* and *“solution”* (Figure 2.4). The connection between them is established by three activities: *"analysis"* of the problem, *"synthesis"*, concerning the generation of the solution, and *"evaluation"* of the solution. Lawson does not indicate any sequence for these activities. His proposal is not a design method but a representation of the design process. Besides, Lawson (2005, pp. 83-111) provides a *"model of design problem"*, as a mean to better understand design. This conceptual model describes the categories of design constraints that characterize design problems. The categories are determined by a three-dimensional matrix. One direction of the matrix corresponds to the agents constraining the design - the architect, the client, the user and the legislator. The second direction indicates if the constraints are internal or external to the design: the internal constraints are produced by design decisions, whereas the external ones are dictated by the context of the design problem, such as the geographical location of the building. The third direction corresponds to the kind of function that the building has to satisfy.

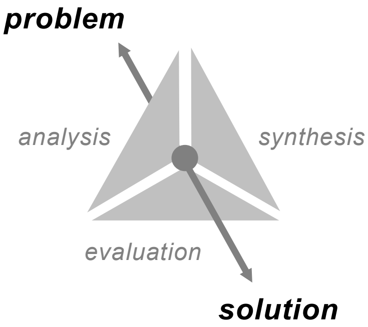

Figure 2.4. Lawson describes the design process as a negotiation between the problem and the solution (figure adapted from Lawson, 2005).

Spekkink (2005, pp. 19, 44, 43) represents the design process according to a performance-based design approach. The process is seen as a chain of demand and supply (Figure 2.5). The chain follows a general to detailed progression. At each step, the performance requirements demanded, for instance, heating consumption of building, are verified against the performance supplied by a design solution proposed by the designer. The performance supplied is determined as a function of the specifications of the solution proposed. For instance, heating consumption of building is obtained in function of envelope and heating system characteristics. These specifications, for example, the transmittance of envelope, provide new performance requirements for further development of the design solution. The process continues according to the same pattern of demand and supply. At each step new performance requirements are more and more specific and detailed, until the final design solution is completely developed.

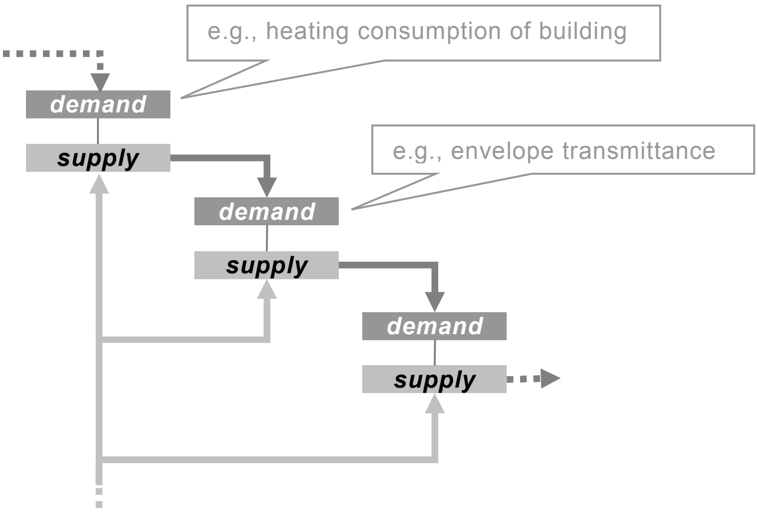

Figure 2.5. The design process as a chain of demand and supply (figure adapted from Spekkink, 2005).

The previous examples refer to comprehensive models of the entire design process. So as to deal with a specific phase or task in the design process, particular methods and simple strategies exist. Predetermined and structured methods have been developed to help designers to tackle specific design tasks. Also designers tend to exploit design strategies which are loosely defined and sometimes are not conscious and predetermined (Cross, 2006, p. 109; Lawson, 2005, pp. 181-199). Some examples are considered hereafter.

Several Multi Criteria Decision Making (MCDM) methods have been developed to help design teams to decide among alternative design solutions. MCDM requires identifying the main aspects of a design problem (for example comfort, energy, cost and form), and defining specific performance indicators or qualities to evaluate the alternative solutions. Finally, specific procedures are established to rank the alternative design solutions. Alanne (2003) and Augenbroe (2011, pp. 16-25) describe typical procedures that reduce heterogeneous performance indicators (as energy consumption and maintenance cost) to a single metric in order to rank alternatives. In practice, this kind of method, being proposed in theory for performance-based design, is scarcely applied by design teams. In part, this is due to the complexity added by MCDM to design methodologies, the difficulty of quantifying heterogeneous aspects by means of a unique metric, the complexity of embracing a comprehensive set of criteria, and the unavoidable components of subjectivity of decisions.

In the building design process, a common strategy used by practitioners to formulate design solutions is parallel thinking. Lawson (2005, pp. 143, 154-155) has observed and analysed this kind of strategy. It consists of developing several paths in parallel to solve a design problem. For example, architects use parallel thinking when simultaneously developing a large-scale solution for the whole building and small-scale details of a component. Another example is the parallel development of two alternative solutions to a given problem. Parallel thinking is not necessarily an entirely conscious and intentional strategy. But it seems common in design practice.

Continuing with this literature review, in the next section we focus on a particular disciplinary area concerning sustainable building design.

2.1.2 Sustainable building design

Gauzin-Müller (2002, pp. 12-18) describes how sustainability of buildings has spread as a design paradigm in the last few decades. The diffusion of this concept is the consequence of a new awareness of environmental problems that has been growing since the oil crisis of the 1970s. As it is generally meant, sustainability looks for a compromise between environmental preservation, social needs, and economical values[1]. Frequently in sustainable design, a particular emphasis is put on environmental goals. To achieve them, sustainable design deals with the flows of energy, materials and water, trying to minimise the consumption of resources and the production of waste (or emissions). Presently, energy use is one of the dominant concerns in design.

In order to produce sustainable buildings, several design methodologies have been proposed by authors such as Baker (1999), Roaf (2007), Mendler (2002), Kwok (2007), INTEND (2009), Heiselberg (2009), Cuchí (2009) and Krygiel (2008). Some of them are presented hereafter.

The Integrated Design Process (IDP) is a design method that has been conceived to optimize building performance (Heiselberg, 2009, p. 17) with an integrated design approach. In fact, the IDP is intended to guide design teams to cope with the interaction of multiple aspects of building performance, such as lighting, heating and cooling (Figure 2.6). According to the IDP an inter-disciplinary team has to be created and work together from the beginning of the process. In this method the structure of the design process follows a linear sequence of design phases: *"building location / building brief; development of design concept; system design and preliminary performance evaluation; component design; operation and management"*. At each phase, team members work separately following iteration loops. By these iterations they analyse the design problem dealing with separated design aspects, such as heating, cooling, lighting and ventilation. The iterations involve a sequence of

[1] According to the debate which grew around the concept of sustainable economic development initially formulated by Barbier (1987).

steps[2], which is repeated at each phase (id. p. 25). In terms of energy performance, the sequence is based on a strategy of reducing the energy demand before adding mechanical systems (id. p. 19). Specific kinds of tools and methods are indicated for each phase (id. pp. 85-87): experience, rule of thumb and decision tools are suggested in the phase of *"development of design concept"*; simulation tools are contemplated in the phase of *"system design and preliminary performance evaluation"*; finally, calculation and dimensioning tools are proposed in the phase of *"component design".*

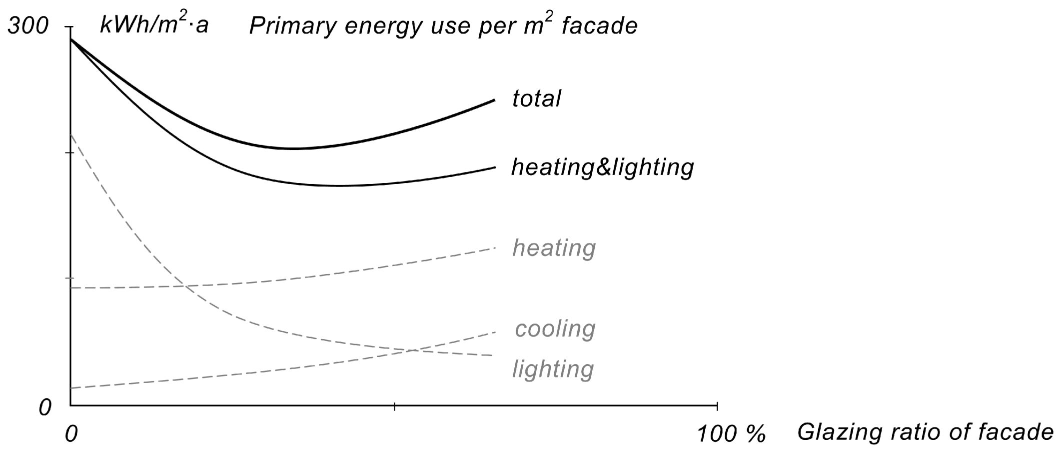

Figure 2.6. An example of a combination of multiple performance aspects provided in the IDP method. The graph shows the effect of the glazing ratio of the facade in an office building in Copenhagen. The separate and combined effects on heating, cooling and lighting energy is shown (figure adapted from Kristensen and Esbensen, cited in Heiselberg, 2009, p. 24).

In the Integrated Energy Design (IED) guide, a method to design low-energy buildings within an integrated design approach is described (INTEND, 2009). In order to integrate building energy design with other design aspects, the main idea is to involve different specialists from the beginning of the design process. This method identifies nine steps, essentially focused on the organization of stakeholders' work, including meetings, planning, documentation, contracts and so on. According to the IED guide, nine main activities are likely to be useful for integrated design processes of low-energy buildings. These activities are to *"select a team; analyse the boundary conditions; make a quality assurance program and a quality control plan;*

[2] The sequence includes six steps: *"basic design focusing on reduction of energy demands"*; *"climatic design though optimization of passive technologies"*; *"integrated system design and application of responsive building elements"*; *"design of low exergy mechanical systems"*; *"efficient design of conventional mechanical systems"*; and *"design of intelligent control for optimized operation"* (Heiselberg, 2009, pp. 19-21).

arrange a kick-off workshop; facilitate close cooperation; update the quality control plan; make – boosting – contracts; motivate and educate workers; and *make a user manual"*. These activities do not correspond to an evident chronological sequence. The whole design process, represented in Figure 2.7, is structured in *"roughly defined phases"* which encompass: *"programming, concept design, and detailed design"* (id. p. 36). A number of *"milestones"* are established at the end of each phase in order to evaluate the status of the design at that point, to take major decisions, and to produce documentation. In each phase, the design team follows an iterative loop made up of a sequence of *"main tasks"*, which are, to *"define the goals; develop and decide strategies to meet the goals; make activity plans (like quality assurance plans, control plans); evaluate the design; and make corrections if needed"*. The three phases and the corresponding iterative loop described above only correspond to the design process. In this method, two additional phases are established after the design phases: *"construction"* and *"operation"*.

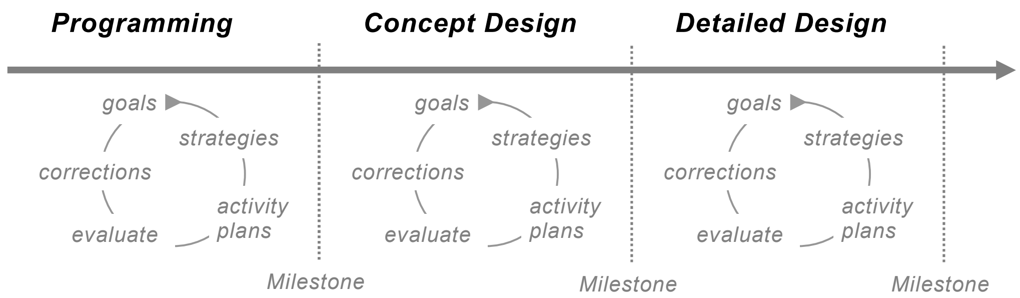

Figure 2.7. Main phases of the design process proposed in the IED guide (figure adapted from INTEND, 2009)

Krygiel (2008, pp. 75-204) describes a design methodology for green buildings aimed at integrating all members of the design team along the design process. A sequence of operations is defined (id. p. 76): *"understanding climate, culture, and place*; *understanding the building type*; *reducing the resource consumption need; using free/local resources and natural systems; using efficient man-made* [mechanical] *systems; applying renewable energy generation systems; offsetting remaining negative impacts"*. The sequence is applied to deal with several sustainable design *"concepts"* identified by the author (id. p. 129): *"building orientation, massing studies, delighting, water harvesting, energy modelling, renewable energy* [and] *materials"*. According to the methodology, these *"concepts"* are not treated in a precise and explicit order; yet, the author indicates, for example, that *"building orientation"* is to be considered in early design. Among the tools proposed in this design methodology, the author attributes a central role to Building Information Modelling (BIM) tools. The purpose of BIM is to enable the creation of models that contain consistent information about a building. Such models are not limited to the geometry, but they are supposed to include information regarding different design aspects, such as cost and properties of materials, among others. In that way, BIM should provide support to specialists involved in the design team, to help them share information and offer interoperability with other tools, such as energy simulation tools. In particular, the use of energy simulation is proposed for initial *“massing studies”* (id. p. 147) and for more detailed *“energy modelling”* when design solutions are more developed (id. pp. 184-192).

The design methodologies for sustainable design outlined above have an underlying energy strategy in common: that is the *“Trias Energetica”* approach (Lysen, 1996), reproduced in different variants. Trias Energetica is a definition of priorities for a sustainable use of energy. In essence these priorities consist of reducing the energy demand before consuming energy by adding mechanical systems (Figure 2.8). This approach applied to the building design consists of trying, as far as possible, to achieve comfort conditions with passive design by defining the shape, the orientation, the envelope, and other features of the building architecture. Then, the passive design is complemented by active mechanical systems (for heating, cooling, hot water, and other uses) powered by renewable energy sources. The use of cleaner fossil fuels is the very last option to complement renewable sources.

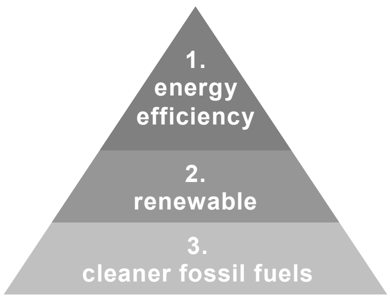

Figure 2.8. Lysen (1996) defines in the Trias Energetica the *“three major elements of all energy strategies: 1. permanent increase in energy efficiency; 2. augmented use of renewable* [energies]*; 3. cleaner use of remaining fossil fuels* [compared to standard energy production, distribution and transformation]*”.*

Another common characteristic of sustainable design methodologies is their adoption of a performance-based design approach. In order to deal with various aspects of sustainable design such as energy, materials and water, performance indicators are often evaluated. In most cases performance indicators are obtained by quantitative analyses. In sustainable design, MCDM methods have been proposed by authors as Balcomb (2000), Alanne (2003) and San-José (2010), to evaluate multiple sustainable design criteria (such as indoor quality, energy performance, embedded energy, consumption of water, and other environmental impacts)[3].

Throughout this section we have focused on sustainable building design. In the next section we complete the review, restricting our analysis to a more specialized field of study – energy assessment in sustainable building design.

2.1.3 Energy assessment in sustainable building design

One of the main factors influencing sustainable design is the use of energy. Energy is a quantifiable phenomenon. Therefore, in building design, this may be assessed with quantitative analysis using energy calculation methods. In building physics and environmental engineering research, the development of energy calculation methods (from simplified calculation to complex simulation approaches) has several decades of history. Specialized literature in this disciplinary area is analysed in this section. In particular, we observe how, according to experts, energy modelling has to be integrated in the design process, and we also highlight how the design process is understood by the same experts.

Clarke (2001, p. 7) discusses the use of energy modelling as a support to the design process. Energy modelling is seen as a means that helps practitioners to answer design questions regarding the energy performance of the building and to take more conscious design decisions. Clarke recognizes that the design process is characterized by various stages, and that specific design decisions may be associated to each stage. He provides an example of a possible design process in which decisions regarding *"zone layout and constructional schema"* are taken at *"early design stage"*, and decisions regarding *"alternative control scenarios"* and *"local renewable"* devices at later stages (id. pp. 5-6). Actually, the structure of the whole design process is not his main concern. His research focuses on energy simulation, rather than the design process. Consistently with this, he argues that *"the problem of predicting energy consumption* [with simulation models] *has traditionally been divided into two distinct stages"*. The first stage consists of designing the building in order to reduce the energy needs, and the second consists of designing the plant to match the comfort requirements with minimum consumption of energy (id. p. 13). Anyway, it is not evident that the stages just described correspond, in the view of Clarke, with the main stages that structure the whole design process.

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[3] Building sustainability may be supposedly assessed with many rating systems such as CASBEE, BREEAM, Minergie, LEED and VERDE, which are based on a trade-off of multiple criteria. However, many of them were not created specifically to assist the design process.

Clarke and McElroy provide some methods to apply simulation tools in a design process. In particular, they consider the work performed by the energy assessor within the design team. The methods proposed are focused on the energy and environmental comfort aspects, and they define the task of energy modelling. Clarke (2001, p. 295) has developed a Performance Assessment Method (PAM), consisting of a generic sequence of eleven steps that energy assessors should follow in their projects. In the generic PAM it is recommended to, 1°, *"establish a computer representation corresponding to a base case design".* 2°, *"calibrate this model using reliable techniques".* 3°, *locate representative boundary conditions of appropriate severity".* 4°, *"undertake integrated simulations using suitable applications".* 5°, *"express multivariate performance in terms of suitable criteria".* 6°, *"identify problem areas as a function of criteria acceptability".* 7°, *"analyse simulation results to identify cause of problems".* 8°, *"postulate remedies by associating problem cause with appropriate design options".* 9°, *"for each postulate, establish a reference model to a justifiable level of resolution".* 10°, *"iterate from step 4 until the overall performance is satisfactory".* 11°, *"repeat from step 3 to establish replicability for other weather conditions (where applicable)"*.

More recently, McElroy (2009, p. 207) has described a set of procedures that the energy assessor should follow. The tasks to be carried out by the energy assessor are not detailed as they are in the PAM, but a more comprehensive description of the role of the energy assessor during the design process is provided. In the following sequence McElroy proposes to, 1°, *"identify issues to be addressed and simulation objectives. Translate to simulation approach, and agree required output format and key indices required to judge performance".* 2°, *"abstract the essence of the design, and develop model at a level of detail appropriate to the focus of the study".* 3°, *"organise problem files and documentation, and proceed with simulations – this reduces the risk of not archiving at the end of the process".* 4°, *"run initial simulation and* calibrate *model to instil confidence in all parties".* 5°, *"after simulating, results must be interpreted, performance assessed, reports written and presented to the client".* The eleven steps specified in the PAM seem to be assimilated into the last two steps indicated by McElroy.

In the methods presented above, Clarke and McElroy address the need of Integrated Performance Visualizations (IPV). An IPV has to be produced by the energy assessor to facilitate the global view of all performance aspects. The IPV is intended as a means to express the interpretation of results, and then, to communicate, discuss and evaluate the overall performance with the design team or the client.

2.2 DISCUSSION

In the precedent sections we have presented a literature overview including three disciplinary areas: building design, sustainable design and energy assessment in design. In this section we discuss several views of the design process emerging from the three areas considered. In the discussion, we identify similarities and differences in the visions presented in the previous sections.

In the analysed literature, models appear to have an essential role in the design process. In the words of Cross (2007, p. 125), *"modelling is the 'language' of design"*. In fact, models are a means for designers and design teams to represent design scenarios. We meet a similar idea observing literature on sustainable design. For instance, the building model as a means to share information within the design team is at the core of the design methodology of Krygiel.

In performance-based design, a particular kind of model is needed. Models used for performance analysis are not a mere description of the building and its environment. They also produce information on the performance achieved by the building. Performance analysis requires the description of the behaviour of the analysed system (ASHRAE, 2005, p. 32.1). In that sense, a *"model is a description of the behaviour of a system"*. This kind of model is applied in the analysis of different performance aspects, such as structural analysis or energy analysis. In the disciplinary area of energy assessment, this notion of model is implicit when the authors refer to energy modelling. As Clarke (2001, pp. 3-7) explains, a building energy model represents the behaviour of the building, which is intended as an energy system.

In design we can recognize a dualism between a **design scenario** and the **model** which represents that scenario. In theoretical terms several authors such as Cross (2007, p. 53) and Augenbroe (2004, pp. 6-7, and 2011, pp. 16-17) have recognized this duality, although in a real design process the distinction between a design scenario and its model is not so evident. Identifying and defining all design scenarios and corresponding models involved in a design process is complicated. Also it is not trivial to track and understand the dialogue between them along the process. This is due to the complexity of design, resulting from the dynamic nature of the process and the interaction of the multiple design aspects along the process. Then, to better understand how modelling, and in particular energy modelling, may be integrated in a design process, it is necessary to analyse in more detail the dynamic and holistic nature of the design process. A deeper analysis is presented in the next two sections.

2.2.1 The dynamic nature of the design process

In this section, we focus on the dynamic evolution of the design process. Some considerations are made hereafter based on the literature in the three disciplinary areas that have been observed.

a**. The view of design process as a structured sequence appears controversial.** The analysed references show very different ways to understand the dynamic nature of the design process. At the scale of the whole design process a lineal sequence of phases is often recognized[4], whereas at a more detailed scale, a sequence of actions, steps or tasks (either lineal or iterative) is usually defined[5]. However, some authors are of the opinion that real design practice cannot be generalized with representative maps of the workflow and are rather unsure that a sequence of specific steps (either lineal or iterative) could be defined a priori and successfully applied (Lawson, 2005, p. 40). It has also been observed that a sequence of design phases does not necessarily entail an increasing level of detail (id. p. 37). Existing studies show that some architects start designing from details from the beginning of the design process (id. p. 39). Nevertheless, team organization (id. pp. 233-264), contractual agreements and most existing regulations[6] impose fixing at least some milestones a priori, which typically mark design phase transitions (as proposed by INTEND, 2009, pp. 36-37, and Heiselberg, 2009, p. 25). At each milestone a design team is expected to achieve specific intermediate goals, demonstrating the progress in the definition of the design solution. Also design strategies focused on the energy aspects may embody a more or less structured view of the design process. Design strategies such as Trias Energetica can be applied differently. In fact, the three priorities of Trias Energetica (improving energy efficiency, using renewable energy, and using fossil fuel) may be interpreted as a structured sequence of steps, or just used as guiding principles.

b. **The understanding of the design problem changes over time by exploring possible design solutions.** Several ideas exist regarding the relationship between design problem and solution during the design process. Opposed approaches are often associated to engineers and architects. According to INTEND (2009, p. 32) an engineer *"likes to have a precisely*

[4] That is the case in the in the RIBA plan of work (RIBA, 2007).

[5] This is shown in the models of the design process proposed in several references as RIBA, (2007), Krygiel (2008), INTEND (2009), Clarke (2001) and Spekkink (2005).

[6] In Spain for example the technical code of construction, CTE (Ministerio de la Vivienda, 2006), prescribes two main design phase basic design and executive design. The code defines a priori the information to be delivered at the conclusion of each phase including design requirements and design specifications which have to be documented.

defined problem as a starting position"; an architect instead *"starts with a scarcely defined problem"* and simultaneously investigate the solution and problem. In the traditional view proposed by Munari (1983) problem and solution correspond to the starting point and the end of the design process. If we radicalize this view, the problem is defined first and later the solution is developed. In later design studies, the process is seen rather as a co-evolution of both problem and solution: the problem formulation impulse the generation of possible solutions and vice versa (Cross, 2007, p. 102). Similarly, the performance-based approach described by Spekkink is based on a dialogue between problem and solution. Performance-based design involves verifying several times if the solution developed answers to the problem formulated. More precisely, Spekkink (2005, pp. 19, 44, 43) refers to the dialog between *"demand"* and *"supply"*, that structures the entire design process. Performance requirements demanded over the process are repeatedly verified against the performance specifications supplied by the design solution.

c. **The object being designed is approximated, not unique and changing over time.** The object to be described is quite evident when a specific building, univocally defined, such as an existing building, is analysed. Nevertheless, this is not the case in building design. In fact, in a design process the following conditions have to be taken into account:

- The design solution is an abstract object. It is undefined, more or less vague and **approximated** (Cross, 2007, p. 108). This fact is evident also in design methods for low-energy building: for instance, INTEND (2009, p. 34) suggest developing *"building concepts"* at initial design stages by exploring *"schematic options"*. Such approximated definition of the design solution regards the building as a whole and each part of it. The level of definition of each part of the building is changing throughout the process.

- Often the design solution is **not unique** (Cross, 2007, pp. 106-107; Lawson, 2005, pp. 121, 154), and the number of alternative options can vary throughout the process. In its Performance Assessment Method Clarke (2001, p. 295) proposes to develop alternative design options when performance requirements are not satisfied.

- The design solution is **constantly under evolution**, being subject to possible to changes throughout the whole design process (Cross, 2007, p. 102; Lawson, 2005, pp. 198, 274-275). The evolution of the design solution involves simple improvements or substantial changes, producing a design solution radically different from its original conception.

These three conditions[7] make the analysis of the design object dramatically more complex than the analysis of a clearly defined object as an existing building. This fact also complicates energy assessment.

d. **It is possible to recognize various time scales in the design process.** Several authors represent the design process as a sequence of stages and each stage as a series of steps[8]. This representation embodies the implicit definition of different time scales: the entire design process can be measured by phases, while each design phase can be measured by shorter steps. All analyses conducted to evaluate design solutions are affected by the temporal dimension of the process. The whole amount of time necessary in a project for energy assessment is considerably relevant at the scale of the design process and at the scale of specific tasks' iterations. The extension of each design stage, along with the duration of any design iteration, substantially constrains energy assessment. In conclusion, to study the integration of energy calculation in design, it is fundamental to recognize various time scales in the design process.

e. **The building design process is a part of the whole project life cycle.** Especially in recent years, the design process has been intended as a segment of a larger temporal frame: the whole building life cycle[9]. This comprehensive view is also shown in sustainable design methodologies, and particularly in energy assessment. In fact, it is acknowledged that the environmental impacts, including the energy footprint of a building, are spread throughout the whole product life cycle (from resource extraction to building disposal). Moreover, according to a performance-based approach, the project evaluation must be conducted through different phases of the project life cycle. A complete frame is considered necessary to ensure that the requirements formulated in the design stages are satisfied when the building

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[7] These conditions have to do with the intrinsic uncertainty of the design process, which has been object of previous literature. There are studies on performance-based that deal with the uncertainty existing in the design process (Spekkink, 2005, pp. 32-33). Likewise, uncertainty is an object of concern in energy assessment, and especially since in the last decade, it has become a central research topic (de Wit, 2001).

[8] Several models of the design process have this kind of structure, for instance those described by RIBA (2007), INTEND (2009) and Heiselberg (2009).

[9] For instance, in RIBA plan of work the design process is preceded by the Preparation stage and followed by the Construction and Use stages. Similarly in sustainable design methodologies proposed by INTEND (2009) and Heiselberg (2009), the design process is treated as a part of the project life cycle. INTEND and Heiselberg pay attention to the construction and the use phases, when the characteristics and the energy performance of a building under real conditions may be verified. Concern on various phases of the building lifecycle is shown in sustainable design guides by several authors as Mendler (2002), Kwok (2007), and Cuchí (2009).

is used and its actual performance shows up. Despite the thesis focusing on the design process, it is necessary to take into account that this is a segment of a larger process whose continuity should be assured.

f. **The definition of design phases is not sharp, univocal, and completely predictable.** Most of the authors describe the design process as a sequence of phases, although there are no shared definitions of design phases in literature. No clear patterns define how many phases can be established, how each phase is characterized, which features differentiate consecutive phases, and finally, when and according to which criteria the beginning and the end of each phase are established. For example, several authors identify a *“concept design”* phase, although it is quite difficult to find a common idea of what exactly *“concept design”* means. The definition of the phases of a design process may depend on many circumstantial factors. It certainly depends on how the designer faces the design problem. Design decisions being considered differ substantially according to the designer and his or her approach to the conceptualization of a design scenario. For example, at early design stages, someone might decide on the building shape and orientation, thus conceptualizing the building as a volume, while someone else might consider space distribution and conceptualize relations between functions.

To some extent, the lack of shared definitions for the design phases relates to the dynamic nature of the process. In fact, it is often impossible to determine which design decisions will be at stake, or which constraints will exist at a future design phase, before knowing the outcome of the previous ones. In a project, the effects of one phase to the next are complex, so it is quite difficult to define future phases in advance. Therefore, it is hard to predict how future phases will be characterized. Likewise, it is difficult to know the precise moment when the relevant events that produce the transition to a different design phase will occur.

g. **Despite the difficulty in clearly defining design phases, there are some usual distinctions among phases.** Whatever models of the design process are analysed from literature, it is evident that each design phase has some specificities. The variables that differentiate design phases typically include:

- The domains of competence and the specialists integrated in the design team. INTEND (2009, pp. 10-11) and Heiselberg (2009, p. 16) observe that in traditional design process the specialists’ competences are involved in late design phases,

- The density of the information about the project. Von Buelow (2007, pp. 26-27) evidences the progressive accumulation of information that is produced during the process. According to Mahdavi (1999, pp. 427-428), an increasing information density is traditionally associated to the transition from early to advances phases,

- The design goals, constraints, and decisions. Cross explains that design goals and constraints are not clear at the beginning of the design process, and are more precisely specified during the process. Many authors associate specific design decision to each design phase. For instance, Heiselberg (2009, pp. 24-29) proposes deciding on the whole building concept at the initial phases, and on components details at final design phase.

Despite the above variables differentiating each design phase, it is not clear if those follow precise variation patterns in real design processes.

h. **The knowledge on the design problem and solution, and the design freedom evolve during the design process.** As observed in precedent studies, design entails a process of knowledge acquisition. At the beginning of a design process the member of a design team already possesses a previous knowledge. Then, during the design process they acquire additional knowledge on the particular design problem that they are analysing. Different studies have observed that, while the knowledge of a design problem progressively increases, the freedom of designers is reduced by the decisions being taken through the process (von Buelow, 2007, pp. 26-27)[10]. At early stages they have wider possibilities to take substantial decisions, actually driving the design and orienting the generation of design solutions in a decisive way (Heiselberg, 2009, p. 16; INTEND, 2009, p. 13). However, due to the limited knowledge acquired on the project they have little possibility to make precise evaluations and assure the achievement of strict performance requirements. Whereas at final design stages it is the opposite, they have little possibility of taking substantial design decisions. Meanwhile, due to the additional knowledge acquired, more precise and reliable evaluations may be carried out to assure specific performance goals.

2.2.2 The holistic nature of the design process

> *"Nothing is as dangerous in architecture as dealing with separated problems. If we split life into separated problems we split the possibilities to make good building art."* Alvar Aalto[11]

We have previously discussed the dynamic nature of the design process. In this section we focus on its holistic nature. Hereafter we make several considerations based on the study of some literature references in the three disciplinary areas being addressed.

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[10] Von Buelow refers to previous studies of Fabrycky, 1991, and de Bono, 1971.

[11] Quoted by Krygiel (2008).

a. **In building design it is necessary to deal with the multiple dimensions of the design problem.** This has been recurrently argued by design theorists. In fact, dealing with a design problem requires considerations on structure, form, cost, comfort, energy, and so on. In the view of Munari for instance, a design problem may be seen as a set of *"sub-problems"*. This approach is meant to help designers to address the project complexity. Heiselberg (2009, p. 10) affirms that an integrated building concept *"includes all aspects of building construction"* like function, structure, energy and others. Augenbroe (1992, p. 150), when discussing performance based design, mentions *"aspects of the design object"* such as *"strength, durability, and cost"*. In performance based design, these must be explicitly identified in order to evaluate each dimension of the building performance. In this line, Spekkink indicates several performance aspects that can be quantified, such as energy consumption (Spekkink, 2005, pp. 60-61, 80-98). But he also remarks on the necessity to take into account quality aspects that are more difficult to evaluate, such as cultural values (id. p. 32).

Also Lawson (2005, pp. 58-59) stresses that design problems are multi-dimensional. He exemplifies the visual and ergonomic aspects of chair design, and he illustrates the design of a window in which lighting, heating and external views must be considered. Compared with these examples, the design of a whole building is considerably more complex. In fact, many dimensions have to be taken into account and any analysis is much more sophisticated. For instance, analysing heat flows in a building is definitely more complicated than analysing them for a window. To analyse all heat flows at the building level a design team must possess deeper knowledge in building physics. Then, to solve the design problem as a whole, it is necessary to deal with an extended range of knowledge domains. For this reason, many competences are needed within the design team (or in support of it). Accordingly, several references, such as INTEND (2009, pp. 10-12), insist on incorporating competences on building energy in the design team, in order to integrate energy performance with other design aspects.

b. **In order to cover all the competences required for a project, a design team has to include a number of practitioners of different profiles**, such as architects, engineers, and energy assessors. The number of professionals involved largely varies according to the project. In a small project different roles may be assumed by a single person, often an architect. As the case may be, a specialist role such as the energy assessor can coincide with the role of designer. As mentioned in some references, for instance INTEND (2009, pp. 11, 16, 20), cooperation between partners and the integration of complementary competences should be tight throughout the entire process. Nevertheless, tight and continuous cooperation seems sporadic in actual practice. Several ways of organizing the design process have been proposed to ensure this close cooperation. For instance, Heiselberg (2009) suggests problem-oriented analyses that are carried out by different specialists separately. The analyses alternate with coordination sessions bringing together all team members. In contrast, INTEND (2009, p. 32-35) proposes joint sessions in the concept design phase in which different specialists may explore, analyse and evaluate design possibilities together.

c. **A particular aspect of design, such as energy performance, may become predominant on the others and drive the design process.** During a design process, practitioners shift their attention among various matters of concern such as structure, form, cost, comfort and energy. A design process may proceed in several alternative directions, depending on the dominant concern that start driving the process from a given moment. Lawson (2005, p. 195) shows an example in which the structural scheme determines the line in which the process proceeds. He observes that the direction taken by the design team is not necessarily right or wrong. In fact, according to the ways by which the process develops, different solutions come out, and each one may be valid. We observe that design methodologies coming from specific disciplinary areas – sustainable design or energy assessment – focus on a limited number of design issues. For example, the design methods described by INTEND and Heiselberg mainly deal with energy and comfort. The application of such methodologies may induce design teams to prioritise particular dimensions of the problem, like energy, penalizing others. In that way, specialized methodologies may influence the direction in which the design process evolves and the solution reached. Likewise, specialized methodologies may affect the allocation of resources among different design aspects, that is to say, the allocation of budget and time among the professional competences that are required. There is a risk that a domain-specific approach impairs the achievement of all project goals. The result is that the building is not capable of meeting all the needs that it is expected to satisfy, so the whole solution is not satisfactory.

d. **The final goal of design is achieving a satisfactory solution for all the dimensions of the design problem.** The quality of the solution is a matter of judgment that depends on the priorities of the client between different design goals (Lawson, 2005, p. 122). However, to achieve equilibrated solutions, the resources available for the building design have to be allocated in a way to cover all the aspects of the project. For instance, if the solution was very efficient from the point of view of energy performance but economically unfeasible, then it would not be satisfactory. With a balanced distribution of resources it is possible to make cost, energy and other analyses, keeping similar quality levels for all the aspects that have to be examined. This helps to result in a solution that fulfils all project goals. For example, the evaluation of a design proposal can be based on a very accurate and precise quantification of energy consumption, and at the same time on a too vague estimation of acoustic performances. Indeed, a very precise verification of energy requirement may be done, while a very poor verification of acoustic requirements is provided. This unequal quality of analysis would compromise the overall evaluation of performance, and therefore, the attainment of project goals.

e. **Any decision taken during the design process simultaneously affects several aspects of a design problem.** As Lawson (2005, p. 60) highlights, often this fact is not fully understood. He explains that it is improper to solve each individual dimension of the design problem by developing separately each piece of the design solution. In such a way it is not possible to solve the design problem as a whole. In fact, the consequences of any design decision have to be considered under different domains of analysis[12]. Only in that way it is possible to solve the design problem as a whole with a unique consistent solution. The multiple consequences of design decisions pose a major challenge for design teams. Whenever a design decision has to be evaluated, the design team must be able to identify and analyse the most relevant design aspects being affected.

f. **The multi-faceted character of building design problems is deeply related with the dynamic nature of the design process.** During the design process practitioners shift the attention from one dimension of the design problem to another in quite an unpredictable way. A particular solution that emerges throughout the process may require changing the direction of inquiry toward a specific facet of the project not yet considered in depth. For instance when large glazing is introduced, it becomes important to pay attention to thermal comfort, because the incoming solar radiation and the thermal losses through the glazing strongly affect comfort conditions. Even if a designer has a grasp of the relevant facet of a design problem, the precise map of the issues to be studied through the process is dynamically constructed and difficult (or impossible) to anticipate. *"It is clear that many components of design problems cannot be expected to emerge until some attempt has been made at generating solutions."* (Lawson, 2005, p. 120)

g. **The competence involved in the design team may vary at each design stage.** The competences available are determinant to cope with the multiple aspects of a design problem. Multi-faceted design problems may be treated varying the compositions of the design team in each design phase. Often, at the beginning of the project, the design team is composed of one or more architects and there are no other professionals with specialised competences. Architects are presumed to have a broad view on the design problem, which is necessary to have a holistic approach to the project, but usually they are not expected to possess specialised knowledge on individual fields such as building energy. The energy assessor and the other specialists are included in the team – if needed – only in advanced design phase (INTEND, 2009, pp. 10-12). Currently several authors (see for example, INTEND, 2009; Clarke 2001; and Serra, 2000) maintain that the energy assessor should be integrated from the beginning of the process.

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[12] Citherlet (2001, pp. 165-169) provides various examples of combined effects in various domains of building physics.

h. **Various methodological approaches have been proposed to achieve integrated design solutions.** In the references consulted, especially the most recent ones, we find claims for integrated methodological approaches that help to consistently solve all aspects of a design problem[13]. Different points of views exist on how to satisfy this need. We have identified two general approaches in the references that we have analysed:

- Conducting joint valuations of different design aspects. Quality assurance procedures, proposed by INTEND (2009, pp. 28-29) foster the joint valuation of all design aspects by a systematic description of all project goals. Likewise, the IPV, proposed by Clarke (2001) and McElroy (2009), has the purpose of facilitating overall valuation, by providing an integrated view of multiple performance aspects. Also MCDM are aimed at the same purpose.

- Integrating project information with models that help to ensure the consistency of multiple design aspects. Different kinds of tools follow this line. BIM tools (Krygiel, 2008) incorporate in one model data regarding different dimensions of the project and facilitate the information exchange with other tools dedicated to specific performance analysis. Likewise, integrated energy modelling tools (Clarke, 2001, and Citherlet, 2001) are intended to integrate, in a single model, the design domains that are more tightly related with the energy phenomena.

Combining energy analysis with the different aspects of building design is particularly challenging as the energy domain in itself is complex and embraces several sub-domains, such as thermodynamics, fluid-dynamics and indoor environmental quality. Hence, embedding energy analysis in design requires extensive knowledge and great effort from the design team and the energy assessor.

[13] This is still considered a gap in the building sector by Klotz (2009). Moreover in many cases it is not completely clear how these methodologies pursue a holistic design. For example, INTEND (2009) proposes to integrate the architect, the system engineer and energy assessor in the design team, but other competences that are also needed are not mentioned.

2.3 CONCLUSIONS

In the analysed literature, we have observed that there is not a single conception of the design process. It seems that the work carried out in the field of design studies has not completely reached specialized research fields[14]. In the technical discipline of energy assessment, the design process is often seen as a clearly structured and explicit process. Nevertheless, design studies questioned the structure of the process and showed that it is in a large part implicit. These differences also convey diverse ideas about design methodologies. In fact, there is no agreement on the usefulness and applicability of established design methods in real design practice. Looking at the professional world, the term design process encompasses a wide range of practices, which often respond to alternative and dissimilar ways to carry out the design of a building.

In the light of the precedent discussion, we avoid the temptation of adopting a firm and precise representation of a generic design process. Instead, we propose a less structured and more synthetic view of the design process resulting from a critical interpretation of the references consulted. In Figure 2.9, we describe the design process as a dynamic process that is characterized by the interaction of multiple dimensions of the design problem. In building design, the energy performance is just one aspect out of many. As such, it has to be integrated and balanced throughout the entire design process with other dimensions of the design problem in order to ensure a satisfactory solution.

As discussed, in each project various design dimensions relate in a non-predetermined way according to the dynamic evolution of the design process. This involves not only the generation of a unique architectural solution, but also the articulation of a unique design process for each project. The design of a building may respond to an undetermined and immense variety of possible design processes.

In the next two chapters we will analyse how the dynamic evolution and the holistic nature of the design process influence the deployment of energy calculation methods and tools. We will also observe how the singular circumstances of each project and the design stage considered are determinant for the suitability of a particular tool and the underlying calculation method.

[14] This lack of shared understanding of the design process possibly relates with the segregation of disciplines, and a lack of knowledge exchange, and also with non-shared points of view.

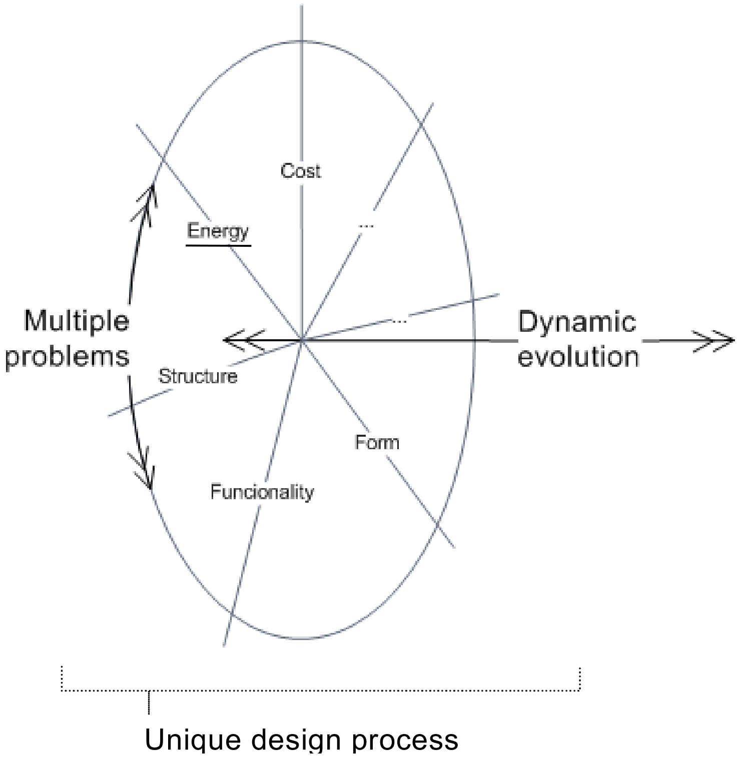

Figure 2.9. The building design process is characterized by a dynamic evolution and by the concurrence of multiple design aspects. It is not possible to establish in general terms which aspects affect the design problem, when and how those are involved in the process dynamics. It depends on each individual design process.

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Chapter

3

Energy calculation and its application in building design

CHAPTER 3: TABLE OF CONTENTS

In the precedent chapter we have analysed the design process through a critical review of specialized literature, setting the context in which energy calculation is used. In the present chapter we treat the central argument of the thesis, focusing on energy calculation methods. In particular, a broad view of existing energy calculation methods is presented and their application in building design is considered. In this chapter we do not have the pretention to provide a systematic screening of individual energy calculation methods and tools already provided in specialized literature. But we provide a global view that is necessary to analyse the application of energy calculation methods in the context of design. Therefore, the theoretical analysis is complemented by the analysis of the actual use of energy calculation in design practice. The chapter is not limited to a state of the art overview, but it also provides critical reflections on what the use energy calculation method implies in design.

The chapter is structured as follows. The subject of energy calculation is introduced in Section 3.1 through some fundamental concepts; in Section 3.2, the calculation process from the inputs to the outputs is described; in Section 3.3, the variables affecting energy performance are identified; in Section 3.4, the boundaries of the analyses enabled with existing calculation methods are considered; in Section 3.5, some salient characteristics of energy calculation method are highlighted. In each section from 3.1 to 3.5, we repeat the same internal structure. First, we analyse consolidated knowledge in literature about energy calculation methods. Then, we discuss the implications derived by applying these methods in building design. In Section 3.6, we present the current application of energy calculation tools in design practice, stressing existing obstacles. In Section 3.7, the conclusions of the chapter are reported.

3.1 WHAT IS INTENDED AS ENERGY CALCULATION METHODS

This section is divided into two parts. In Section 3.1.1, we present fundamental concepts consolidated in specialized literature which are necessary to introduce building energy calculation methods. In Section 3.1.2, we analyse these concepts from the design perspective.

3.1.1 State of knowledge

ASHRAE (2005, p. 32.1) introduces the estimation of building energy use defining the concepts of *"mathematical model"* and *"forward modelling"*.

"A mathematical model is a description of the behaviour of a system. It is made up of three components:

1. *Input variables* […] *which act on the system (e.g. climate).*
2. *System structure and parameters, which provide the necessary physical description of the system (e.g. thermal mass or mechanical properties of the elements).*
3. *Outputs* […] *variables* [that is to say, energy performance outputs].*"* (ib.)

A mathematical model may be employed in order to estimate energy use resulting from the whole or a part of the system made up of the building fabric and the mechanical systems for heating, cooling, ventilation and other uses.

The so called forward modelling approach is usually adopted in order to estimate energy use of building. The objective of forward modelling is to predict the output variables of a specific model with known structure and known parameters when subject to specific input variables (ib.). In building energy modelling, we can express the objective of forward modelling in a more specific way: the energy performances of a building and its mechanical systems are predicted with a known calculation method and known physical description of the building and mechanical systems when subject to specific operational and climatic conditions.

The ASHRAE definition of the *"mathematical model"* as description of something implies the dualism, mentioned by Augenbroe (2004, pp. 5-6; 2011, pp. 16-17), between *"physical entity and phenomena"* to be described, and its *"mathematical model",* or in other words, the dualism between a piece of reality and its model.

Several energy calculation methods have been developed to analyse buildings and their mechanical systems. Existing energy calculation methods are based on quite different mathematical models. Each energy calculation method provides the description of a particular calculation algorithm and defines a specific set of input variables, system parameters and outputs. A common criterion in literature to classify different calculation methods is made in relation with the time dimension and its influence on the analysed phenomena. According to this criterion, a first general distinction is made for thermal modelling[1] between steady state methods and dynamic methods.

- Steady state methods perform an approximated calculation[2] over a sufficiently long time to ignore heat stored in, and released from, the

[1] This distinction refers to thermal modelling, although in energy modelling the thermal domain is often coupled with other domains (such as lighting, fluid-dynamic, etc.). In Section 3.4, we discuss the interaction of multiple domains.

[2] Thermal calculation methods are generally based on heat balance (for example the methods described by ISO13790:2008, p. 15). Complex methods also take into account mass balance and momentum balance (Clarke, 2001, p. 7).

mass of the building. In mathematical terms, this means assuming that all quantities are constant in relation with time.

- Dynamic methods perform the calculation over short time intervals (for example one hour, or less) to take into account the heat stored in and released from the mass of the building, and the time of reaction of mechanical systems. In mathematical terms, this means that the quantities involved in the calculation are variable in function of time, as it occurs in physical phenomena.[3]

Actually, there are many methods which are not either purely steady or fully dynamic methods, but something between them. For example, in the standard ISO 13790:2008 (p. 15), a definition of quasi-steady-state methods is proposed. Quasi-steady-state methods calculate the heat balance[4] over a period of time (typically one month or a whole season) that is long enough to enable taking dynamic effects into account by empirically determined gain and loss utilisation factors.

According to the way they are implemented, energy calculation methods can also be distinguished between manual and automated. This distinction has to do with the historical evolution of the application of energy calculation methods that is described by Clarke, (2001, pp. 3-4), Augenbroe (2004, pp. 5-11) and Hensen (2011, pp. 4-5). Clarke in particular describes *"the evolution of design tools, from traditional manual methods to contemporary simulation"*. As Clarke explains, traditional manual methods are simplified methods. In fact, they reduce the complexity of the equations in order to lessen the computational load by neglecting part of the equations, approximating time dependent variables, or simplifying boundary conditions[5]. Advanced simulation instead is based on mathematical models that aim to represent all possible energy flow-paths and their interactions. The methods implemented in several tools, including EnergyPlus, TRNSYS, ESP-r and BSim, among

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[3] The opposition of steady state and dynamic methods are well known in literature. The definition of steady state methods that we propose in the text is deduced in opposition to the definition of dynamic methods provided by ISO13790:2008 (p. 15). Such opposition is founded on the following basic assumption that distinguishes steady state from dynamic methods. In some applications, time dependency of some thermo-physical properties may be ignored and thermo-physical properties assumed constant (Clarke, 2001, p. 8). The definition of dynamic methods that we propose is based on the same ISO13790:2008.

[4] The heat balance equation establishes that the amount of heat that enters and the one that leaves a building (or a zone) within a given period are equal. That is to say, the sum of all heat contributions is equal to zero.

[5] Boundary conditions are values (or restrictions) assigned to some parameters based on initial assumptions on the analysed phenomena. For example, a calculation method may be based on the assumption that ventilation flow rates are known. This approximation on ventilation parameters allows simplifying the calculation method.

others (US Department of Energy, 2013), have been developed with this aim. In sum, we can say that simplified methods aim to explain physical phenomena but do not have the pretention to emulate it. In turn simulation aims at emulate phenomena by reproducing them with their complexity. Any calculation method entails a trade-off between explaining and reproducing reality.

Certainly the progress of informatics' technology facilitated the application of increasingly complex calculation methods, but the general shift toward automated implementation also involved simple methods. The interest in simple calculation approaches still persists both in research and in design practice. Recently, methods aimed at reducing the complexity of buildings and mechanical systems have been developed by several authors, such as Fabrizio (2010), Caldera (2008), Corrado (2007) and Serra (2000), and sometimes they have been used in design practice, for instance by Waltz (2000). Recent examples of a simple approach include the seasonal and monthly balance methods defined in the standard ISO 13790:2008. Both are quasi-steady-state methods. In the same standard, a simple dynamic hourly method is described. An example of quasi-steady-state seasonal method is provided in the Austrian norm OIB-382-010/99 (1999). This kind of method has some use as a design tool, as we show next, in a case study of a residential building in Vienna. Even some calculation methods, that are simple enough for manual application, still persist; for instance, the one developed by the research group of Serra (2001, pp. 378-380) and used by the same architect.

3.1.2 Implications in building design

In the historical overview of Clarke, he refers to the implementation of calculation methods. Such historical perspective is useful for our analysis. In fact, with the progressive automation of energy calculation, many practitioners identify energy modelling with software tools, but it is important to make a distinction between **calculation methods** and their **implementation** (either manual or automated). This distinction is not always clear and explicit in literature. Most calculation methods that are treated in this thesis are implemented through automated calculation (either simple calculation methods or simulation methods). In the thesis, we investigate the implications of the calculation method on the design process and we do not deal specifically with the implications of the implementation technique[6].

[6] Calculation method and implementation technique are deeply connected and in the actual design practice it is difficult to judge them separately (see Chapter 4). Nevertheless in this thesis, we do not deepen implementation issues (such as user interface, software interoperability role of internet support).

We have mentioned the dualism between *"physical entity and phenomena"*, and its *"mathematical model"*. For a real building, *"physical entity and phenomena"* constitute a tangible reality which can be distinguished from its model. In that case, the dualism it is quite obvious. A different situation arises in a design context. In this ambit, *"physical entity and phenomena"* refer to an abstract design scenario. The model created to represent and analyse it provides the main explicit evidence of the underlying design scenario. Indeed, it is quite difficult to demonstrate and make explicit the dualism that we have identified between a **design scenario** and its **model** (Figure 3.1). However, this dualism exists in design and it can also be recognized in energy modelling. Hand (2008, p. 675) deals with energy modelling in design, and in his words, the separation of these two concepts is implicit when he distinguishes the *"simulation input data"* from the *"reality in the mind of the designer"*.

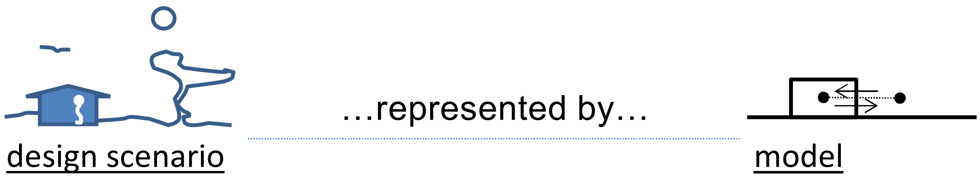

Figure 3.1. The **design scenario** and its **model.**

We previously referred to the *"input variables"* and *"system parameters"* of ASHRAE (2005). We will deal now to the energy modelling inputs to indicate both *"input variables"*, such as climate data, and *"system parameters"*, such as construction materials and component properties. In fact, in terms of modelling task, both must be defined by the energy assessor as inputs for the energy calculation. In a design process, specifying *"system parameters"* is essential for the design team: this means representing the design solution(s) that they generate. In fact, from the perspective of designers these parameters correspond to design variables.

Therefore, we prefer to put forward a distinction that is more relevant and appropriate for energy modelling in the context of building design. Distinction is made between variables influencing energy performances – expressed by energy modelling inputs, and energy performances – expressed by energy modelling outputs (Figure 3.2).

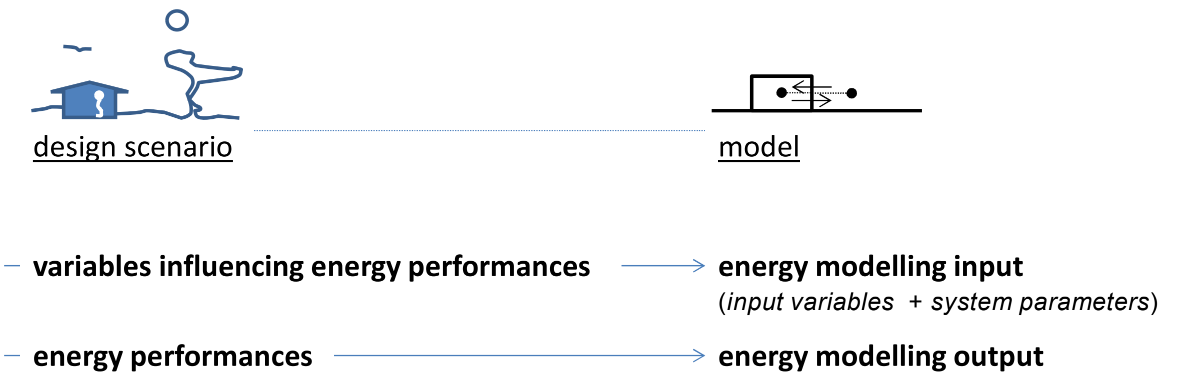

Figure 3.2. The variables influencing energy performances and the energy performances are expressed respectively by the inputs and the outputs of the energy model. We deal with the energy modelling inputs to indicate both *"input variables"* and *"system parameters"* definer by ASHRAE.

3.2 FLOW CHARTS OF BUILDING ENERGY CALCULATION

We have discussed the fundamental concepts that are necessary to introduce the energy calculation methods treated in this thesis. Now in Section 3.2.1, we will focus on the calculation flow charts of energy calculation methods. In Section 3.2.2, some considerations will be made on the use of energy calculation in design, looking in particular at the flow chart of a calculation method.

3.2.1 State of knowledge

The flow chart of an energy calculation method describes the process of calculation from the inputs' definition to the final results. The calculation flow charts can be more or less extended according to the type of performance analysed. The generic flow charts of ASHRAE (2005, pp. 32.2, 32.17) or CEN (CEN/TR 15615:2006 (E), p. 18), are representative of the analysis of a comprehensive range of performance variables. The performance variables that are quantified typically include: indoor comfort parameters such as temperature and humidity; demand for space heating and cooling; energy consumption of mechanical systems for heating, cooling, hot water, lighting, appliances, cooking and other uses; primary energy consumption and emissions (Table 3.1).

Table 3.1. Typical performance variables with some common units.

Indoor comfort parameters...		Operative temperature (°C) Relative humidity (-)					
		Space Heating	Space Cooling	Domestic hot water	Lighting and appliances	Cooking	Other uses
Energy demand (kWh/m²a)	for	x	x				
Energy consumption (1) (2) (kWh/m²a)	for	x	x	x	x	x	x
Primary energy consumption (kWh/m²a)	for	x	x	x	x	x	x
Emission (Kg/m²a)	for	x	x	x	x	x	x

1: The mechanical systems may be alimented by several energy carriers (such as gas, oil and electricity). Energy consumption must be expressed separately for each energy carrier.

2: As an alternative to energy consumption it is possible to express the corresponding consumption of each energy carrier with its unit, such as gas in m^3/m^2a, oil in litres/m²a, or electricity in kWh/m²a.

The performance variables are progressively obtained through a sequence of steps defined by the calculation flow chart (Figure 3.3).

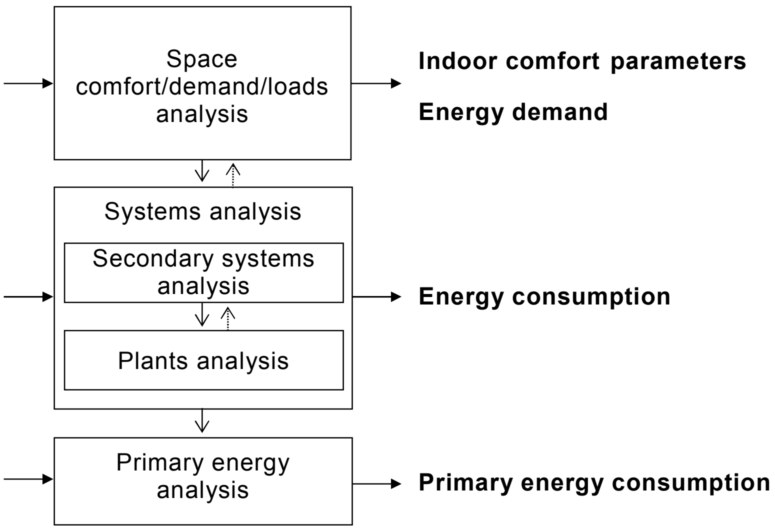

Figure 3.3. Calculation flow chart (adapted from ASHRAE)

In particular the schema of ASHRAE encompasses the following steps.

First, the analysis is performed at the level of indoor space, taking into account that all heat gains and losses of the space balance each other. In that way space loads may be analysed. This means that the heat to be delivered to, or extracted from, a space to maintain a given level of thermal comfort is determined. From this step it is possible to obtain the demand for space heating and cooling, that is to say, the amount of heat to be delivered to, or extracted from, the space over a given period (for example a month, or a year). At the level of indoor space, it is also possible to determine indoor comfort parameters when mechanical heating and cooling are not used: indoor temperature may be determined as a function of the heat gains and losses of the space.

In the next step, the analysis is performed at the level of mechanical systems to determine energy consumption for heating, cooling and the other uses. The heating and cooling consumptions are calculated based on the space loads obtained in the previous steps and the characteristics of the mechanical (heating and cooling) systems. In some calculation methods, a distinction is made between the plant that generates the energy and the secondary system that distributes it into all the building zones. In this case the analysis is split into two sub-steps providing secondary systems' and then plants' performances. The energy consumption is provided separately for each energy carrier that aliments the mechanical systems (such as gas, oil and electricity). Further steps provide the calculation of energy cost, primary energy use and emissions.

In the calculation flow each step depends on the previous ones. Therefore, space loads' analysis can be performed alone; in turn, mechanical systems' analysis cannot be performed without space loads' analysis, and so on for the next steps.

The range of performance variables included in the outputs' set may differ from one energy calculation method to another; so that the number of calculation steps required to obtain the outputs changes accordingly (Figure 3.4). In turn, the modelling inputs needed for the calculation respond to the calculation steps involved in the process. For the first step of space loads' analysis, the building description is required, and then, if further analyses are conducted, the description of mechanical systems is also required, and so on. In many traditional calculation methods, these steps follow a lineal sequence and are completely separated. This is a simplification of reality that is used in traditional calculation methods. The methods implemented in tools such as BLAST and DOE-2 (Trčka, 2010, pp. 93-99) are based on this kind of simplification. Instead, more complex simulation techniques tend to reproduce more accurately physical phenomena, in which space loads and mechanical system loads are interdependent. That means that the analysis of the mechanical system feeds back space loads analysis (as shown for the method

C in Figure 3.4). These techniques are implemented in tools such as ESP-r, EnergyPlus, IDA ICE and TRNSYS (ib.). With the most accurate simulation technique (typically, numerical techniques), the solutions of space loads and system loads are fully simultaneous (Clarke, 2001, pp. 13-14).

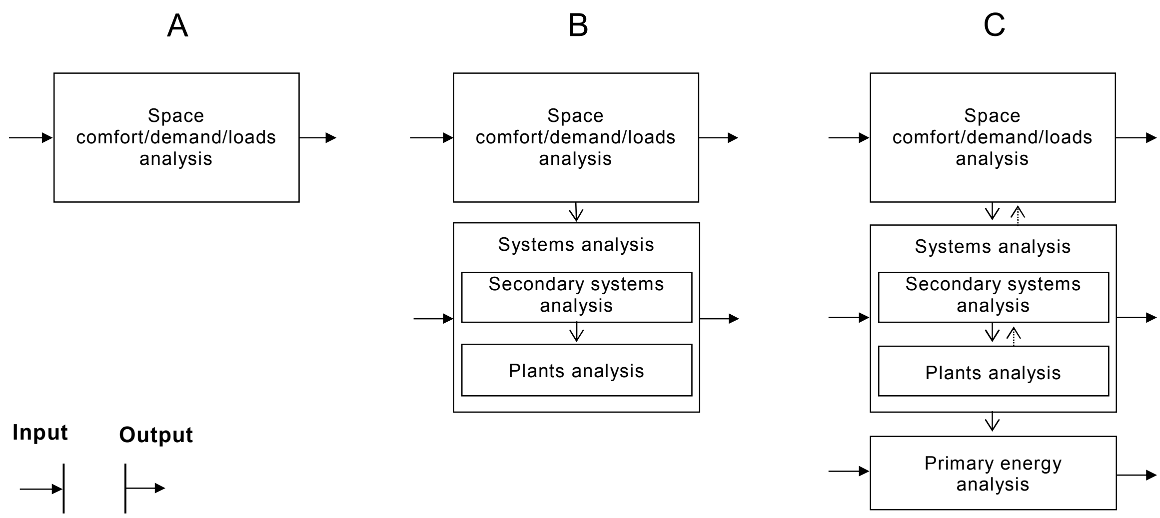

Figure 3.4. Schematic calculation flow charts of three different types of calculation methods, A, B and C. The calculation steps that are included, starting from space loads analysis, varies incrementally from A to C.

3.2.2 Implications in building design

As we have observed, in a project, several ways to approach a design problem exist. After an approach is taken it influences the progress of the design process, that is to say, the evolution of the design solution, and then, the final design product. In this section we show how calculation methods may be more or less suitable for different ways of facing a design problem. In particular the calculation flow chart of a calculation method may be more or less adequate for the approach taken to achieve energy performance goals. To clarify, let us consider, for example, two typically opposed ways of achieving energy performance goals.

The first one consists of focusing on the passive design of the building and, if required, integrating it with mechanical systems[7]. That entails an incremental design process which requires a sequence of performance analyses: initially, space loads are analysed for the passive design, and later, mechanical system will be analysed if the supplement of mechanical systems would be

[7] The first strategy essentially refers to the concept of *“Trias Energetica”* opposed to the second strategy.

considered necessary. The second design approach consists of considering mechanical systems simultaneously with the passive design of the building from the beginning of the process. Then, in the first case, a calculation method limited to space loads analysis would be sufficient for the initial evaluation of passive design. Instead, in the second case, it would be insufficient to evaluate mechanical systems from the beginning of the design process. In fact, space loads analysis provided by the tool would be necessary but not sufficient: an additional calculation step would be required for mechanical systems analysis.

This example helps us to show that, according to the approach of designers for generating the design solution, the information that a calculation method can provide may turn out to be insufficient, sufficient, or it may be even more than required.

3.3 VARIABLES INFLUENCING ENERGY PERFORMANCES

In the precedent sections, we have made a distinction between the energy performances, and the variables influencing them, which may be expressed respectively in terms of modelling outputs and modelling inputs. Then we have considered the flow chart of energy calculation methods, which describes the calculation process from input to the output. In Section 3.3.1 we are going to focus on the variables influencing energy performances. In particular, we will identify the main variables required as inputs according to the flow chart of a calculation method. In Section 3.3.2, we will make some considerations concerning energy analysis in building design, discussing how the variables of energy performance may be distinguished in relation to design decisions.

3.3.1 State of knowledge

The variables influencing energy performances are well known in literature and may be classified under different categories[8]. Based on the Annex 53 of the International Energy Agency (IEA-ECBCS, 2012), we classify the variables influencing the energy performance in these categories:

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[8] Several classifications exist: examples are provided by ASHRAE (2005, p. 32.2) and ISO13790:2008 (p. VII). They fundamentally agree on the essential variables that affect building energy performance which are well known in building physics. In Annex 53 (IEA-ECBCS, 2012), the following categories are identified: *"Climate", "Envelope", "Systems"*, and other three categories concerning use related factors: *"Operation"*, *"Indoor environment quality"* and *"User behaviour"*.

- Outdoor environment – concerning outdoor climate conditions and specific elements of the surrounding that affects the building, such as, other buildings and vegetation that shade or reflect solar radiation.
- Building – concerning the morphology of the building and of its internal spaces, along with the characteristics of the envelope, the partitions and other elements inside the building, such as internal masses.
- Mechanical systems – concerning the mechanical systems that transform, transport and deliver energy to keep the conditions of comfort that are required for the occupants inside the building.[9]

We also report three other categories regarding the user interaction with the building and mechanical systems:

- Operation – concerning control settings for the operation of the building and mechanical systems, such as the thermostat settings and the control of openings and blinds.
- Indoor environment quality – concerning the levels of comfort to be ensured inside the building for the occupants.
- User behaviour – concerning, first, the interference of user behaviour with building operation (for instance, when users open and close windows), and second, the natural effect of occupants, that generate heat and humidity by their activities.

Depending on the specific performance analysis which has to be conducted, the use of an energy calculation method requires a given sub-set of information from the above categories. Let us consider the calculation steps identified in a generic calculation flow chart (Section 3.2). For space demand analysis the modelling inputs required include the description of the building, integrated by the description of the outdoor environment and use related variables (namely indoor environment quality, user behaviour, and operation of the building). For further analysis of the mechanical systems, the former description must be complemented by the description of the mechanical systems and their operation.

[9] In the list presented in the text, we have adapted some categories reported in Annex 53. We replace *“Climate”* with Outdoor environment, which has a more comprehensive meaning. In fact, this term is more appropriate to include, together with the climate conditions, the elements of building surroundings that have an impact on the building behaviour. *“Envelope”* has been replaced by Building, whose broader meaning is more appropriate to include, together with the envelope, other parts of construction such as internal masses and internal spaces morphology.

The completeness of the representation of the object to be analysed is a necessary condition to determine its performances with a given calculation method (Suter, 2000). That is to say, the set of inputs required by the calculation method must be complete in order to perform the analysis. For instance, if the description of the thermal characteristics of the building envelope is not exhaustive, it is not possible to calculate space heating demand.

Provided that any calculation method requires complete information to perform an energy analysis, the same information can be described with different sets of inputs that are specific for each calculation method. For example, we can compare the different calculation methods employed in three energy modelling tools: Ecotect (Ecotect, n.d.), Archisun (Serra, 2000) and EnergyPlus (US Department of Energy, 2012). In each one, the thermal characterization of a wall is expressed in a different way. The admittance method, at the core of Ecotect, requires admittance and time-lag in order to characterize a wall. In Archisun, the wall is characterized by U-values, weight and insulation position. In EnergyPlus instead, conductivity, thickness and heat capacity of each layer of the wall are necessary. The three tools may be used to represent exactly the same wall, but the set of inputs required correspond to a different format according to the calculation method implemented in each tool. So it is evident that the data necessary to complete the model depends on the calculation method being used.

In general, if we exclude steady state calculation methods and consider dynamic (or semi-dynamic) calculation methods used in automated implementations, they usually require an appreciable number of input data. The size of the input data set is extremely variable depending on the calculation method that is considered. The suitable resolution for the input data set of the calculation method essentially depends on the scope of the analysis. For instance, if a small municipality wants to identify the more effective renovation measures to be incentivized, a sub-hourly multi-zones simulation is unaffordable to model all buildings in the municipality. In fact, it would require a massive amount of inputs. In contrast, if a laboratory wants to investigate the impact of a new material in a multi-layer construction component on the thermal consumption of a building, a quasi-steady-state method based on U-values is unsuitable. In fact, such a simple method would not allow defining individual layers, as it is necessary to reproduce the dynamic behaviour of a multi-layer construction.

3.3.2 Implications in building design

We have treated the inputs necessary for the creation of an energy model. Hereafter we make several considerations on the edition of the model and in particular the definition of the inputs within the context of the design process.

The creation of the model and the definition of its input have to be intended as a task that is integrated into the design process.

During the design process, part of the work of designers consists of defining (or re-defining) the constraints of the design problem and, in function of these constraints, elaborating (or re-elaborating) possible design solutions. That means defining and elaborating much information. In the process, models play a role to give a support for such information. In design the work of energy modelling involves getting separated pieces of data (such as, floor areas indicated by the urban regulation, use and functions demanded by the client for different building spaces, and so on) and converting them into a coherent set of inputs. The transformation of project information into modelling inputs must conform to the format established by the calculation method being used.

Elaborating the data needed to create the model requires two things: the capacities (knowledge and skills) of the energy assessor and a tool with appropriate modelling inputs. On the one hand, the knowledge and skills of the energy assessor to cope with modelling process are essential. For instance, the practitioner must know the meaning of the inputs required to build the model. Moreover the energy assessor must be able to make reasonable assumption when some data are missing. These capacities are not possessed by default. On the other hand, a tool with appropriate modelling inputs for the specific design situation is needed. For instance, the tool inputs should suit the level of resolution required for the analysis. For that, the identification of a proper design tool is a core issue.

Moreover, the design team is expected to translate information among various domains of knowledge along with building energy. The coherence of the energy model with other representations of the design scenario requires a coherent definition of model inputs. Again, on the one hand this depends on the design team, which must combine multiple competences and coordinate the energy model with the other representations of the design scenario. On the other hand, the consistency of various domains may be facilitated by tool features: for example, some calculation methods integrate multiple analyses[10]. We will deepen this discussion later in Chapter 4.

To understand what creating an energy model means and defining its inputs within a project, it is necessary to take into account which variables are under the control of the design team and which ones are not.

In design, we can observe a conceptual distinction between what is designed and what is not. Several variables influence building energy use, but the

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[10] Various studies deal with modelling tools and information exchange through different domains of knowledge (Augenbroe, 2004, pp. 12-16; Citherlet, 2001, pp. 13-22; Eastman, 1999; p. 6).

designers can design just the building and mechanical systems, while they exert a little influence on the variables concerning the outdoor environment and building use, which are mostly not “designed”, but simply given[11] (Figure 3.5). This is reflected in the use of energy calculation, in particular, in the definition of the inputs. Thus, modelling inputs may be distinguished in relation to the design decisions. In fact, they correspond either to features of the design solution on which the designer takes decisions - expresses intentions and proposals - or to rigid external constraints that are given to the designer and are not depending on him or her. For example, the type of envelope and its thermal properties are kinds of modelling inputs that express design intentions. In contrast, climate data are modelling inputs that reproduce given constraints. One of the largest sources of uncertainty in calculated performances comes from given constraints[12]. These parameters that are independent to the designer control always have an aleatory component, even after the design completion when the building is in use. A building in service is subject to the evolution of weather, and to the user behaviour, which never reproduce exactly the same patterns.

Given by project constraints

C Outdoor environment
U User behaviour
I Indoor environment quality

O Operation
B Building
S Mechanical systems

Design variables

Figure 3.5. The variables influencing energy performance may be imposed by the context or they may be design variables that the design team can manipulate. This distinction reflects on the modelling inputs.

The creation of an energy model within a design process involves a challenge for design teams deriving from the need for specifying all inputs demanded by the calculation method.

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[11] As observed by Lawson (2006, pp. 97-99), the existence of *“external constraint”* is characteristic of design problems. La Cecla (2008) observes the daily use of existing buildings; in his examples, it is evident that an external variable like the user behaviour is completely out of the designer control.

[12] One of the largest sources of uncertainty in the output of energy modelling comes from climate data (de Wit, 2004, p. 25).

As we observed, quantifying building performances with an energy calculation method requires completely specifying all its inputs. This means that, when practitioners introduce energy modelling in the process, they are forced by the tool to provide all the information required for the analysis. So, the design team should envision a design scenario that encompasses an exhaustive description for the modelling tool. But very often the design scenario is not yet developed enough to provide all inputs. This situation is critical for an energy assessor which has to be able to make reliable assumption for the missing data. In any case, to perform the analysis the practitioners must provide all modelling inputs and match the level of abstraction required by the specific tool[13]. In turn, the selected tool should suit design needs: in other words, the information required by the tool should be as far as possible commensurate with the information in the hands of designers. In sum, in the dialogue of the design team with the calculation method, the characteristics of a specific tool influence the design process; however, the need to get along with the information available is determinant for the selection of the tool. In principle, the project needs are prevalent on the tool: energy modelling must support the design process and not vice versa. For this reason the choice of the tool is a primary step.

An additional challenge for the use of energy modelling tools in design regards the dynamic nature of each design process. As we remarked, the design solution is more or less vague, it is not unique and it is changing, and the information density evolves throughout a design process. This complicates the modelling process and in particular the tasks of creating and editing the model. The process of specifying and modifying the inputs is connected with and influenced by the continuous changes in the modelled object.

3.4 WHERE ARE THE BOUNDARIES OF THE ANALYSIS

In the precedent sections, the energy calculation flow chart and the inputs required for modelling have been described, but the boundaries of the phenomena analysed with the energy calculation methods have not been described yet. In Section 3.4.1, we are going to focus on them. Then, in Section 3.4.2, we will consider some implications in design, discussing the use of calculation methods when coping with multiple-faceted design problems.

[13] The extension of the description required depends of the analysis conducted and hence the calculation method: an exhaustive description of the design solution may require only the building features, or both, the building and its mechanical systems, depending on the performance indicators analysed and the calculation method used to determine this indicator.

3.4.1 State of knowledge

When the energy phenomena affecting a building are examined, some boundaries need to be established to circumscribe the analysis. This requires discriminating what is taken into account and what is neglected in the analysis.

According to the performance variable, or set of performance variables, that have to be quantified, it is necessary to analyse a particular system identified by specific boundaries. The Federation of European Heating, Ventilation and Air-conditioning Associations (REHVA) provides a set of system boundaries and equation for the calculation of different energy performance variables (Kurnitski, 2013).

A calculation method is developed in order to quantify specific performance variables, so that in each calculation method specific boundaries are defined. In this regard, existing calculation methods may differ substantially.

First of all, the extension of the calculation flow chart varies between calculation methods. It depends on how many steps of performances analysis are enabled by the calculation method: only space loads, or space loads plus mechanical system loads, or even more calculation steps. In that way the boundaries of the analysis change between different calculation methods.

Besides, energy performance embraces different domains, such as thermodynamics, fluid-dynamics and lighting. The boundaries of the analysis vary between calculation methods, as each calculation method encompasses a different combination of domains. Furthermore, the analysis of an individual domain, for instance, thermodynamics, may cover the assessments of indoor comfort and of energy use. Depending on the kind of method, it is capable to support only one or both assessments.

Actually, some calculation methods overcome the limits of building physics. In fact, the domains of analysis may be extended ad libitum, to life-cycle analysis, economic analysis (ASHRAE, 2005, p. 32.2)[14], occupant behaviour analysis (Fabi, 2011; Mahdavi, 2011), and so on. The term “energy calculation method” would be insufficient to refer to all performance aspects covered by the calculation.

Taking into account all the different possibilities just mentioned, the panorama turns out to be quite varied. In fact, existing energy calculation methods embrace many diverse combinations of performance aspects. The set of domains covered by an energy calculation method is determinant for its

[14] For example, the flow chart of energy calculation method proposed by ASHRAE (2005, p. 32.2) includes economic analysis.

suitability for a specific scope. For instance, if one investigates the thermal performance of a building with innovative natural ventilation strategies, a calculation method might be necessary that tightly integrates thermal and fluid-dynamic domains.

Energy calculation necessarily involves simplifications. The definition of the boundaries of analysis involves a simplification of reality. In fact, the real behaviours a building and its mechanical systems are strongly interrelated and the phenomena investigated by individual domains of building physics (and beyond building physics) are strongly coupled[15] (Citherlet, 2001, p. 21; Clarke, 2001, pp. 4-7; ASHRAE, p. 32.2; Hensen, 2004, p. 1). Therefore, when representing the reality, it is difficult to insulate individual phenomena. Their boundaries in fact can hardly be marked off in absolute terms without neglecting connections between interrelated physical processes. However, any calculation method entails fixing some boundaries. The assumption of boundaries is essentially a matter of choice when an energy calculation method is developed, and also when it is selected for a practical application.

3.4.2 Implications in building design

As we observed, building design requires a holistic approach to cope simultaneously with multiple aspects of the design problem, such as energy, cost and form, which demand a coherent solution. Some calculation methods support an integrated analysis of those phenomena that are more tightly interrelated, for instance integrating thermal and fluid-dynamic domains. However, a calculation method never covers all design aspects. That is because any calculation method restricts the analysis within predefined boundaries that never encompass all the design aspects that arises in a project. As a consequence, whatever calculation method is used, the development of an integrated design is up to design teams' members, which must overcome the boundaries of energy analysis. In fact, they must be able to establish relations between all facets of the design problem in order to develop a satisfactory design.

In order to cope with the huge panorama of existing calculation methods, we limit the field of research covered in the thesis as follows. The focus is on the energy employed for the use of the building, while the other phases from material extraction to building disposal are not considered. The performances considered are limited to energy and indoor environment assessment, with occasional references to other quantitative or qualitative aspects (for instance,

[15] For instance, Mahdavi (2011, pp. 80-81) stresses the deep interrelation between occupants behaviour – out of domains of buildings physics – and the physical phenomena in buildings, envisioning the future development of coupled models.

cost or aesthetic). Within energy and indoor environment performances, special attention is paid to the thermal domain, because it is one of the more complex ones in terms of energy modelling and also one of the most relevant ones in terms of energy consumption. Other domains (such as, lighting and ventilation) are secondary in this research: they are considered in relation with thermal analysis, in order to appreciate the interrelation among multiple domains.

3.5 COMMON CHARACTERISTICS OF BUILDING ENERGY CALCULATION METHODS

A broad picture of the wide variety of existing energy calculation methods has been provided. In the next Section 3.5.1, we are going to highlight some typical characteristics of energy calculation methods, the complexity and the uncertainty affecting energy analysis. In Section 3.5.2, we will discuss how these characteristics hinder the applicability of energy calculation methods in building design.

3.5.1 State of knowledge

The phenomena that are related to energy use and indoor environmental quality of buildings involve several processes interacting in a non-trivial manner – including, air movement, radiation exchange, daylight distribution and so on. Each process depends on many variables, giving rise to a large number of combinations. In addition, the variables evolve dynamically through time. *"In short, energy calculation is complex"* (Clarke, 2001, p. IX).

The distinction that we stressed, between the phenomena to be described and their model, is useful to better understand where the origin of this complexity lies. Actually, such a complexity is in the first instance inherent to the analysed phenomena. As a consequence, energy calculation methods tend to be relatively complex in order to represent real phenomena with enough accuracy. However, the representation of these phenomena can be more or less complex: each calculation method is defined deliberately assuming a level of abstraction to represent reality.

The complexity of energy calculation and underlying phenomena has a close relation with the uncertainty of the analysis (Clarke, 2001, p. 18). It is difficult to know precise values for the large number of variables that influence energy performance, and then calculation inputs are necessarily uncertain. The uncertainty of numerous inputs propagates through the calculation flow, resulting in outputs' uncertainties, which may be much larger than inputs' uncertainty (ISO 13790:2008, p. 130)[16]. Most existing calculation tools do not provide any assessment of uncertainty risk (de Wit, 2004, p. 25)[17]. On the one hand, a complex modelling approach, which carefully reproduces physical phenomena with a robust calculation method, would be more accurate and reduce the uncertainty of results. On the other hand, the uncertainty of results is strongly conditioned by the inputs' uncertainty[18] and then it can be even more dramatic for large and complex inputs' combinations (Trčka, 2010, pp. 93-99).

3.5.2 Implications in building design

Due to the interaction of multiple design aspects and the dynamic nature of the design process, complexity and uncertainty are also intrinsic design characteristics. Thus in design, the complexity and uncertainty of calculation are dramatically amplified. For this reason, the use of energy calculation in design is not trivial and its limited application is not surprising.

Dealing with the complexity and uncertainty of energy calculation makes the task associated to the energy modelling very demanding. This is especially problematic in building design. Energy modelling requires both specialized and interdisciplinary background of theoretical and practical knowledge. It requires a large amount of time (for beginners, to learn theoretical principles and how to use the tools, but also for expert energy assessors, to define the inputs and analyse the outputs). Managing the complexity of energy modelling also requires some rigour. In order to exploit energy calculation the energy assessor (or more generally, the design team) has to cope with this arduous task. This is problematic, because in current design practice the resources available may be quite limited, varying according to the project. Currently, this problem is only partially mitigated by informatics' technology which supports the application of many energy calculation methods[19] [20]. The fact that

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[16] According to the example provided by ISO13790:2008, studies made to test existing calculation methods have shown that an uncertainty of 5 % on inputs (namely, the heat transfer by transmission) produced an uncertainty of 20 % to 35 % in the calculation result (the energy need for heating).

[17] Most investigation efforts concerning uncertainty in building energy modelling are quite recent (Augenbroe, 2011, p. 24).

[18] Typically, wind data and most of the user related variables are highly uncertain modelling inputs (Clarke, 2001, p. 299).

[19] The role of informatics' technology to help practitioners to manage the complexity of energy modelling is discussed elsewhere (Augenbroe, 2004, pp. 12-16, 8-9; Clarke, 2001, pp. 4-5, 18, 281, 283; McElroy, 2009, pp. 293-305).

modelling tends to be demanding, especially when sophisticated simulation tools are adopted, strongly limits the use of energy calculation methods in design. With this regard the selection of a suitable energy calculation method is determinant.

3.6 CURRENT APPLICATION OF ENERGY CALCULATION IN BUILDING DESIGN

The analysis conducted through the precedent sections provides a theoretical view of existing energy calculation methods and their usage in building design. In this section we instead intend to present a more pragmatic view observing the application of energy calculation in building design in current design practice.

3.6.1 Why and how

First of all, we intend to clarify why energy calculation is (or should be) used in the design process. Energy modelling provides the means to predict future building behaviour (Hensen, 2011, p. 6), that is to say, it allows to know in advance the performance that may be expected from a design solution. Therefore, energy modelling is intended as a means to inform designers when they have to take design decisions that influence the energy performance.

Design teams may take some decisions based on their own experience and knowledge. Possessing theoretical principles is essential to identify passive design strategies and conceive a reasonable design solution. For example, having a clear vision of the physical phenomena that govern the space heat balance of building is fundamental to identify proper strategies for each season. But experience and knowledge are often not enough. In each project, there are some specific questions that cannot be answered only with evidence from precedent cases or with learnedness of basic principles. For instance, it is known that enlarging south facing windows direct heat gains increase, and ventilation and transmission heat transfers also increase. However, for a specific building, under particular conditions of climate and operation, the size of each heat gain and loss is not obvious. And it is even less evident which

[20] Beyond the concept of the energy simulation software considered in insulation, recent research is currently in progress on integrated and shared ITC environments provided by platforms and repositories. The research projects IntUBE and REPENER of the ARC research group addressed this line of investigation exploiting the web to provide services which allow sharing information and knowledge among different stakeholders of the building sector.

proportion of openings in the facade provides lower space demand for heating and cooling[21]. In such cases, energy calculation may expand the capacity of designers to provide answers to design questions, that is, to enhance their knowledge on a specific design problem.

Calculations may expand background knowledge already possessed by the energy assessor. On the contrary, calculations can by no means substitute this background (Augenbroe, 2004, p. 13), which provides practitioners with the capacity to master the tool. Besides, energy calculation may be used to strengthen the confidence of the client and other stakeholders in the design proposals (Waltz, 2000, pp. 4-5).

Having considered why, we have to also clarify how energy calculation may be used in the design process. In the design of a building, the energy assessor may choose a calculation method that already exists for the project. Upon it, he or she generates the model of a specific design scenario. To do this, he or she only needs to specify the inputs' values, while the calculation method is given[22]. This requires a calculation method that is transparent for the user, so that the user can go through the different steps of the calculation process. In this way, a learned user should be able to interpret the relations between the modelling inputs and outputs.

We have clarified why and how energy calculation may be used in the design process. But, it seems that the promising potentials of energy modelling are moderately exploited in reality.

> *"Clearly, the construction industry has some way to go if it wishes to incorporate a rigorous life cycle analysis into its future design practice"* (Clarke, 2001, p. IX)

3.6.2 Application in the ordinary practice of building design

Concerning the exploitation of energy calculation in the design practice, high expectations are expressed by several experts in this field (as Waltz, 2000, p. 162). Many authors agree that preventing the consequence of design

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[21] A similar example is illustrated in Case A (Chapter 5).

[22] The case of an energy assessor that creates and manipulates all the components of the energy model, including the underling calculation method, is rare. That would require competences which are not available in existing professional markets for ordinary design practice. That may occur in exceptional situations which are not the main object of this research. For instance, the energy consulting firm of Waltz (2000, pp. 22-25) created a *"simple spreadsheet simulation tool"* specifically created for the energy assessment of large college campus. The same tool was used later for another project of a small community hospital. Both projects represent typologies that are not frequently demanded on the market.

decisions by predicting the future behaviour of buildings during the design process is far more effective and economical than fixing the existing building (Hensen, 2011, p. 6). According to Clarke (2001, p. IX), *"cheaper"*, *"better"* and *"faster"* building design may be produced using energy simulation. Based on the opinion of experts, we could expect a reduction of environmental impacts and in particular energy consumption and emissions by exploiting energy calculation in the design practice.

Nevertheless, at present, energy calculation has a very limited application in ordinary building design practice (ib.; McElroy, 2009, p. 290) especially in early design phases (Clarke, 2001, p. IX; Hensen, 2011, p. 6). The use of energy modelling tools is mostly limited to exceptional situations: for instance, studies of intervention on heritage buildings that require a strict control over indoor climate (Corgnati, 2010), or the design of new emblematic building of big companies and institutions (Kolarevic, 2003, pp. 25-26). These sporadic cases have a very limited influence on the total environmental impact of the building sector. In contrast, the product of ordinary design practice has a huge impact: common buildings, which represent most of the building stock, are very relevant for the environmental impact of the whole building sector. The main potential reduction of energy consumption and emissions lies in this kind of buildings. Thus, taking advantage of energy modelling in the design of such buildings is a promising opportunity, which at present is largely wasted.

The openness and attitude to introduce simulation is probably quite variable among different segments of the designers' community, as suggested by Hensen (2011, p. 9). McElroy (2009) has reported direct experiences with practitioners: she collected the results of a public initiative in the United Kingdom aimed at introducing the use of simulation among professionals. The initiative has involved several professionals over many years. She was able to observe that in ordinary building design practice several barriers persist in the deployment of energy simulation.

Nowadays, an impulse to the integration of performance evaluation in design comes from the regulation, which imposes the verification of increasingly strict requirements for building energy performance[23]. In many countries, regulation in force imposes the application of energy calculation methods, although the verification is only demanded for the final delivery of the project. Therefore, the regulatory calculation methods and tools have not been conceived (in the first instance) as a support to the design process and the decision making.

[23] The EPBD, the Europe the Directive on Energy Performance of Buildings (European Parliament & European Council, 2002 and 2010), gave impulse to technical regulation, which imposes the verification of minimum performance requirements and the energy certification. After the European impulse, member states have been updating national regulation. In Spain for instance, new technical regulation has been developed, the CTE for buildings (Ministerio de la Vivienda, 2006) and the RITE for mechanical systems (Ministerio de la Presidencia, 2007).

Usually, they are not exploited throughout the process, but at the very end, having limited impact on design decisions (Hensen, 2001, p. 6).

Historically, the development of energy calculation tools evolved from simple calculation methods to advanced simulation techniques (Clarke, 2001, pp. 3-4), which carefully reproduce real phenomena, based on first-principles of physics. However, the progress of research toward more and more sophisticated energy calculation methods has had limited repercussions on design practice. Like other researchers in building simulation, Mahdavi (1999, p. 427), affirms *"the necessity for a physically consistent (first-principles-based) performance modelling approach throughout the design process"*. Some of these authors are sceptical about the use of simplified calculation tools in building design (id. p. 428). Other experts, and especially experienced practitioners, are convinced that in professional activity simplified calculation methods are also suitable in many circumstances (Serra, 2000; Waltz, 2000). At least for some projects they prefer simple tools (ib.). Some authors consider them more effective especially at early design stages (Baker, 1999, p. 6). Cross (2006) has observed opposed opinions throughout the history of design on the scientific approach to the design activity. In the use of energy calculation in building design, this contraposition is reproduced between simplified calculation methods, which admit several approximations – *"heresy"* in a science based analysis (Clarke, 2001, p. 3), and simulation, which carefully reproduce analysed phenomena with rigorous scientific application of first principles of building physics.

It is fundamental for this discussion to define the final function of energy calculation methods in design. The reason for realizing energy calculations in a project is to support design; it is not the analysis of physical phenomena in itself. Certainly examining the energy phenomena in a building enables a better understanding of the design problem. But, the final goal of design is to find an acceptable solution, not to analyse the design problem (Cross, 2006).

To address the discussion it is also necessary to define the temporal horizon one is looking at. We outline two temporal horizons: for the present (or near future), a widespread and immediate application of energy calculation in ordinary design practice is needed; for the future, it is reasonable to envision an "ideal" framework for the application of energy calculation in building design. To reach first horizon, a compromise that sacrifices in part the rigor of analysis for handier approximated calculation seems more pragmatic. At present in fact, most practitioners are not prepared to master complex simulation techniques now available. Likewise, the possibility to use complex analysis methods is severely limited by the budget and time of most projects. These circumstances explain the openness of some experts to the use of simplified calculation methods. To reach second horizon, the application of more and more rigorous calculation approaches over time would be desirable, to improve the quality of assessment and finally the buildings' future performance[24]. In this research, we primarily deal with the first horizon, because we focus on the limits and potential for a widespread and immediate application of energy calculation in ordinary design practice.

Another controversial matter of debate in literature is the choice of one single tool or a progression of tools throughout the stages of the design process. Some experts maintain that one single calculation tool must be used throughout the entire design process, which should be a detailed simulation tool (Mahdavi, 1999; Clarke, 2001, pp. 5-6). Other experts instead maintain that each design stage is different and may require different calculation tools and methods (McElroy, 2009, p. 303; Heiselberg, 2009, pp. 85-87; INTEND, 2009, p. 34). Both approaches have advantages and inconveniences. Clarke (2001, pp. 5-6) observes that the use of a single energy model throughout the design process prevents *"theoretical discontinuity and pernicious assumption"* which occurs when *"a progression of tools – from simplified to detailed –"* is used. Moreover, using a single tool may prevent re-modelling a design scenario from scratch, as it might be required when using a progression of tools. In turn, the study of McElroy on the experience of practitioners reveals that, *"even the most advanced and fully integrated simulation applications do not fully support users* [...] *at all stages* [...] *and throughout the* [entire] *design process"* (McElroy, 2009, p. 303). In fact, different design stages usually do not have the same requirements. When a single method is used throughout the whole design process, it can be suitable for one design stage, while inadequate for another stage. The method might turn out to be inadequate because it is either insufficient to answer new design questions, or redundant and overwhelming for the limited resources of practitioners.

We have conducted a survey as a preliminary analysis for the Case A. The survey provides some information on the dilemma between using a single tool for all design phases or a progression of tools. Different design firms (in Spain and Italy) were asked about the use of energy calculation at different phases of the design process in their offices. In the prevalent situation the same tool is not used for all design phases but it is restricted to one single stage. The result of the survey may not be generalized, as only 5 design firms have taken part in it. The survey is reported in Annex 1.

[24] According to some researchers, the developments of informatics' technology are likely to play a central role in the future application of energy simulation in building design and operation. In particular, developments are expected in computer-supported design environments (Clarke, 2001, pp. 4-5, 308-323) and in the expanding potentials of Internet (Augenbroe, 2004, pp. 4-5, 8, 11-12). Developments of informatics' technology are not examined in this thesis.

3.6.3 Current obstacles

The limited deployment of energy modelling in routine of ordinary buildings' design relates to several obstacles that have been identified by precedent authors such as McElroy (2009, pp. 286-293)[25]:

- It is difficult turning energy modelling outputs into useful information for the decision making (getting feedback from predicted performance to manipulate design variables is not trivial; it requires practitioner capacities, for instance interpreting results and postulating new design options).

- There is a risk of misunderstanding and misusing the calculation methods.

- The integration of an expanding range of new aspects, such as energy and environmental issues, makes design more and more complex for practitioners.

- Many tools and underling calculation methods are highly complex for the background knowledge possessed by practitioners.

- Different authors, including Augenbroe (2011, pp. 16-17), denounce the lack of consolidated procedures to assure the quality of the assessment, such as: the establishment of acknowledged performance indicators in simulation tools, procedures to control model changes, and to evaluate alternative designs.

- For many calculation methods, there is a lack of meaningful model validation guarantees to assure reliable results and inspire confidence in the user (Augenbroe, 2004, p. 10).

- There is a considerable risk of error associated with the high uncertainty in energy analysis.

- It is impossible to represent and asses the uncertainty of the building behaviour with most modelling tools (in fact, most of them are conceived for a deterministic representation of phenomena) (ib.).

- The pressure of time limitations in design practice and the need for rapid evaluation of alternative designs hinder the integration of performance assessment.

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[25] McElroy detected existing barriers in the use of simulation observing the practice of different professionals over several years in the United Kingdom. In this section, the obstacles identified by McElroy are mentioned and integrated by other references cited in the text.

- Energy modelling is made considerably more complicated by the need for adapting the analysis to changing levels of complexity throughout the project.

We have mentioned above the obstacles recognized by precedent authors. The critical reflection on design studies that we have conducted allows us to identify additional obstacles in the use of energy modelling in design:

- With most modelling tools it is difficult to represent and asses a design solution which is ambiguous and changing throughout the design process. Most tools are essentially prepared for a fixed representation of a determined object, and a design solution is not like this.

- There is a gap between the nature of forward modelling oriented to problem analysis, and the nature of design practice oriented to the solution production. The crude function of forward modelling is to analyse energy performance, whereas the scope of designing is to determine the design variables that configure a satisfactory design solution.[26]

- The applicability of structured procedures for the use of energy modelling tools in the design process - such as, strictly prescribed performance assessment methods, procedures to control model changes, and to evaluate alternative designs - is controversial.

3.7 CONCLUSIONS

In Chapter 2, we observed how the design process of a building is complicated, and then, how the applicability of design methodologies based on a preconceived structure of the design process is far from being obvious. In fact in the universe of building projects, the variety of possible design processes is immense and essentially undetermined. In Chapter 3, we observed the complexity inherent in energy modelling and how wide and variegate the panorama of the energy calculation methods implemented by existing tools is (Figure 3.6).

[26] Under the perspective of developers and experts in energy modelling, bridging this gap requires a deeper understanding of the scope design activity, which design studies have tried to clarify. Under the practitioners' perspective, this requires a deeper understanding of performance quantification methods and how performance analyses feed-back design problem and solution definition.

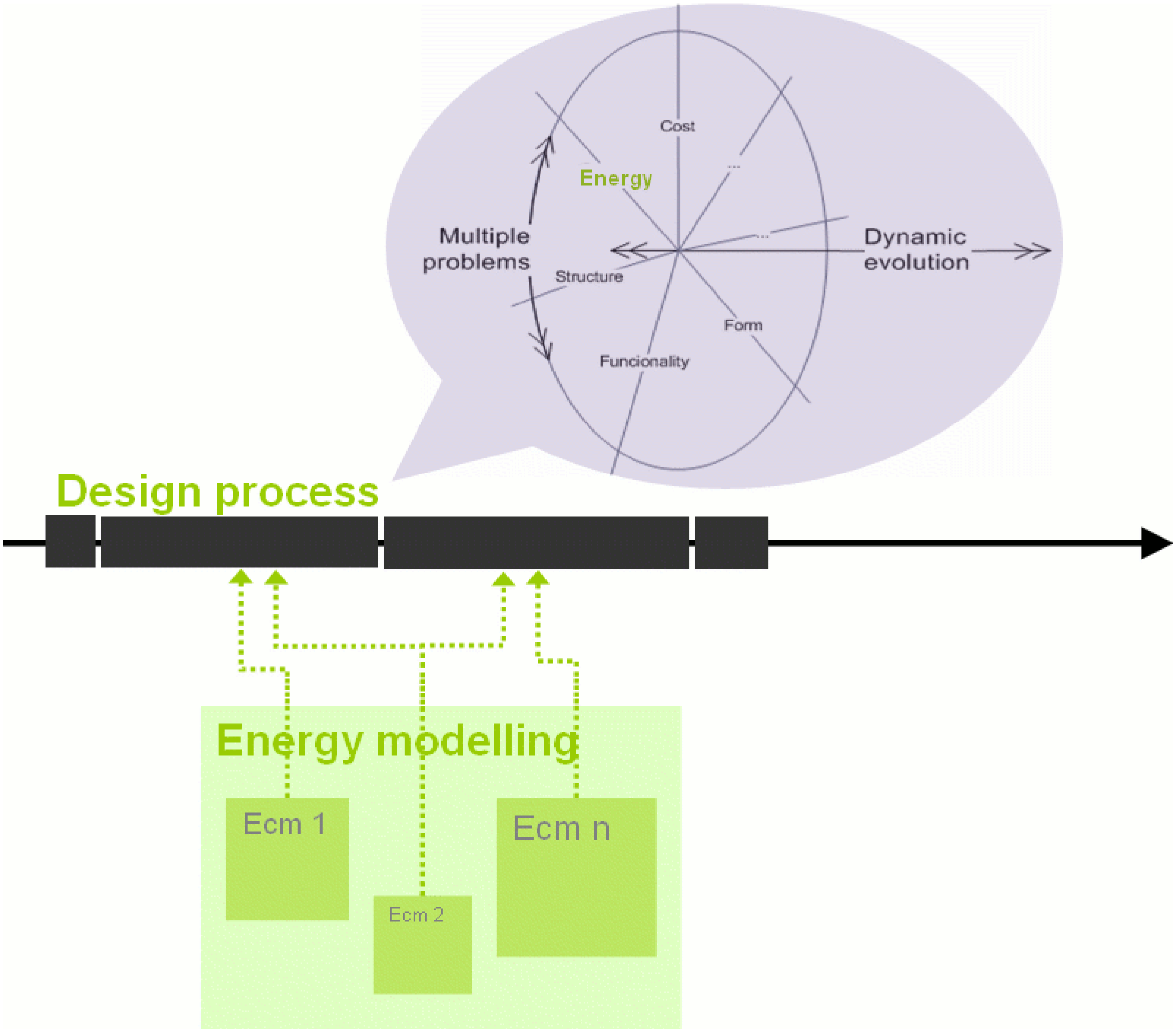

Figure 3.6. Integrating a calculation tool in a project is a challenge for practitioners: tools (with their inherent complexity) must be selected from the wide panorama of existing energy calculation method in order to adapt the analysis to the complexity of the design process.

Being the panorama of both (1) possible design processes and (2) existing tools widely and strongly diversified, we make some considerations. First, the choice of a tool for each design process and stage prefigures innumerable and diverse possibilities. Thus the selection of the calculation method is not obvious for practitioners. If we consider in addition the inherent complexity of design processes combined with calculation methods complexity, it is not surprising the integration of energy modelling in design is challenging, and it turns out to be very limited in ordinary practice. These considerations support the opinion of Waltz (2000, pp. 15-26) that the tool choice is a key step to assure that energy calculation could really provide an effective aid to design.

Relating the large diversity of design processes and the broad variety of calculation methods is essential to comprehend that the identification of suitable tools is not secondary. This reveals that a large potential improvement in tool application lies in understanding appropriate matches between calculation method and specific design situation.

It is hardly possible to state a priori firm criteria which help to establish the appropriate calculation methods for any building design. As we argued, in fact, any design process entails a particular case that more often than not escapes clear categorizations. Therefore, the suitability of the calculation methods depends on the specific case. For instance, choice of a tool depends on the budget and resources available during the design process; it also depends on the methodological approach of the design team, and in particular, on the ways to formulate energy performance goals, and to achieve them. We also underlined the existence of different stages throughout the process: design stages typically differ for the competences and knowledge domains involved, the information density, the design goals and constraints, and the decisions at stake. Indeed, calculation tools have to satisfy different needs at each stage of the project.

A systematic approach for the identification of suitable energy calculation methods, based on a deeper understanding of the design process, is addressed in Chapter 4.

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Chapter 4

Suitability of calculation methods to design needs: an analysis from the design perspective

CHAPTER 4: TABLE OF CONTENTS

In the precedent chapters, we have analysed the building design process and the variety of existing energy calculation methods through a critical review of specialized literature. Then we have considered the use of existing calculation methods in current design practice. In this chapter, we analyse in detail how existing methods may suit the necessities of the practitioners involved in a design process.

The chapter is organized according to the following structure. In Section 4.1, we show the need for more research on the match of calculation methods with necessities of each project and design stage. In Section 4.2, we present a systematic analysis that we have made to identify the key factors for the choice of suitable energy calculation methods. Each factor we have examined is presented in a dedicated sub-section. In Section 4.3, we differentiate initial and final design stages in the choice of suitable energy calculation methods. In Section 4.4, we draw the chapter conclusions.

4.1 OPEN RESEARCH ISSUE: CRUCIAL MATCH OF METHOD FEATURES WITH DESIGN NEEDS

In Chapter 3, we referred to the obstacles that prevent a broader application of energy calculation tools in the ordinary activity of design teams. To overcome these difficulties, the implication of both researchers and practitioners is necessary.

Probably, time is needed in order to overcome these obstacles: both the research community and practitioners should be investing effort and be maturing during the next years. Both would better understand how energy calculation may be exploited in design. In addition, a period of practice would be necessary for practitioners to assimilate energy assessment within design routine. The necessity of a time of transition for practitioners and researchers has specific reasons that are associated with the present historical context:

1. Research on design is a relatively young discipline (Cross, 2007, pp. 120-121, 123) and more research is needed in the field of energy modelling, especially for its exploitation in design (Clarke, 2001, pp. 3-4);

2. Besides, many practitioners involved in ordinary design practice are still not familiar with sustainable design and energy modelling (Hensen, 2011, p. 9);

3. Meanwhile, substantial and rapid changes are occurring, such as the rapid degeneration of environmental, energy crisis, financial and economic crisis, global economy transformation, and finally, the rapid evolution of information technology. These transformations are likely to

affect design practice. Certainly, the integration of energy calculation in design processes also undergoes the uncertain future of design practice.

Let us focus on the role of research community. As argued, research is needed to overcome the obstacles to the use of energy calculation in ordinary design practice. In particular, research is needed to improve both the tools toward a new generation of tools (Augenbroe, 2004, p. 10) and the design process management and organization toward new models (ib.; Hensen, 2011, pp. 7-8).

Nevertheless, in the light of the tremendous environmental urgencies of the present, it is absolutely reasonable to investigate the potential offered by existing tools. Or better said, it is imperative to investigate what could already be done by effectively exploiting the huge variety of existing tools in routine design practice. This is a primary concern in our research.

In particular, **the aim of the research presented in this chapter is to help to understand more about the choice of suitable calculation methods.** More precisely, the aim of the work is:

- To study the acceptable match between the features of calculation methods and design needs in diverse design situations
- And, at the same time, to understand the extent to which this match is possible.

Waltz (2000, pp. 15-26) asserts that the choice of the energy calculation method is fundamental and he recommends avoiding default choices. In the opinion of Trčka (2010, pp. 93-99), more research is needed on the selection of appropriate modelling approaches for design[1]. We highlighted that a huge matrix of combinations exists if one combines the variety of possible design processes and the diversity of the existing calculation methods. In such a variegate context it is clear that the choice of effective energy calculation methods is nothing obvious. According to ASHRAE (2005, p. 32.3), the most important step in selecting energy analysis methods is matching method capabilities with project requirements. That means that it is fundamental to clearly understand the particular circumstances of the project and the design stage in which energy analyses are required, in order to identify which sort of calculation method is needed.

In the 1980s, Sonderegger indicated some factors to be considered for the choice energy analysis method, including accuracy, sensitivity, versatility,

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[1] The conclusion of Trčka refers in particular to existing modelling tools for Heating, Ventilation and Air Conditioning mechanical systems (HVAC).

speed and cost, reproducibility, and ease of use. The factors that he identified and described are still assumed as the main reference in recent publications of ASHRAE (2005, p. 32.3). Also the ISO 13890:2008 (pp. 127-130) reports something analogue, indicating a number of *"quality aspects"* that have to be taken in to account to apply appropriate calculation methodologies in the context of building regulations (Table 4.1). However, the quality aspects described in the ISO standard are conceived for normative calculation purpose, which is not the same as the use of calculation to support the design process, as we have already clarified.

Table 4.1. Relevant factors for the choice energy analysis method according to precedent literature.

Quality aspects - ISO 13890: 2008	**Factors -** ASHRAE/Sonderegger
Legally secure	Accuracy
Unambiguous / reproducible	Sensitivity
Enforceable	Versatility
Verifiable	Speed and cost
Consensus (national/regional)	Reproducibility
Credible and accurate	Ease of use
Distinctive	
Transparent (internal)	
Transparent (external)	
Robust	
Affordable and efficient	
Innovative, open to future developments	
Flexible	

The accuracy is always considered among the factors identified by the mentioned authors. Calculation accuracy has been a primary object of concern and debate for several authors in the field of energy performance analysis (as Clarke, 2001, p. 18; Waltz, 2000, pp. 15-26; ISO 13890:2008, p. 127). In energy assessment, concerns with accuracy are quite logical, as the object of this research field is the analysis in itself. In building design however, performance analysis is not the final goal. The scope of design is producing a design solution. For the scope of building design many other factors, which are less considered in literature, have primary importance and the priority among them is nothing obvious. For instance, versatility, ease of use, speed and cost mentioned by Sonderegger are essential for a feasible design process. The trade-off necessary to employ energy calculation methods and tools that suit these necessities is deeply related with the specificity of each design process and of each design phase. In the 1980s, when Sonderegger presented his study, little research was consolidated on the nature of the design process, as we have observed in the writings of Cross (2007, p. 123). Furthermore, from that time available calculation method evolved. Therefore, it is wise to reconsider the suitability of calculation methods for design in the light of research progress. We also notice that the choice of appropriate energy calculation methods has been investigated by experts in energy assessment, engineering and building physics. In existing design studies instead, research on this topic can rarely be found, to the best of our knowledge. A deeper investigation from the design process perspective would not simply provide a different point of view, but it appears very necessary.

Indeed, we reformulate within our study the key factors for the choice of the energy calculation methods. Our immediate scope is not instructing practitioners with practical guidelines. Before that, it is providing the necessary theoretical insight on how and how far the integration of an energy calculation method in a design process can go.

4.2 SYSTEMATIC ANALYSIS OF KEY FACTORS FOR THE SUITABILITY OF CALCULATION METHODS IN BUILDING DESIGN

The suitability of energy calculation tools depends on the specific necessities of practitioners for each project. As we discussed in Chapter 2, building design implies a dynamic process through which energy and other aspects of the design problem must be treated in order to reach a holistic solution. The dynamic and holistic nature of the design process has important implications on the suitability of calculation methods in design, and makes the choice of the methods a non-trivial matter. To understand these implications, we identify and analyse a series of key factors for the suitability of energy calculation methods (Table 4.2).

Table 4.2. Key factors for the choice of appropriate energy calculation methods

Key Factors
Level of discretization
Level of complexity of calculation algorithm
Responsiveness to design decisions
Flexibility in representing design scenarios
Flexibility in design modification
Feedback immediacy
Accuracy
Suitability for holistic design
Data coherence preservation
Transparency

The evaluation and the weight of each factor differ according to the methodological approach of the design team and the specific circumstances of each project. Hereafter, we analyse each factor that is identified in the table in a dedicated section.

4.2.1 Level of discretization

Existing calculation methods differ substantially from each other for the level of discretization in the abstraction of reality that each one enables. Phenomena can be modelled with a variable spatial discretization, describing physical reality by a more or less fine separation by parts. For example, indoor space may be represented as a single zone, or multiple zones, or smaller volume elements; the envelope can be represented by physical characteristics of the entire envelope, or by separated components, or at the level of each material assembled within a component. Phenomena can be also modelled with different time discretization, by characterizing their evolution for more or less extended time intervals. For instance, climate may be represented by seasonal, monthly, hourly or sub-hourly values. The level of discretization is mainly determined by the tool. Nevertheless, some calculation methods are more flexible, giving the energy assessor some freedom to decide on the level of discretization of a particular model. For example, using a multi zone calculation method, an energy assessor is free to decide to represent conditioned volume as multiple zones or as a single zone. The level of discretization regards both energy modelling inputs and performance outputs.

The level of abstraction and the information used in the project are very variable from one project to another; moreover, they evolve with the progression of the design process. Therefore, the level of discretization required by a calculation method should be commensurate as far as possible to the detail managed in the project at each design stage. In that way, the calculation inputs and outputs have the appropriate resolution to support design questions and decisions at stake (McElroy, 2009, pp. 110-116). For instance, if space distribution is to be decided in relation to comfort and energy performances, these have to be assessed in the different spaces of the building. In this case then, energy modelling must allow representing separate inputs for each zones and provide separate performance outputs. Instead, if the orientation of a rectangular building is to be decided, possibly a calculation method that only enables modelling a single zone is detailed enough. Throughout the design process, the management of large sets of inputs and outputs involved in the energy calculations is complex for the energy assessor, especially if he or she uses a calculation method characterized by a high discretization. Sometimes it is believed that the answers to this problem may be committed to the features of software used to implement energy calculation methods. According to Clarke (2001 pp. 18-19, 283), software should protect the user from the calculation method complexity, for example implementing default inputs' specifications (ib.; Hopfe, 2005, pp. 2-3). Nevertheless, no tool can substitute the responsibility of design teams to determine design specifications. In fact, the performance prediction really corresponds to a design scenario only if the calculation inputs match the reality prefigured by a design team[2]. To assure this correspondence, the resolution of the calculation method inputs should be commensurate as far as possible to the information available on the design proposal being developed. Many experts (such as Waltz, 2000) agree that the minimum detail necessary to answer a design question should be used in energy modelling. Unfortunately, the dynamic of the design process may entail a new unexpected design question, requiring to move to a higher or lower level of detail. If an energy calculation tool is already in use and its level of discretization is not appropriate (too low or high) to answer the question, it may be necessary to use a different calculation method and tool.

The level of discretization is strongly related to accuracy, level of complexity of calculation algorithm and in different degrees with all the other factors. For that, appropriate discretization level is very important to achieve a satisfactory trade-off. Low or high discretization of the tool inputs and outputs is not positive or negative in absolute terms. This relates to the fact that many of the factors affected positively or negatively by the discretization level are in conflict with each other.

Table 4.3. Key factors related with the level of discretization

Level of discretization	
Level of complexity of calculation algorithm	
Responsiveness to design decisions	
Flexibility in representing design scenarios	
Flexibility in design modification	
Feedback immediacy	
Accuracy	
Suitability for holistic design	
Data coherence preservation	
Transparency	

Related factors

[2] As Hand (2008, p675) observes, for a valid prediction of energy performance the values introduced into the model must correspond to the reality in the mind of who creates the model.

4.2.2 Level of complexity of calculation algorithm

The level of complexity of the calculation algorithm differs according to the energy calculation method. This occurs as the same phenomena can be differently modelled and it is possible to calculate the same performance variable (such as space heating demand) with substantially different levels of approximation to real phenomena. For example, steady-state equations necessary for calculating space heating demand are quite simple; instead, calculating the same performance variable with dynamic calculation methods, that takes into account thermal inertia of buildings, may become much more complex.

Moreover, the complexity of a calculation method depends on the number of analysis steps that the calculation flowchart encompasses, and then, the range of performance variables that may be quantified. For instance, the algorithm complexity increases if, besides calculating space heating demand, the method includes additional equations to quantify energy consumption of the mechanical system.

Furthermore, the calculation algorithm complexity increases if more interacting phenomena are integrated within the calculation method. This is the case of some dynamic calculation methods that integrate thermal and air flow modelling. At each time step zone temperatures are calculated and used as inputs to calculate air flows through the zone boundaries, and vice versa, the fluid dynamic calculation results provide inputs for the thermal analysis. Modelling this dynamic interaction requires complex calculation methods.

In a building design, the complexity of the calculation method largely depends on which performance goals have to be verified during the design process. In fact, as we argued, the complexity of the calculation algorithm required is largely determined by the performance variable to be calculated. However, we also noticed that it is possible to calculate the same performance variable with substantially different levels of approximation to real phenomena, and then, the energy assessor has some freedom to adopt more or less sophisticated calculation algorithms to quantify the same performance variable(s).

As with the level of discretization of inputs and outputs, the complexity of calculation algorithm also influences most of the other factors. Likewise, it may positively or negatively affect them. So, low or high complexity of calculation algorithm is not positive or negative in absolute terms. The complexity of calculation algorithm and the level of discretization of inputs and outputs are strictly interrelated. In fact, the level of discretization that is possible using a calculation method is dictated by complexity of its calculation algorithm. For instance, if a calculation algorithm reproduces the building behaviour by short time intervals such as one hour, then it requires inputs with a level of discretization of one hour or less.

Table 4.4. Key factors related with the level of complexity of calculation algorithm

Level of discretization	
Level of complexity of calculation algorithm	
Responsiveness to design decisions	
Flexibility in representing design scenarios	
Flexibility in design modification	
Feedback immediacy	
Accuracy	
Suitability for holistic design	
Data coherence preservation	
Transparency	

Related factors

4.2.3 Responsiveness to design decisions

When a tool is involved in the design process, the responsiveness of the tool and the underlying calculation method to the specific design decisions considered is probably the primary factor for its choice. It is intended that one of the primary scopes of energy calculation methods in design is to inform design decisions. Then, when design decision is expected to have influence with respect to performance goals of the project an energy calculation tool may be used. Clearly, the tool is chosen as far as its outputs inform on the performance goal affected. Moreover, it is chosen in relation with the possibility to represent the design solution (or alternative solutions) on which the decision has to be taken. In particular, the tool must allow properly characterizing the specific elements of the solution that differentiate one building design solution from another. This is necessary to compare them in terms of energy performances. For instance, an architect is designing a house and he or she needs to decide whether or not using a ventilated facade to improve the thermal performances of the building. Therefore, the design team needs a tool capable of properly modelling the ventilated facade option, which precedes in importance to other design details that are not the object of decision.

A tool which enables properly representing the design options considered is also useful as it forces the energy assessor (and the design team) to make explicit the object of decision, and to focus on it. In that way the tool turns out to be an effective representation medium for the design team through the process. In fact, the energy modelling process is not simply useful for performance prediction. But the model is also a support for the energy assessor to express the design solution and clarify the design problem, sharing his or her understanding with the design team. Such a process of knowledge acquisition begins before performance prediction, since the energy assessor starts describing the design scenario[3] to build up the model. For this kind of knowledge acquisition, a modelling tool which enables a fitting and precise abstraction of the design scenario being analysed is needed.

The responsiveness of the calculation method to design decisions is conditioned by the level of discretization enabled by the method. The level of discretization of inputs and outputs should be commensurate to the design decision that is considered. In fact, according to the project and the design stage, a decision may be addressed at different levels of detail. That also depends on the subjective approach of each one in the conceptualization of a design scenario. For instance, let us consider a designer that conceptualizes building as a mass with amorphous surfaces. For him a responsive tool is not expected to allow representing the geometry of each facade with relative position of all openings, but rather he requires a tool that enables modelling the geometry of the whole building volume. If instead the designer focuses on the facade composition, a responsive tool should allow specifying the dimensions and positions of the openings on each facade.

Unfortunately, as we observed, the design process dynamic often entails considering some decisions that were not initially planned. When it is necessary to evaluate the consequences of a new decision on building performance, the support of energy modelling may be required. A tool previously used during the process may be not suitable anymore for the new analysis. The responsiveness of the tool to design decisions that are initially considered is not sufficient. For this reason the tool flexibility in representing changing design scenarios, may prevent from substituting a tool already in use with a new one – an occurrence that can require a considerable effort.

[3] As we have argued, we intend as design scenario not only the design solution proposed for the building and its mechanical systems, but also the context in which this solution is envisioned. This context includes, for instance, site and use conditions, which are determinant variables of the energy performance along with the features of the building and the mechanical systems.

Table 4.5. Key factors related with the responsiveness to design decisions.

Level of discretization	
Level of complexity of calculation algorithm	
Responsiveness to design decisions	
Flexibility in representing design scenarios	
Flexibility in design modification	
Feedback immediacy	
Accuracy	
Suitability for holistic design	
Data coherence preservation	
Transparency	

Related factors

4.2.4 Flexibility in representing design scenarios

An energy assessor may be involved in very different projects, making use of energy modelling tools. It is evident that the design scenarios prefigured by design teams in distinct projects may be completely different. A tool may be more or less versatile to represent the diversity of possible design scenarios which may appear in the deferent. Also within the same project, it may be necessary to analyse different design scenarios. Often, they consist of different design alternatives which have to be compared. A tool should be versatile to represent all of them quite faithfully. In addition, the model should as far as possible adapt to the design process dynamic. In fact, the design solution may evolve in a rather unpredictable way, for instance, the openings in a facade may change. Likewise design constraints, such as the dimensional limits resulting from the regulations, may require adaptations in the project (Lawson, 2005, pp. 274-275; Cross, 2007, pp. 99-100). More often than not, this occurs and the model generated has to be adapted to represent something different from the design scenario initially modelled. If the modelling tool is versatile enough it will be possible to reproduce the new design scenario, otherwise it will be difficult. Moreover, the tool should not limit the representation of non-conventional design proposals (ISO 13790:2008, p. 130) which might emerge through the design process. On the contrary, energy modelling tools – similar to the other media used to represent design scenarios – should support and foster the emergence of design solutions. Design tools may even *"provide the stimulus that leads the user to discover the design solution"* (von Buelow, 2007, p. 32).

We essentially referred so far to the flexibility of the tool to represent different design scenarios. However, the flexibility in the representation also involves the possibility of describing a design scenario in different ways. This provides the energy assessor (or more precisely, the modeller) with freedom to interpret the design scenario when creating the model. It allows the energy assessor to express the design scenario through the model according to its own sensibility and personal way of abstraction. For example, when a calculation method allows an energy assessor to decide the number and the geometry of thermal zones, it provides him with flexibility to represent indoor building spaces.

The flexibility in representing design scenarios depends on the level of discretization of the tool inputs. High discretization tends to enhance such versatility. For instance, profiles of occupancy expressed on hourly bases can adequately describe very different occupancy patterns. Instead, if occupancy patterns are expressed as a time fraction over 24 hours with one value for each season, the flexibility is clearly more limited. The flexibility in representing design scenarios is also enhanced by the possibility provided by some tools of creating the model by using alternative inputs' sets. For instance, the shape of a building may be described through the space volume and the compactness, or alternatively, the space volume and the floor surface. These alternative possibilities may support different conceptualizations of a design scenario.

The flexibility of the representation positively affects the responsiveness to design decisions. A flexible tool easily adapts to the representation of different options contemplated when considering a design decision. In turn, it may be conflicting with other factors, such as the feedback immediacy: when the flexibility is achieved by selecting a tool with complex and detailed inputs, the feedback immediacy is penalized.

Table 4.6. Key factors related with the flexibility in representing design scenarios.

Level of discretization	
Level of complexity of calculation algorithm	
Responsiveness to design decisions	
Flexibility in representing design scenarios	
Flexibility in design modification	
Feedback immediacy	
Accuracy	
Suitability for holistic design	
Data coherence preservation	
Transparency	

Related factors

4.2.5 Flexibility in design modification

The responsiveness to design decisions and the flexibility in representing design scenarios do not ensure the flexibility in design modifications. In fact, as we discussed, a tool can enable proper representation of different design scenarios; but this does not mean that the process of model editing corresponds to the process of evolution of the design solution. Not just a design solution, but also the shift and the transformation of one solution into another should be closely reproduced with the modelling tool. That is to say, the variation operated on modelling inputs should reflect directly the changes occurring in the design solution. A modelling tool which is flexible to design modification is, for the design team, an instrument to explore possible design solutions easily. It allows a timely response to design changes, being synchronized with the connected tasks developed throughout the design process.

When changes in modelling inputs correspond closely to the modifications envisioned by the design team for the solution, practitioners get more direct perception of modifications effect on building performance. In fact, a tight superimposition of designing and modelling facilitates practitioners: it allows them to focus mainly on designing, instead of concentrating on the modelling process and the tool.

Sometimes designers tend to the fixation and attachment to early concepts, even if during the design process they prove to be poor solutions for the design problem (Cross, 2007, pp. 104-106). A tool which is not flexible to design modification may contribute to the fixation of practitioners on a design solution. It is evident that when modifying the model is hard and complicated, a practitioner may be more reluctant to modify or explore different concepts.

The flexibility in design modifications cannot be judged simply in relation with the tool, but it is strictly related with the specific design circumstances in which it is used. In particular the tool should respond to the specific design decisions addressed and adapt to the corresponding modifications brought to a design solution. For instance, when a design team is deciding to modify the orientation of a building, a supporting tool should be flexible to this specific modification. In that case, if the tool has one input to indicate the orientation of the whole building, then, the modification may be easily reproduced by editing the model. If instead the tool requires such inputs as the space coordinates of different points to define geometry of the building and its orientation, then, it is very difficult to edit the model in order to reproduce the modification.

Table 4.7. Key factors related with the flexibility in design modification.

Level of discretization
Level of complexity of calculation algorithm
Responsiveness to design decisions
Flexibility in representing design scenarios
Flexibility in design modification
Feedback immediacy
Accuracy
Suitability for holistic design
Data coherence preservation
Transparency

Related factors

4.2.6 Feedback immediacy

Providing feedback within an appropriate period of time is fundamental in design practice. Only under this condition, the use of a tool and the underlying calculation method is affordable in a design process.

Time required by energy modelling is not a minor detail. It is worth reasoning on what it depends: the energy calculation method (and more in general the tool) that is used, and the specific project circumstances.

Depending on the modelling tool used, more or less time is required to represent a design scenario, that is to say, to build up the model specifying all the inputs required by the calculation method. The time needed for representing a design scenario is strictly conditioned by the level of discretization of the model inputs. Additional time is required to run the calculation depending on the calculation method used (and how it is implemented)[4]. This tends to be longer when the level of complexity of the calculation algorithm is higher. Then, time is needed to coordinate the information between different models. In fact, it often occurs that different design aspect are analysed separately with a dedicated model. Related domains, such as thermal behaviour and air quality, may be analysed with a single calculation method which couples various domains, or with separate calculation methods implemented with dedicated tools. In the last case, separate models are generated, and it is necessary to coordinate them. Furthermore, additional time is required for calibrating the model and finally for post-processing and interpreting the results. The time required for

[4] As we have observed, most calculation methods analysed in this thesis are implemented with software applications. This means that, in general, the time required to complete the calculation is dramatically reduced in comparison with manual calculation.

calibrating and post processing are conditioned by the tool inputs and outputs and their level of discretization. In fact, if a large amount of data has to be elaborated, the task of the energy assessor may become quite long.

The total time required by energy modelling also depends on the specific case of application. Time needed is deeply related with the expertise and cleverness of the energy assessor. With these regards, the level of specialization of the energy assessor (architect, engineer or energy specialist) may be very different according to the project; likewise, the specialists involved may vary in the same project from a design phase to another. Time required depends on the availability of input data during the design process. For example, climate data for some building locations are not easily available, and gathering them takes time. Time also varies substantially according to the size and complexity of the building to be modelled. Besides, it depends on the performance indicators to be evaluated. For instance, it is not the same calculating space heating demand or primary energy consumption: the calculation flow charts required in the two cases do not have the same extension and complexity. Moreover, time required is deeply related to the density of the information managed at the design stage when the model is used.

It is fundamental that the time required for the modelling process suits the timing of each design stage. In fact, at least two kinds of time-related limitations exist in each project. First, the period of time available for each design phase is limited. Secondly, design tasks of stakeholders must be synchronized throughout the process, that is to say, energy modelling must be synchronized with other design tasks. Therefore, energy modelling is assumable, if it satisfies both necessities.

Considering the first necessity mentioned, in principle, the more immediate the energy analysis feedback, the better it is. Nevertheless, stakeholders – inclusive of the client – must accept that any aspect of the design problem that is systematically analysed during the design process, such as structure, cost, or energy, requires time. In particular, they must know and accept that, energy and comfort analysis are especially time demanding. Time should be allocated among energy analysis and other aspects of design with the right balance, according to the depth and accuracy considered necessary to examine each aspect.

Moreover, it is not clear that diluting the design process in a long period for deep and accurate analyses benefits the understanding of the design problem for all stakeholders, and then, if it benefits the design outcome. Let us consider the period from when a design scenario starts to be modelled, to the moment when a design decision is taken based on the model results. If the period is short, a fresh memory of the design scenario may help the design team to have a clear insight into the problem at the moment of the decision.

Conversely, a certain amount of time is necessary to mature an acceptable insight on the design problem.

We also mentioned above a second time-related design need, which is to synchronize energy modelling with other design tasks. For that the fact that the design problem and solution evolve in a dynamic process is important: while alternative proposals are generated, the problem is adjusted and reformulated. This requires bringing frequent changes to the model. Therefore, timely responses are continuously necessary to synchronize energy modelling with different design tasks carried out by the members of the design team.

Feedback immediacy is generally limited by a high level of discretization and a high level of complexity of the calculation algorithm. Therefore, it may be in conflict to other factors, such as accuracy, which may be fostered to some extent by high level of discretization and level of complexity of the calculation algorithm.

Table 4.8. Key factors related with the feedback immediacy.

Level of discretization	
Level of complexity of calculation algorithm	
Responsiveness to design decisions	
Flexibility in representing design scenarios	
Flexibility in design modification	
Feedback immediacy	
Accuracy	
Suitability for holistic design	
Data coherence preservation	
Transparency	

Related factors

4.2.7 Accuracy

Often much attention is paid to the accuracy of the calculation method, in particular in specialized literature. But in a project what really matters is the accuracy of the performance outputs for specific design scenarios, not the accuracy of the method in itself. Certainly the precision of predicted performance depends on the calculation method, although it does not only depend on it.

Concerning the calculation method, the outputs' accuracy depends, in particular, on the hypotheses at the base of the calculation method. In fact, a faithful modelling is possible when the founding hypotheses of the calculation method match the patterns of the analysed phenomena. Analysis accuracy relies on the capacity of the calculation method to capture the interaction of the multiple phenomena to be analysed. Then, accuracy somehow relates with the level of complexity of the calculation algorithm. Usually, the outputs' accuracy is also associated to a high level of discretization of tool inputs, which enables describing in detail the design scenario analysed. Nonetheless, Trčka (2010, pp. 93-99) reveals that beyond a certain level of model complexity, the probability of errors increases. Hereafter, we provide additional arguments strengthening this consideration.

We affirmed that the outputs' accuracy is not only affected by the characteristics of the calculation method, in fact, it is also affected by the values assigned to the input data. These values are established by the energy assessor using the information available on the design scenario being analysed. The precision of input values is determinant: without this, the calculation method accuracy (deriving from high level of discretization of inputs and high level of complexity of calculation algorithm) is by no means a sufficient guaranty of accurate results. If the information available from the project is much less than the detail required by the calculation method, several inputs must be introduced as pure guess. Such input values do not reflect the design scenario envisioned by the design team, and then, the outputs may be completely unreliable[5]. In addition, we remark that in a design process the availability of information necessary to assign values to the modelling inputs it is not obvious. In fact, the inputs depending on the design decisions are initially unknown in large extent, and they tend to be clarified through the design process. While the inputs that are independent to the design decisions and are given by the project context (the building site and use) remain in some degree aleatory during the whole design process. Even at the end of the design process and later when the building is in use, the lack of results accuracy deriving from these aleatory variables can hardly be avoided. That happens independently by the calculation method used. This typically occurs with the climate data and especially with user related variables.

We have analysed so far the main reasons that determine the accuracy of calculation outputs. Now we are going to discuss the choice of the calculation method. Some experts (Clarke, 2001, p. 18, Mahdavi, 1999) maintain that only the application of first-principle of building physics guaranties a proper accuracy of energy calculation. That it is motivated by the argument that a calculation method that embeds excessive simplifications may produce misleading results that induce the design team to take wrong design decisions

[5] Some supports, external to the design team, can partially fill the gap of missing inputs, mitigating the lack of accuracy associated to input data. In this line, the research project REPENER proposes web services for design team conceived to provide them with missing information for energy analysis (Madrazo, 2013).

(Clarke, 2001, p. 341). In contrast, other authors prioritise the idea that the right answer is needed for each question (Augenbroe, 2011, p. 23). Waltz (2001, p. 15) expresses this idea in these terms: if a question is satisfied with an error tolerance of 10%, why should I pretend a tolerance of 1% from the tool? A trade-off is necessary between accuracy and other factors that tend to be in conflict with accuracy. In fact, while accuracy is favoured to some extent by high discretization and complexity of calculation algorithm, other factors may be penalised, such as feedback immediacy, data coherence preservation and transparency of the calculation method. To make a trade-off it is fundamental to establish the purpose of calculation in the context of a project. In some cases the design team and the client need a realistic prediction of energy performances. In other cases they only need to understand if and why there is a performance difference between alternative design scenarios. In the second case they would not need as accurate results as in the first one. The design team and the client must also clarify the final goal of energy calculation. Some clients (and practitioners) intend to contribute to the reduction of the environmental impact of the construction sector. More often, the client wants to reduce the energy bill of the individual building that has to be designed. At the scale of the construction sector, accurate predictions of individual buildings' performances would not be a priority. In fact, at the scale of the construction sector over and under-estimations of individual buildings' performances are likely to be compensated. Instead if the focus is on an individual building, then the accuracy of performance prediction is more important.

In all cases, we propose as a basic principle the fulfilment of the minimum accuracy necessary to avoid answering a design question based on misleading results. This principle may apply either at the building level or at the level of building sector. Unfortunately, in a practical case it is not trivial to state any precise accuracy criterion to know if a tool provides the minimum accuracy required in each case. Validation procedures such as BESTEST have been developed to test accuracy of calculation methods (Clarke, 2001, pp. 282-283). But, as argued by Waltz (2001, pp. 7-8), they do not provide strong guaranties for practitioners. Unfortunately, it is extremely difficult to establish generic criteria having validity for all cases. Each project is characterized by a huge combination of variables which are difficult to contemplate within validation procedures. Moreover, there are infinite design questions that calculation could answer. They are different for each project and they can arise throughout the process. So it is difficult to establish a priori, with a standard validation procedure, the appropriate level of accuracy for a particular design question. In the light of these considerations, competences and experience of the design team (in particular the energy assessor) probably play the main role, when they have to understand the accuracy required from the tool for a specific project.

Table 4.9. Key factors related with the accuracy.

Level of discretization	
Level of complexity of calculation algorithm	
Responsiveness to design decisions	
Flexibility in representing design scenarios	
Flexibility in design modification	
Feedback immediacy	
Accuracy	
Suitability for holistic design	
Data coherence preservation	
Transparency	

Related factors

4.2.8 Suitability for holistic design

In building design it is fundamental to resolve with a single solution multiple aspects of the design problem, including energy and comfort along with others such as structure, cost and form. An effective integration of all these aspects depends on the capacity and coordination of the design team, and it is also conditioned by the set of analysis methods and tools chosen - including those dedicated to energy analyses.

As we said, the design team is responsible for producing an integrated design solution. For that, being able to establish relations among all problem areas is essential. The energy assessor, along with the other members of the team, must have the competence to establish appropriate inputs for energy modelling, taking into account their coherence with other domains of analysis. For instance, energy modelling inputs regarding building use may not be dissociated from the analysis of space distribution and occupant behaviour. In the distribution of a house, the design team might decide to put the kitchen and the living room in separate spaces. The resulting separation of occupant activities entails diverse thermal conditions in the two spaces. This must be taken into account by the energy assessor to define appropriate inputs for energy modelling. Likewise, the design team must have the competence to interpret and exploit analysis outputs. In fact, energy calculation results may inform the analysis of other domains. For instance, the calculated energy consumption along with other running costs might be used by the design team to estimate the total maintenance cost of the building. The design team must also be able to interpret energy calculation outputs and evaluate them in combination with other design aspects in order to take rational design decisions.

Furthermore, the design team, in particular the energy assessor, must possess the competence to understand the calculation method being used.

This is essential to capture the interaction of connected phenomena. In fact, any calculation method is made to analyse specific domains and it necessarily neglects, or approximates, some interactions with other domains. For example, in energy calculation methods often the interaction between heat and air flows are neglected; air flows are provided as boundary conditions instead of being modelled. Knowing this approximation is essential for the energy assessor, especially if ventilation strategies are exploited in the project.

Beside the competences available, the production of an integrated solution relates with the organization of the design team. As we observed, it may be composed of a variable number of professionals such as architects, engineers and energy assessors. In more complex organizations even the energy assessment tasks may be divided: the energy assessor supervises the modelling process and the energy modeller directly edits the models. The more articulated the organization is, the more crucial the coordination and communication are for the achievement of a holistic solution.

Also the tools being used affect the integration of the different design aspects involved in design. Energy modelling tools (and more in general, modelling tools) may be capable of analysing different aspects of a design problem reproducing building behaviour concerning different domains. In particular, we observed that existing calculation methods respond to a variety of approaches: a calculation method may focus on a few specific phenomena analysis or integrate a wide range of analyses addressing the interaction of several phenomena. In short, the calculation method chosen may have wide or narrow approach to integrated analysis. For instance, some calculation methods are made only for thermal analysis, and they calculate exclusively space heating demand. On the contrary, wider-approach methods may enable the combination of thermal, moisture and air flow modelling, and provide the calculation of heating and cooling demands, along with energy consumptions. However, even wide-approach calculation methods are unlikely to integrate the entire range of analysis which a project may require.

The range of analysis integrated by the calculation method relates to its complexity: a calculation method covering a wide range of analyses tends to be more complex. In fact, if the method contemplates the interaction of multiple phenomena the level of complexity of the calculation algorithm increases. Moreover, different phenomena often differ from each other for the level of discretization they require. For instance, the time discretization used to model the thermal behaviour of a building may be insufficient to model the response of the mechanical system. As a consequence, the level of discretization of the whole model tends to increase to enable the integrated analysis of multiple phenomena. In sum, the resources necessary for tools use in practice may be substantially different between, a calculation method that is restricted to a single aspect and another enabling a wide range of integrated analyses[6].

The limited resources available during a design process are determinant in order to end up with one design solution able to resolve the multiple aspects of the design problem. The design solution must satisfy each design requirement with an acceptable balance between them. To achieve this balance, the resources available for the project must be allocated accordingly to solve all aspects of the design problem. Therefore, given the resources available for the project a design team should evaluate which amount of them may to be dedicated to energy modelling, and chose accordingly the tool and the associated calculation method. In fact, it is not sensible to use a calculation method that is too complex to manage with available resources. When the level of discretization of the model and level of complexity of the calculation algorithm are excessive, feedback immediacy is insufficient and the transparency needed to understand the building behaviour is penalized. Such kind of tools requires high-level competences in energy assessment and it absorbs a long time, in detriment to the remaining resources available to solve other fundamental design aspects. The other way round, dedicating nearly all resources to other aspects such as form, functional distribution and cost impairs energy assessment. Adopting oversimplified calculation methods to estimate energy performance, or worse, completely neglecting the energy aspect, seriously compromises the overall quality of the design process outcome.

Table 4.10. Key factors related with the suitability for holistic design.

Level of discretization	■
Level of complexity of calculation algorithm	■
Responsiveness to design decisions	
Flexibility in representing design scenarios	■
Flexibility in design modification	
Feedback immediacy	■
Accuracy	■
Suitability for holistic design	
Data coherence preservation	■
Transparency	■

■ Related factors

[6] The resources necessary include time, money and different competences of architect(s), engineer(s) and energy assessor(s).

4.2.9 Data coherence preservation

In a design process information is incessantly elaborated. The definition of the design problem and solution continuously evolves. Throughout the process the focus of practitioners jumps through different design aspects (such as energy, comfort and cost) and moves through different design scales. Therefore, preserving the information consistency throughout the process is not trivial for the design team. Such consistency depends on the organization and coordination of different competences within the design team and it is also conditioned by the tools.

Energy calculation methods that integrate different design aspects and are capable of coordinating different scales of data could improve the information consistency throughout the design process. Nevertheless at present, *"even the most advanced and fully integrated simulation applications do not fully support users* […] *at all stages* […] *and throughout the design process"* (McElroy, 2009, p. 303). A consequence of this fact is that the translation of the information through different design tools is mainly in the hand of the design team.[7] Certainly high level of discretization of the model inputs and outputs makes more difficult data coherence preservation, because ensuring the consistency of a large amount of data is not trivial.

[7] Recent research effort has been focusing on the information consistency through different design tools. That may result in the improvement of data coherence throughout the entire design process, and beyond, throughout the entire project life cycle. In the field of energy calculation, the definition of standard calculation methods enhancing the compatibility among different levels of details was pursued at the European level (CEN/TR 15615:2008). Moreover, in modelling tool development, mechanisms to deal with different levels of details improved. Also in the line of web applications, research has been done. For instance, in the research project IntUBE, a platform was proposed to improve the compatibility of data from different applications. The platform was intended to convert heterogeneous information from different applications to a common standard data set. Thus, comparison of models generated with different energy modelling tools throughout a design process could be compared. A case study of the design process of a residential building at the concept design stage is described in Madrazo (2010).

Table 4.11. Key factors related with the data coherence preservation.

Level of discretization	
Level of complexity of calculation algorithm	
Responsiveness to design decisions	
Flexibility in representing design scenarios	
Flexibility in design modification	
Feedback immediacy	
Accuracy	
Suitability for holistic design	
Data coherence preservation	
Transparency	

Related factors

4.2.10 Transparency

The transparency of the calculation method is important for its application in the design process[8]. A calculation method is transparent if the set of equations, or more in general the calculation algorithm, is clear for the user. The transparency is often associated to the fact that a calculation method is based on parameters with a known background, as affirmed in ISO13790:2008 (pp. 128-130). In addition to this, we remark that transparency depends on and cannot be dissociated by the background possessed by the user. In design, it is essential to take into account what kind of knowledge is held by practitioners. In ordinary design practice, the background of a practitioner is certainly much more generic than the knowledge of a researcher in building physics.

Under the perspective of practitioners, a calculation method is transparent if it can be easily learnt and well understood by the energy assessor, and then, if it makes it easy to interpret the results. If the energy assessor makes a straightforward interpretation, his or her conclusions are easier to understand for the other members of the design team. A correct interpretation of results is fundamental. In fact, misunderstanding the model is dangerous, not just because the effort of energy modelling becomes useless, but because it may result in pernicious design decision with negative impact on the future comfort and energy performances of the building.

[8] According to ISO13790:2008, (pp128-130) the calculation method should be transparent, robust, unambiguous, reproducible and verifiable for normative scope. In design transparency and these related characteristics are also important, in part for the same reasons, but also for different reasons related with the design scope, which are explained in this sections.

In design, the scope of energy modelling is also to expand the knowledge and the understanding of the design problem being analysed. That means, understanding the phenomena behind the equations of the calculation methods. Indeed, the scope of energy modelling is not merely a mechanical and uncritical prediction of the performance values that result from a combination of design variables. In this sense, a calculation method should not be just a “black box” which delivers performance values to unconscious and “domain-ignorant” designers.

With this regards, the transparency of the calculation method relates to the level of complexity of calculation algorithm. On the one hand, a low level of complexity of calculation algorithm may correspond with a lack of transparency of the calculation process. In some methods simplifications are introduced to reduce the complexity of calculation algorithm. It may occur that such simplifications impede to provide clear explanations of a building behaviour that a design team has to analyse. For instance, a steady state method that ignores heat stored in mass of the building is not useful to study the behaviour of a building with massive walls.

On the other hand, an excessive level of complexity of calculation algorithm hinders the understanding of the model. In fact, for a complex dynamic model integrating multiple domains, the extended set of equations used to model each phenomenon may be in large part unknown even for a learned expert. Then it is very probable that, in a building design, the energy assessor would not know each detail of the calculation algorithm. In the best cases a practitioner is knowledgeable enough to get a deeper understanding in those parts of the calculation method that are crucial for the building under consideration. Thus, the transparency of the tool cannot be dissociated by the background knowledge possessed by the design team and the energy assessors in particular. Indeed, the complexity of the calculation method should match the level of specialisation and the competences available in each project and design stage.

Besides, the competence available in a design team, also the limitations of human minds have to be considered: *“most design problems are* […] *far too complex for the designer to hold all the factors in mind at once”* (Lawson, 2005, p. 182). This reflects on the calculation method used to analyse the behaviour of the building and its mechanical systems. In fact, most existing calculation methods are too complex for an energy assessor to keep in mind all variables and equations at once. In many existing methods, the level of complexity of calculation algorithm and level of discretization of the inputs and outputs are very high for the human mind. We present an example that illustrates the importance of mind limitations. It is taken from the conversations we held with the architect Rafael Serra, a pioneer in energy efficient design in Catalonia. His research group has developed both a manual calculation method[9] and a simple software tool[10] for thermal and energy analysis. He explains that he has used the manual calculation method more often than the simple automated tool in his projects. The manual method used by Serra is only made of two equations that express indoor temperature mean and its daily swing, then, it is quite simpler then the automated one. It is reasonable to suppose that when modelling with the manual method a design scenario he has the entire calculation algorithm rather clearly in mind and he may recognize quite immediately its meaning in terms of building behaviour.

Table 4.12. Key factors related with the transparency.

Level of discretization	
Level of complexity of calculation algorithm	
Responsiveness to design decisions	
Flexibility in representing design scenarios	
Flexibility in design modification	
Feedback immediacy	
Accuracy	
Suitability for holistic design	
Data coherence preservation	
Transparency	

Related factors

4.2.11 Summary

In the precedent sections we have analysed ten key factors that determine how apt an energy calculation methods is in a design process (Table 4.13). Eight factors in the table correspond to a positive quality for the application of a calculation method in design. Concerning the first two factors, level of discretization and the level of complexity of calculation algorithm, the quality of the tool cannot be considered positive or negative. However, both are determinant for the suitability of a calculation method in design. In fact, the level of discretization and the level of complexity of calculation algorithm, have great influence on the other factors. The definition of appropriate levels of discretization and complexity is not obvious: it depends very much on the relative weights of the other factors, in each particular design case.

[9] The tool Archisun (Serra, 2000).

[10] The manual calculation method developed by Serra (2001, pp378-380).

Table 4.13. Key factors for the choice of appropriate energy calculation method during the design process.

Key Factors		
Ld	Level of discretization	~
Lc	Level of complexity of calculation algorithm	~
Rd	Responsiveness to design decisions	↑
Fr	Flexibility in representing design scenarios	↑
Fm	Flexibility in design modification	↑
Fi	Feedback immediacy	↑
Ac	Accuracy	↑
Im	Suitability for holistic design	↑
Dp	Data coherence preservation	↑
Tr	Transparency	↑

To answer design needs:

↑ The higher the better
~ Controversial

In Table 4.14, we summarize the relations among different factors. In the table, we indicate the factors having a direct relation. As we said, most factors strictly relate with (and often depend on) the level of discretization and the level of complexity of calculation algorithm. We also specify if the factors are in evident concordance or conflict with each other, or if they have a controversial relation. It can be observed that most factors are interrelated, and in several cases they are in conflict. Some relations between two factors are complex and controversial, so that we could not simply affirm that they are in conflict or in concordance.

	Ld	Lc	Rd	Fr	Fm	Fi	Ac	Im	Dp	Tr
Ld		☺	~	☺	~	☹	~	☹	☹	~
Lc	☺		~	-	-	☹	~	~	☹	~
Rd	~	~		~	-	-	☺	-	-	☺
Fr	☺	-	~		-	~	☺	~	☺	☺
Fm	~	-	-	-		☺	-	-	-	☺
Fi	☹	☹	-	~	☺		☹-	☺	☺	☺
Ac	~	~	☺	☺	-	☹-		~-	☺	☺
Im	☹	~	-	~	-	☺	~-		☺	☺
Dp	☹	☹	-	☺	-	☺	☺	☺		☺
Tr	~	~	☺	☺	☺	☺	☺	☺	☺	

The factors are:

Related
☺ In concordance (17)
☹ In conflict (7)
~ Controversial (11)

Table 4.14. Relation between factors. It is specified if they are in concordance or conflict.

We said that the weight of each factor differs according to the methodological approach of the design team and the circumstances of each project.

Therefore, the suitability of a calculation method must be evaluated in each case depending on to the weight of each factor.

4.3 SUITABLE CALCULATION METHODS AT DIFFERENT DESIGN STAGES

Besides the specificity of each design process, in any project the stages of the process differ from each other. Some essential distinctions we have highlighted in Chapter 2 regard:

- The level of specialization available within the design team at each design phase
- The information density existing at each design stage
- The decisions and design goals that characterize at each design stage

These differences affect the individuation of proper energy calculation methods. For this reason, the key factors we have identified are examined for different design stages.

As an approximation we simply distinguish between initial and advanced design stages, instead of referring to a more specific and structured sequence of stages. Taking into account the dynamic nature of design, and in particular the uniqueness of each design process, we intentionally avoid referring to one determined structure.

4.3.1 Initial design stages

Hereafter the ten factors identified and analysed in Section 4.2 are discussed in order to examine how calculation methods may suit the design needs that exist at initial design stages.

- **Level of discretization.** Often initial design stages are characterized by a low level of detail in the design abstraction, although there are no rigid patterns of relation between the level of detail and the design stages. Even if there is not a firm rule, and some designers start designing from details at very early design stages, it is extremely difficult to immediately produce a detailed and complete description of the whole building. The use of building performance calculation requires a complete description of the building (and its environment). Therefore, until a comprehensive idea of the whole building is defined, it is impossible to model building performance. So, if the solution is developed from the beginning in detail, more time is needed to define a comprehensive model, and performance calculation can inform design questions later. Hence, a model that requires very detailed inputs can hardly be exploited from the very beginning of the project. On the contrary, simpler methods are more likely to provide calculation results at the very initial design stages, as soon as the design team defines even a rough but complete picture of the design scenario. Certainly the possibility of creating a simple model to some extent lies in the capacity of the energy assessor.

- **Level of complexity of calculation algorithm.** Low or high complexity of calculation algorithm is not positive or negative in absolute terms. Therefore, no clear indications can be suggested for initial design stages, although low discretization tends to favour the transparency and feedback immediacy that initial design stages usually require. An appropriate level complexity of calculation algorithm should enable a trade-off between other factors as transparency and accuracy that are related with the complexity of calculation algorithm.

- **Responsiveness to design decisions.** Typically, initial design stages are associated with specific decisions regarding, for example, the form, orientation, and building fabric. But there is no clear consensus in literature on which are the specific decisions that are associated to initial design stages. IEA (2009, p. 17), for instance, considers the possibility of integrating mechanical systems from the beginning of the design process. In the same line, Serra (2001, p. 8) developed a tool that enables analysing renewable energy systems such as solar collectors right at early stages. Instead, many authors (as Baker, 2003, p. 3; Hensen 2011, p. 6) associate decisions on mechanical systems to advanced design stages. The lack of clear agreement is explained by the fact that each design process represents a particular case. Moreover, some decisions initially taken may be reconsidered in a later stage, as a consequence of the necessity to reformulate the design problem. In a project then, it is often impossible to confine a decision to a design stage. So, a tool that enables modelling options for the building orientation, form and building fabric, among others, is typically required at the initial design stages. Yet it is true that a tool that also permits evaluating other kinds of decisions is likely to be needed.

- **Flexibility in representing design scenarios.** At the inception of the project a detailed solution is not yet needed as it is at the end of the project. At early design stages the level of abstraction of the design proposal may be very high. The way each practitioner understands the design problem and abstracts the solution may be substantially different. Thus, the calculation method and tool used in a project must be flexible to adapt to the particular way of representation of the practitioners involved in that project.

Furthermore, the flexibility of the tool is especially crucial at initial design stages, because several radical changes and completely different design solutions are likely to emerge in a short time. If a tool in use is not flexible to represent different unexpected scenarios, it can rapidly become useless. If instead it is flexible, it is more likely to help in answering new questions that emerge through the process.

- **Flexibility in design modification.** This factor is important at all stages: the tool, in fact, should easily reproduce design changes occurring throughout the entire design process. However, such capability may be particularly relevant at initial design stages. Often in fact, designers tend to operate a larger number of design modifications in a short time interval if compared with advanced design stages. The modifications frequently involve radical changes. In general, it is easier to reproduce design modifications into the model at the beginning of the design process, when little definition of the design scenarios exists, so that the model tends to be relatively simple.

- **Feedback immediacy.** It is very necessary at initial design stage, because several radical changes and completely different design solutions are likely to emerge in a short time. If a tool is not able to provide feedback with the required frequency, it becomes an obstacle to the progress of design and the coordination of tasks. If it is immediate enough, it increases the possibility of exploring many different design options and outlining a wider picture of the design problem, within an acceptable time.

- **Accuracy.** It is important, but very hard to achieve at initial design stage. In fact, the information regarding the design solution is still very limited, therefore only rough approximations of performance variables may be quantified. This limitation is intrinsic to design problems, indeed it has no easy solution and it can hardly be overcome by the selection of the calculation method. It is true that detailed calculation methods would be potentially able to provide very accurate results. But as it is impossible to provide them with adequate inputs, then it is also impossible to obtain accurate results. Surprisingly, some authors suggest that too detailed models may provide less accurate results compared with simpler ones, as the risk of error in the model inputs increases substantially when the model is very complex (Trčka, 2010, pp. 93-99). It is worth being aware of this for the choice of calculation method.

  The lack of information and the inapplicability of over-complex methods must also be carefully considered in the formulation of performance goals. That is to say, it makes no sense to pretend to verify extremely precise requirement at initial design stages when calculation results accuracy is ineluctably limited.

- **Suitability for holistic design.** At initial design stages, the design team has acquired a very limited knowledge of the design problem being analysed. Often the design evolves by multiple tries in order to outline design solutions. Some design aspects are studied when devising initial solutions. This process usually raises new design questions on design aspects that are still unexplored. Design teams must understand which relevant aspects are affected by decisions in hand and identify appropriate indicators to quantify them. Moreover, the design solution may change radically and very frequently. Rarely, this rapid dynamic can be planned by practitioners. So, at initial design stage it is especially difficult to select calculation methods that can timely support all rising aspects and provide the required indicators. Calculation methods that integrate multiple design aspects could in part prevent the need to use different tools during the process whenever a new a design aspect arises. However, a calculation method that integrates multiple domains is more complicated for the user, and therefore, it could hinder the design progress. Instead, a very simple calculation method dedicated to a specific design aspect provides a rapid response, and the attention of designers can shift rapidly through different design aspects. In turn, a tool that is limited to a single domain will soon become insufficient to cope with new analysis that may be required. Then the design team will need different tools as soon as a new design aspect has to be addressed.

- **Data coherence preservation.** Preserving information consistency through the design process is not trivial especially at the initial design phases, when the design iterations are rapid. As we observed, the need to use different tools during the process requires translating information between them. At early design phases this may occur very often. That may involve some inconsistencies related to the heterogeneity of tools and the approximations and errors of practitioners. In design practice, the occurrence of some inconsistencies is unavoidable. They can be tolerated especially at initial design stages, when precise specifications about the design solution are still not needed. Inconsistencies are acceptable, as long as the workflow is coordinated to control the solution coherence. In fact, data coherence itself is not the goal of the design process. The goal of design is instead achieving a satisfactory solution.

- **Transparency.** At initial design stages, a simple and clear model is likely to be beneficial. For the energy assessor, such a model is especially important to facilitate the interpretation of the results and share his conclusions with the rest of the design team. All of this is particularly important at early stages, because the design problem is largely unknown, and have to be clarified through the design process with the support of the model. Moreover, several possibilities for the design solution are often investigated over a short time, and they have to be understood with immediacy. A simple calculation method (low level of discretization and low complexity of the calculation algorithm), that is easy to understand and interpret, may be more adequate for this stage. In sum, the transparency required for initial design stages is likely to be achieved by using a tool based on a simple calculation method.

4.3.2 Advanced design stages

We have focused above on initial design stage. Here, we report the same analysis focusing instead on advanced design stages. The ten factors defined in Section 4.2 are discussed in order to examine how calculation methods may suit the design needs that characterize advanced design stages.

- **Level of discretization.** In the final phases of design, a detailed and comprehensive picture of the building has been achieved as a result of the design process developer so far. Generally, design questions tend to relate to project details. However, in some cases project circumstances bring the necessity of substantial revisions that entail returning to large scale decisions. The calculation inputs and outputs must have the appropriate resolution to support design questions and decisions at stake. Then, practitioners can better represent the final solutions with a method that enables detailed input, although this requires a considerable effort. Such a method might be overcomplicated if large scale decisions have to be assessed in which details are secondary.

- **Level of complexity of calculation algorithm.** As we observed for initial design stages, also for advanced stages, no clear indications can be expressed concerning the complexity of calculation algorithm. In fact, the level complexity of calculation algorithm is appropriate if it enables a trade-off between other factors that strongly depend on it. To some extent more complex calculation algorithm may be better exploited at late design stages, when more precise and complete information is available compared with initial stages. In fact, sophisticated calculation algorithms provide their best in terms of accuracy only when precise inputs values are available.

- **Responsiveness to design decisions**. Typically, at advanced design stages final specifications about the building fabric are provided and mechanical systems are developed (Hensen, 2011, p. 6). Usually, when getting to the end of the process, it is only possible to make very specific decisions for the refinement of the design solution. Then at advanced design stages, a tool that enables modelling in detail different options, ranging from construction materials, to mechanical systems and operational settings, is likely to be useful. But as we discussed in the precedent section, we can hardly generalize, by associating specific decision to the advanced design stage.

- **Flexibility in representing design scenarios.** At final design stages the high level of abstraction used to represent design scenarios tends to disappear. It is substituted by technical specifications that are necessary to start the construction. This entails that the model tends to approximate the literal description of the real building. Along the process, the particular ways different practitioners may use to abstract a design scenario tend to converge to a more neutral expression required to describe the technical specifications of the design solution. Hence, it is less important than it was at the early stages that the calculation method is adaptable to the particular way each practitioner expresses abstract design scenarios. In this sense the flexibility to enable different ways to represent one scenario is not so important. However, a different kind of flexibility is needed. In fact, it is usual at the final stage that precise answers are required for technical questions. In that case the calculation method and tool must be appropriate to the literal representation of technical details. Then the tool must be flexible to enable analysis of a variety of detailed solutions.

  Furthermore, at advanced design stages the design solution tends to be quite defined and established. Radical changes in design solution may occur, but are not as common as at initial design stages. So, flexibility of the tool is important, but not so crucial. Often the adjustment of details, like schedules and components' features, is where more flexibility is needed at advanced design stage.

- **Flexibility in design modification.** This factor is always relevant. As far as possible, the tool should reproduce design changes easily. In general, it is more difficult to reproduce design modifications close to the end of the design process, when the design solution is completely defined, and consistent and comprehensive details for most parts of the building and mechanical systems have been specified. At this stage, radical design changes may have large consequences, making it especially difficult and laborious to keep the consistency of all project information.

- **Feedback immediacy**. Also at advanced design stages it is necessary to provide energy analysis within a limited period of time, but it is not so crucial. As radical changes in design solution are not as frequent as they are at initial design stages, usually there is not a strong necessity to remodel completely different solutions. Therefore, the time required for remodelling and examining each solution has a minor impact on the time dedicated to the energy assessment. In some cases, other needs such as accuracy, which are in conflict with the immediacy of the tool, have higher priority.

- **Accuracy.** At later design stages it is easier (but not easy) to achieve more accurate calculation results. The information on the design solution is usually more complete and detailed. In that case, a calculation method correctly and precisely informed with available inputs provides more accurate results. For this reason a detailed calculation method is more likely to provide accurate results at advanced design stages than at the beginning of the process.

- **Suitability for holistic design.** At advanced design stages the design team has gained wider knowledge of the design problem being analysed, and then, the relevant design aspects that have to be solved are quite defined. So, it is easier to identify relevant indicators and chose appropriate methods to cover the analysis of the main design aspects. Radical changes of the design solution are not very frequent during advanced design stages, although they may occur. In that case, the tool being used may become inadequate to support major design aspects that could arise.

- **Data coherence preservation.** Also at advanced design phases, preserving of information consistency throughout the design process is not trivial. In fact, even if the design problem and solution are not evolving very fast, the increasing amount of information that has been accumulated since initial design stages has to be coordinated. Moreover, as final results have to be correctly delivered at the end of the process, it is especially important to produce precise and consistent information. Furthermore, it is desirable that the inputs and outputs of energy calculations could be verifiable later at the operational stage. This poses the problem that these data should be comparable with energy bills or monitoring data. The possibility to compare design calculations with bills or field measurements is conditioned by several things. Design calculations and operational data may differ in the parameters used to express analysed phenomena and in the level of discretization of data. Often calculations and operational data are based on incompatible assumptions: typically, boundary conditions assumed for the calculation do not match real climate and use, and hence, the inconsistency between compared data sets has to be solved.

- **Transparency.** At advanced design stages, having precise information is important for the energy assessor, when interpreting calculation results and sharing the model and results. In fact, at this stage the design team is expected to produce precise and explicit technical specifications. A tool that is based on clear and acknowledged variables and that enables modelling exhaustive details of the design scenario might be more appropriate indeed. This would require a tool with a high level of discretization and high complexity of the calculation algorithm.

It must also be considered that project stakeholders are not likely to share common concepts and vocabulary and to possess similar levels of knowledge about design. In this context, it is crucial to share the project documentation among the design partners, client, builder and contractors unequivocally. Unambiguous information is essential to ensure that the expected quality of the product is going to be fulfilled during the construction phase. It is then beneficial to use a transparent calculation method, which provides a clear reference for all parties by leaving little room for interpretation.

In contrast with initial design stages, the transparency required for advanced stages is achieved to a large extent by unambiguous calculation methods.

4.3.3 Summary

We have observed differences between initial and advanced design stages, although no rigid patterns apply for the identification of suitable calculation methods at each design stage. For example, we have mentioned some typical decisions at each design stages that calculation should support, but we also stressed that other decisions that differ in each project are likely to be considered. Also priorities in design needs vary between initial and advanced design stages according to some trends, although, again, no rigid patterns apply. Then the trade-off for an appropriate tool differs from one stage to another, but certainly the difference largely depends on the specific project. For instance, we observed that, at the initial design stages, the flexibility in design modification and feedback immediacy are typically very important compared with accuracy. While in advanced stages the opposite often occurs. However many design processes are in contrast with this pattern. As the case may be, at advanced design stages of a project suddenly a radical change of the design solution may be required, and then, the need for flexibility in design modification prevails upon the accuracy.

4.4 CONCLUSIONS

The systematic analysis of the key factors of suitability of calculation method in design makes evident that “the right calculation method” in absolute terms does not exist. For a specific design situation, probably more than one calculation method may offer an acceptable trade-off among the ten factors, by satisfying all contrasting design needs to some degree. But no calculation method can provide the perfect solution. In most circumstances, the support of energy calculation is possible only in detriment of the levels of satisfaction of some design needs: for instance, accuracy is sacrificed to some degree to fulfil the feedback immediacy required, or vice versa.

It is known that energy calculation has had very limited application until the present. However, it is fundamental to understand why, if we aspire by means of research to foster an effective use of energy calculation. The analysis of the key factors explains (in part) why energy calculation has had very limited application. The analysis explains common barriers to the use of existing calculation methods, by questioning the needs of design activity, and the circumstances that limit ordinary design processes and methodologies. In particular, the distinction of various factors helps to identify and explain possible conflicts between design needs.

Our analysis shows that the existing energy calculation methods have limited potential to be exploited in the current design practice. Nevertheless, it also suggests that, if they were properly selected and used, they could give effective answers to some design questions. It is improbable that energy calculation could provide a continuous support throughout the design process, to analyse each change in the solution and verify all the adjustments of the design goals. And it is difficult to obtain significant results for all design stages by using the same calculation method and tool throughout the whole process. In most projects existing energy calculation can provide answers only to some design questions (the others will be supported by the experience or other means). Likewise, calculation tools are likely to provide support during specific stages of a design process, and not necessarily at each stage. A proper calculation method should help, with quantitative information, to answer important design questions that would not be addressed otherwise. Finally, it is often impossible to plan in advance which tools and calculation methods will be used, being sure that they will provide support to design questions that will emerge later on during the process. Thus, it seems reasonable that the selection of an effective tool could occur during the process, when specific questions emerge.

Throughout these chapters we have provided a broad view on the use of energy calculation in support to the design process, without focusing on particular calculation methods or on specific projects. We have conducted a critical analysis of precedent literature, and based on that, we intended to contribute to existing knowledge with a systematic analysis aimed at understanding how calculation methods may suit design needs. To sum up, the view presented until now is general and mainly theoretical. In the next chapters instead, we analyse two case studies to provide support to the theoretical view: each case focuses on particular projects and specific calculation tools. The key factors that we have defined in this chapter are analysed in the case studies.

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Chapter 5

Case A: design process of a residential building in Barcelona

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In this chapter we consider the project of a social housing block in Catalonia (Spain), actually built and occupied. Instead of analysing the real design process we reconstruct and analyse a hypothetical one. In fact, we retrospectively reproduce a possible design process that might have developed integrating energy calculation to support design decisions. Then we examine the process from the point of view of an external observer.

The case study is aligned to the object of this thesis that concerns the applicability of energy calculation in the common design practice. Therefore **the case taken is not a singular project, but an ordinary one in terms of building use, size, and budget. Likewise, energy modelling is not used by the design team to develop sophisticated and innovative design solutions but to improve the building performance with conventional solutions.** Also the resources of the design team, including the time available to deliver the project, correspond to a quite typical design process. However, we assume an exceptional premise: the client and the design team are motivated to improve energy performance and for that purpose they use energy calculation in support of the design process. In addition, the energy assessor integrated in the team possesses a fundamental background on building physics and some knowledge in the use energy modelling tools, but he does not have high-level expertise. Furthermore, he has no great knowledge of the local climate.

This case study is not focused on the tools and the models used by practitioners, but on the design process in which energy modelling tools are implicated. The extensive description of the tools and the models is provided in the annexes.

The chapter is structured as follows. In Section 5.1, we briefly describe the real building and its design process, which inspire the reconstruction of the hypothetical design process. In Section 5.2, we specify the scope of the case study and introduce the methodology used to reconstruct the design process. In Section 5.3, we outline hypothetical design process, identifying its design stages and the energy calculation tool involved at each stage. In sections 4 and 5, we reconstruct the conceptual design stage and the design development stage, respectively, and we describe how energy modelling takes part in the design process. In Section 5.6, we analyse the tool features in relation with the necessities of the design team to evaluate how far they match. In Section 5.7, we draw conclusions on the case study.

5.1 THE ACTUAL BUILDING AND DESIGN PROCESS

The building is a recently completed 24 apartment social housing block, in Cerdanyola del Vales, close to Barcelona, in Spain, which was commissioned by the public housing institute INCASOL.

The rectangular block is aligned to the street. It is 64 meters long and 12 meters wide. It occupies the maximum surface permitted by the building codes and it has four stories, plus the underground parking. The two lobbies giving access to the apartments and commercial areas –in conformity with urban regulation– are located on the ground floor. The first, second and third floors are intended for residential use. The typical floor plan includes eight apartments. It is organized around two cores, each one serving four apartments (from Figure 5.1 to Figure 5.3).

Figure 5.1. Aerial view of the building site in Av. Cordoba, Cerdanyola del Valles, after the construction of the building (adapted from www.google.com [2014 05 21]).

Figure 5.2. Photos of the building from south-west and north-east (adapted from www.google.com [2014 05 21]).

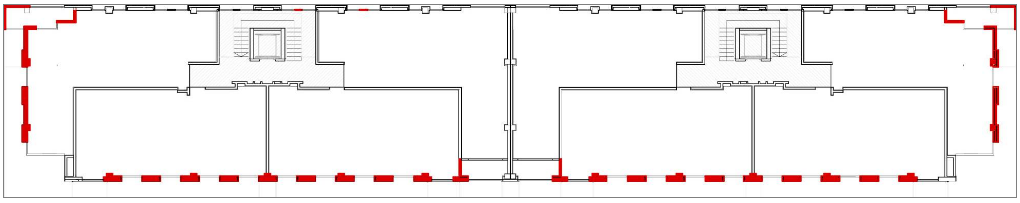

Figure 5.3. Cerdanyola residential building, typical floor plan (adaptation of the project, Frutos, 2006a).

The orientation of the plot facilitates the possibility of achieving good energy efficiency by taking advantage of a large south facade. In the south, east and west facades there are large openings to gain light and energy from the sun. In these facades opaque parts consist of solar walls, with panels of different colours that characterize the formal composition of the facade. In the north facade there are no large windows. Openings are provided with solar protection in the south, east and west facades.

To obtain information about the design process of the building an interview with the architects was conducted[1].

According to the regulation, the design process developed in two stages, *"proyecto básico"* and *"proyecto ejecutivo"* (Ministerio de la Vivienda, 2006). As the architects affirm, the project was very constrained from the beginning of the first stage. In fact, a quite prescriptive building program was defined: for instance, it was prescribed that two independent staircases should have provided access to the flats. Also urban planning provided alignments and volumetric restrictions. Therefore, very limited design options existed for conceptual design decisions such as whole building shape, orientation and layout.

The core of the design team was a small office of two architects. They were supported in energy assessment by external consultants: a research group specialized in building energy simulation. During the first design stage, *"proyecto básico",* the architects developed a design solution and they delivered it to the consultants, which conducted energy performances calculations (GEUMA, 2007) and provided the outcomes back to the architects. It was not possible to repeat this iteration several times. The consultants intervened exclusively at this design stage to evaluate the energy performance at the building level with EnergyPlus, an advanced simulation tool, so that a single tool was used in the entire design process.

As the architects affirmed, due to time restrictions there was no time to perform several simulations, exploring different design options at the first design stage. In addition, energy performances calculation could not be

[1] Interview with the architects Frutos and Sanmartí, in Barcelona [2011 03 28].

completed early enough to anticipate and drive initial design decisions. In fact the outcome of calculation came at the end of the first design stage, when the decisions were already made and the project documents were about to be submitted to the public authorities. Actually, energy calculation could be exploited only to verify the performance requirements when the design solution was already consolidated. In sum, we observe that the support of calculations' results was not continuous throughout all deferent stages of the design process but punctual and limited to the very end of the first design stage.

Despite the fact that building use (multifamily residential) and size of the building (24 dwellings) correspond to a quite common kind of project, the circumstances of the real project were not ordinary. In fact, energy assessors were highly specialized and equipped with human and technical resources. In Spain, the support of this kind of consultancy is uncommon for an ordinary apartment building project. That was possible as the project was financed within a European initiative on pilot energy efficient buildings[2].

A hypothetical design process is reproduced in the thesis replicating some circumstances such as location, functional program and some design decisions from the real project. The hypothetical situation permits excluding extraordinary circumstances of the real project while keeping others such as the building program and site conditions. In the recreated design process energy assessment is not decoupled from the process, as in the real case, but it is deeply integrated in the process. It is assumed in fact that energy modelling is directly carried out within the design team. Further elements of differentiation are that energy calculations are used to support some design decisions (by anticipating them), and that different energy calculation tools are used according to the specific characteristics of each design stage. Under the research perspective, the recreated situation allows us to have a direct experience in the use of energy calculation tools and a deeper insight into the process that we could not have as external observer of the real process.

The recreated building design process is described in the following sections.

[2] The building energy assessment, conducted by the University of Malaga, was founded within the POLICITY project. Energy assessment was carried out at the design phase and at the operational phase. Also in the IntUBE project the building was considered ex post as a case study (Madrazo, 2010).

5.2 SCOPE AND METHODOLOGY OF THE CASE STUDY

The aim of the case study illustrates the application of energy calculation in support of the design process. And in particular, it is to analyse how far the tools and underlying calculation method satisfy the necessities of the design team in this project.

It is clear that a single case study can support but not demonstrate the general validity of the contents exposed in this thesis. The case study is motivated by a different intention, illustrating and testing some of the theoretical assumptions exposed in the earlier chapters. The case study itself is in fact a collection of examples:

- The design process described is a particular example reconstructed according to the analysis of design process and methodologies that we have discussed in the thesis. In particular, we explain with this case the dynamic and holistic nature of the process.
- Likewise, the energy calculation methods used in the project provide two different examples of the energy calculation methods that have been analysed in the thesis.
- Finally, typical situations that occur throughout a design process are reproduced to discuss the suitability of the energy calculation methods used in the project. In that way, the key factors for the choice of energy calculation methods previously formulated are analysed through the examples provided in the case study.

As we argued in the precedent chapters, any design process is complex and largely implicit. Therefore, replicating in detail a complete design process is unaffordable, and it is actually unnecessary. We prefer to extract selected steps, from what occurs throughout the whole design process, in order to support the theoretical part of the thesis. Accordingly, the case study is developed as follows:

(a) It focuses on the energy and thermal comfort, stressing just some of the innumerable relations with other design aspects such as cost, privacy and external views.

(b) For each design stage, only some representative design solutions are taken out of many proposals generated throughout the design process.

(c) Only a limited segment of the design process is described for each design stage.

Based on the analysis of design methodologies reported in precedent chapters, we can make some reasonable assumptions to reconstruct a realist design process. In particular, we assume that the design team follows its own methodology which is specific for the project and is flexible to the circumstances emerging throughout the design process. The methodology of the design team is not formalized, completely explicit and predefined. It is partially implicit and embedded in the design team routine, and at some extent improvised by practitioners to adapt to the project circumstances.

In the case study, as in the thesis, the main focus of our analysis is on the design process in which calculation methods are used, while it is not on the resulting design solution, the tools used and the models in itself.

5.3 OVERVIEW OF THE REPLICATED DESIGN PROCESS

We assume that the whole project life cycle spans from the design process, divided into **conceptual design** and **design development**, to the building use[3] (Figure 5.4). Two energy calculation tools are used in support of the design process. At each design stage (conceptual design and design development) specific design decisions are considered by the design team; likewise, stage-specific constraints affect the design solutions proposed, and then, reflects on their energy models.

[3] Similar sequences defined by several antecedents discussed in Chapter 2, such as INTEND (2009) and RIBA (2007). The two stages sequence proposed is coherent with applicable regulation for this project. In fact, Spanish regulation (CTE. 2006) prescribes two deliveries, first, for the preliminary project (*"proyecto básico"*), and then, for the executive project (*"proyecto ejecutivo"*). In the case study, these two deliveries roughly correspond to the stages that we have proposed: concept design and design development. This is an approximated assumption. In fact, as often occurs in a real design process, formal deliveries and decisive moments of the design process are not fully coincident. For instance, the moment when a design solution is agreed with the client does not necessarily correspond to the legal delivery timing, as this moment is strictly related to the ongoing project circumstances.

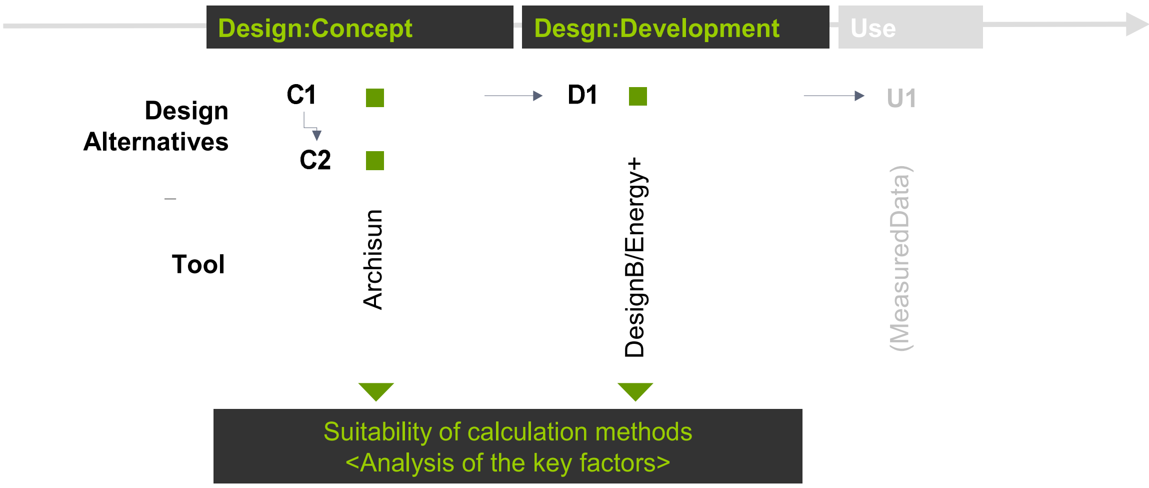

Figure 5.4. Overview of the design process. At each stage of design process a specific tool is used: two design solutions (C1-C2 and D1, respectively) are generated through the process and modelled with the corresponding tool.

At each design stage a different calculation tool is used to make energy performance predictions during the design process. In order to make reliable hypotheses on the tools used at each design stage, we interrogated five firms that make use of energy modelling tools, and we gathered information on their experience.

The detailed information gathered with the survey is reported in Annex 1.

According to the results, different firms use Archisun at initial design stages and DesignBuilder at final design stages. Based on these results, for the case study we assume that Archisun 3.0 is used at conceptual design stage stages and DesignBuilder v2.4.2.026 at final design stages.

The two tools that we have selected are based on substantially different calculation methods:

Archisun 3.0 (Serra, 2000) implements a simple energy calculation method that analyses thermal, lighting and acoustic comfort. It also quantifies energy demand for space heating and cooling and energy consumption for different uses. Thermal analysis at the core of the calculation method is based on periodic functions, and it enables modelling a single zone.

The calculation method is designed to enable the creation of a model by specifying a limited number of inputs (typically 10s-100s of inputs).

The outputs are provided for the whole building. Energy demand for space heating and cooling and consumption for different uses are calculated on annual base; for indoor temperature, average value and average daily variation for each season are provided.

DesignBuilder v2.4.2.026 integrates the detailed simulation engine of EnergyPlus v6.0 (U.S. Department of Energy, 2012), which encompasses thermal comfort and energy analysis. The original core of EnergyPlus is the thermal domain. However, it integrates other domains such as lighting, natural ventilation, moisture transfer. Energy analyses cover energy demand for space heating and cooling, energy consumption for different uses, primary energy and it is complemented by the calculation of emissions production. The tool performs the calculation for hourly or sub-hourly time steps. It also enables modelling multiple zones, many types of mechanical systems, and wide range of components and materials.

Compared with Archisun, DesignBuilder requires considerably more information to generate a model (typically 1000s of inputs).

In addition DesignBuilder outputs include a larger number of indicators. Each indicator is also provided in more detail: results such as temperature and loads are calculated for each time steps and are provided for each zone and system. Therefore, detailed comfort analysis based on hourly (or sub-hourly) temperature values may be elaborated. Likewise, space heating and cooling demand and energy consumption for different uses may be obtained aggregating results for the whole building (monthly or annually).

More extended descriptions of Archisun and DesignBuilder, including the underlying calculation methods, the inputs and the outputs, are reported in Annex 2.

At the conceptual design stage, we assume that the design team envisions many scenarios searching for a possible design solution. We focus only on two design alternatives: C1 and C2, which is a variant of C1. We assume that Archisun is used to predict their indoor temperature and space heating and cooling demand.

At the next design stage, we suppose that the solutions previously outlined at the concept design have evolved. We focus on the design solution D1, assuming that DesignBuilder is used to predict the hours of overheating and the space heating demand.

In this chapter we deal with the reconstruction of the process, while the extended description of the models of C1, C2 and D1 is reported in Annex 3.

The operational stage is not object of a detailed reconstruction in the case study. It is assumed that data from the real building may be acquired in order to verify the match between energy performance predictions from design stages and the actual energy performance.

5.4 CONCEPTUAL DESIGN

The reconstruction of the conceptual stage is reported in the following sections. In Section 5.4.1 the initial constraints of the project are described, and in Section 5.4.2, the design decisions considered at the conceptual stage are identified. Then in Section 5.4.3 we describe how project constraints and design decisions considered affect the definition of the energy model. In Section 5.4.4, all the above is contextualized in a segment of the design process extracted from the conceptual design phase, when design solution is generated and evaluated.

Constraints, design decisions, and modelling hypotheses are not results of a chronological sequence of steps: we assume that different design tasks within the design process are strictly interrelated and we admit the possibility that they may occur simultaneously or in aleatory order.

5.4.1 Project constraints at concept design stage

At the beginning of the concept design phase, the design team is able to formulate an initial view of the design problem, identifying the main constraints of the project: the building program (explicit expression of the client needs), the budget, the site conditions, the applicable regulation, and the design goals[4]. All these constraints are described in this section.

The building program consists of the following points[5]:

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[4] It is reliable that these constraints are initially defined at the beginning of concept design, and then are adjusted through the process. In fact, it may be necessary to redefine specific goals (including regulation requirements) after a design solution has been proposed (Cross, 2007, p. 100). The definition of some performance requirements is possible only after a possible design solution has been generated. For instance, in Spanish regulation, requirements for energy demand are established only if the design solution proposed has an opening ratio higher than 60% of facade area.

[5] Adapted from the executive project report (Frutos, 2006b).

- 24 social housing apartments for rent. One of them must be adaptable
- Two staircases
- Four apartments at each floor for each staircase, with maximum useful floor area 70m²
- Three rooms per apartment, with all rooms visitable
- Five people per apartment
- Commercial areas on the ground floor
- One underground floor for the garage

To realize the program, the public housing institute has a budget that is limited to 3.170.000 euro[6].

The main regulation constraints range from the urban plan (Ajuntament de Cerdanyola del Vales, 2005) to the technical regulations regarding construction (Ministerio de la Vivienda, 2006) and mechanical systems (Ministerio de la Presidencia, 2007). The local urban plan prescribes that the building has to be aligned to the street, lying on the east-west direction. From the street alignment a depth of 12 meters is admitted. The building height is limited to 4 floors. Instead, according to technical regulations, there are restrictions to the thermal characteristics of the envelope for the climate of Cerdanyola. They include minimum values for the facade U of 0.95 W/m^2K, roof U of 0.53 W/m^2K and windows U of 4.40 W/m^2K.

Also site conditions have to be considered by the design team. The building is located in the metropolitan area of Barcelona in Cerdanyola del Vales in a low urban density area a few kilometres from the coast. The site is in a new urban development and no buildings are expected to be erected on the south side. The absence of buildings is relevant for different design aspects: no shadow affects thermal and lighting conditions, and in addition, the view to the landscape is open toward the south.

Furthermore, the design team agrees the project goals with the client for different design aspects, including, among others, energy performance goals. In particular, these indicators are considered:

1. Indoor temperature
2. Space heating and cooling demand
3. Primary energy consumption

[6] Corresponding to the real project budget (INCASOL, 2007).

4. Energy cost

For the initial analyses conducted at the concept design stage, **no strict requirements are defined. Instead of absolute value limits, the design team decides to evaluate performance indicators in relative terms**, observing the variation of performance indicators between alternative design solutions[7].

Energy calculations are made with Archisun to assess the indoor temperature (point 1), and space heating and cooling demand (point 2). In particular, the design team observe the trend of the performance indicators when variations are introduced in the design solutions, so that they get some orientation for design decisions.

The design team chooses the tool based on the performance indicator to be assessed. In fact, with Archisun calculation method they may obtain indoor temperatures for typical days and annual energy demand for the whole occupied space.

5.4.2 Object of design decision at conceptual design stage

Along with other design decisions those affecting energy performances are considered by the design team. At conceptual design stage, the main decisions regard the building and the mechanical systems, while the building use related factors are not yet considered.

Most decisions are addressed at the level of the whole building to orient conceptual design strategies and not to establish detailed design specifications. At the start, the design team consider exploring many design options during the conceptual stage, which deals with[8]:

1. Building orientation, defined for the whole volume
2. Building shape, defined for the whole volume
3. Building envelope opening ratio, for the whole surface of each facade

[7] It often occurs in design practice that design goals are approximate and not strictly defined in terms of specified requirements (Cross, 2007, pp. 78-81).

[8] From the beginning of the concept design stage, the design team members have an idea of what the design decisions are about based on their previous experience. Nevertheless, the unpredictable evolution of the design process reveals the opportunity to consider important decisions that were not initially set out at this stage. The other way round, the design team realize that initial conditions are so constrained that some decisions they intended to consider are precluded a priori. To sum up, it is reliable that decisions at stake in concept design are adjusted through the process.

4. Building envelope and partitions characteristics (general U, g-value, etc. for whole envelope)

5. Mechanical systems' types, for heating, cooling and domestic hot water

6. Mechanical systems to generate renewable energy in-situ

7. Outdoor environment – in particular, the arrangement of the exterior space.

Among the numerous design decisions considered at the conceptual design stage by the design team, we will focus on one of them, analysing how **energy calculation is used to inform the decision on the envelope opening ratio**. In particular, we will observe how the design team use Archisun to know the effect of envelope opening ratio on building performances.

5.4.3 Representing the design scenario through the energy model

During the conceptual design stage, different design scenarios envisioned by the design team are represented through energy models. In this section we focus only on two variants of a same design scenario, corresponding to the design solution C1 and its variant C2. In particular, we make explicit, to some extent, the relation, largely implicit for the design team, between a design scenario and its energy model.

This relation is established by the energy assessor who translates the project constraints such as building use and site conditions to specific boundary conditions for the Archisun model. C2 is a variant of C1 in which most of the design scenario remains the same, so that, the boundary conditions of the model are common for the two alternative design solutions modelled.[9]

When the energy assessor sets up the model, boundary conditions are necessarily fixed for all the variables that are given by the project constraints (for instance, the climate is given by the site). In addition, the energy assessor deliberately fixes boundary conditions for the design variables that are not

[9] This is a simplification of the design problem evolution. In fact, the design problem and solution usually evolve together through the design process (Cross, 2007; Lawson, 2005), as verification of design hypothesis often impose to adjust or even redefine the design problem including the goals and constraint initially defined. So it is reliable that hypothesis for energy calculation are adjusted through the process during the concept design phase. We assume that this simplification is acceptable, as our reconstruction of concept design stage is restricted to only two close variants of the same base solution, and to a short segment of the design process.

object of decisions at this stage, for example the building operation.[10] Then, in Figure 5.5, outdoor environment data (C) about the climate and the building surroundings are fixed, being in a large extent given by the project constraints. The user related factors such as building operation (O) are also fixed, not being object of decisions at this stage. On the contrary, global characteristics of the whole building (E_{glob}) and the main mechanical systems (S_{glob}) are open to design decisions.

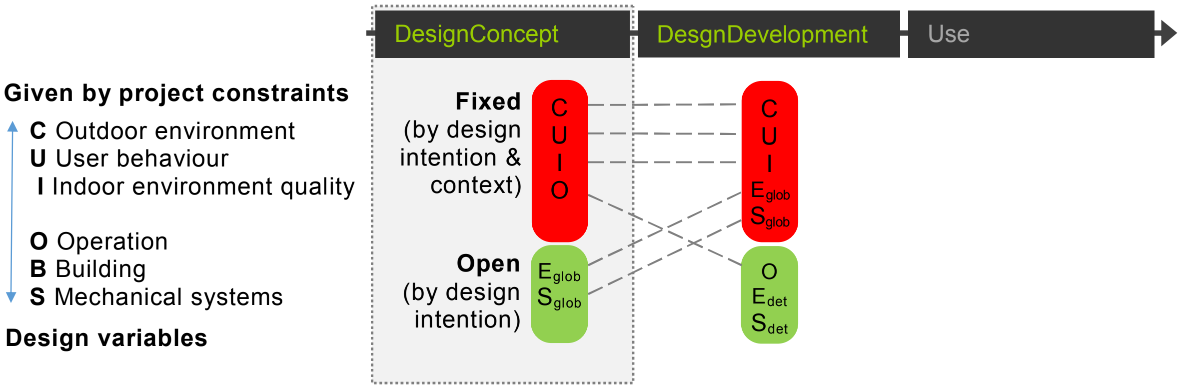


Figure 5.5. Boundary conditions are fixed by the design team for the concept design. Open design decisions mainly regard the global characteristics of building (E_{glob}) and its mechanical systems (S_{glob}).

Likewise, the calculation tool imposes restrictive assumptions and boundary conditions for some of the variables affecting energy performance. These boundary conditions do not necessarily match the boundary conditions the designer would like to assign. At this point, the choice of the tool is fundamental.

The tool chosen by the design team is Archisun, described in Annex 2.

The choice is done in a way that the boundary conditions imposed by the tool were coherent, as far as possible, with the boundary conditions they want to define. In that way, restrictive conditions of the tool do not impede the designer to explore open design variables. For instance, comfort set points temperatures, which are imposed by Archisun for energy demand calculation, coincide with the boundary conditions that the design team intends to fix at this stage of the project. In fact, the design team has no intention of exploring alternative set point temperatures and they postpone the possibility to decide on building operation strategies to later design stages.

[10] Within the variables influencing energy performances, distinction has been made in Chapter 3 between those given by project constraints and those corresponding to design variables.

In Table 5.1, the Archisun inputs are shown in relation with the designers' intention: on the left a summary of the values assigned in Archisun for boundary conditions is reported; in the following column, the parameters that may be manipulated through the tool inputs are indicated; then, designers' intention (to open or fix variables) is expressed.

Table 5.1. The values assigned to the boundary conditions in Archisun are summarized. The column Tool input shows if the modelling data are tool inputs editable by the designer, or parameters constrained by the tool. The column Design wish shows if the intention of the designer is to edit/modify the data (to explore design solution) or to fix them. Besides, the column Design variable specifies if the data correspond to design variables or are given by project constraints. Variables in red are constrained by the tool (Tool input: No) or by the designer intention (Design wish: Fix). Variables in black are constrained neither by the tool nor by the designer intention (Tool input: Yes and Design wish: Open).

Archisun modelling data			Tool Input [Yes/No]	Designer wish [Open/Fixed]	Design Variable [Yes/No]	Notes
OUTDOOR ENVIRONMENT (C) (1)						1: limited options constrained by the tool
Map position	-		Y	F	N(2)	2: given by project constraints (site)
Height over sea level	105	m	Y	F	N(2)	3: taken by tool library / manual input
Urban density	0,7	-	Y	F	N(2)	
..Climate data	-		Y-N(3)	F	N(2)	
..Existing surroundings data	-		Y	F	N(2)	
..New surroundings data	↔		Y	O	Y	
BUILDING (E)						1: it includes only apartments
Volume (1)	4536	m^3	Y	F	N(2)	2: given by project constraints (program prescription:
..Shape data	↔		Y	O	Y(3)	1680m2 useful floor * 2.7m useful internal height)
..Envelope data	↔		Y	O	Y(3)	3: variable range restricted by project constraints
..Interior data	↔		Y	O	Y(3)	(regulation)
MECHANICAL SYSTEM (S)						
..system efficiency data	↔		Y	O	Y	
USER RELATED FACTORS (U,I,O) (1)						1: limited options constrained by the tool
Maximum occupancy	120	pp	Y	F	N(2)	2: given by project constraints (program prescription:
Building use	permanent		Y	F	N(3)	5people * 24flats)
Temperature set point	f(t)	ºC	N(4)	F	Y-N	3: given by project constraints (program prescriptions)
..Ventilation setting data	-		N(4)	F	Y-N	4: imposed by the tool Archisun

From Table 5.1, we can observe that, for all open variables that the designer intends to explore, editable inputs are provided by the tool (whenever Design wish is Open, Tool input is Yes).

We make some further observations to explain how the tool restrictions match with designer intentions. A complete description of the model created by the energy assessor is provided in Annex 3.

At the moment, the design team intends to explore the building whole shape, without concerns about the internal space organization. For thermal analysis, they intentionally treat the building space destined for residential use as one single homogeneous volume without differentiating separate residential spaces and their specific conditions. The Archisun calculation method matches with this initial abstraction of the design scenario. It allows modelling only one single zone, approximating the indoor conditions with homogeneous values for the whole volume and neglecting heat exchanges between different spaces inside the analysed volume.

For indoor spaces adjacent to the analysed volume, the tool imposes the environmental conditions: they are intermediate between the analysed volume and outdoor conditions. This assumption is in accordance with the designers' intention. In fact, they consider the supposition an acceptable approximation at this stage for staircases and commercial areas that are adjacent to the analysed volume, because at the moment these spaces are marginal in the design proposal and are not object of thermal analysis.

Then, the designers fix the volume input for the analysed spaces that include only residential spaces out of the whole building. The value is determined according to the project constraints established in the building program. In fact, the energy assessor deduces the useful volume[11] (4536 m^3) taking the prescriptions of the building program[12], and assigns this value to the *"volume"* input of Archisun.

The other variables regarding the building and mechanical systems are open to explore different design possibilities, in conformity with regulation constraints. They can be reproduced and edited in Archisun (with the inputs of shape data, envelope data, interior data and systems efficiency data, in Table 5.1). For the envelope, the characteristics of opaque and transparent surfaces may be assigned separately by orientation and condition of adjacency (to the exterior, the interior or the ground). The tool does not provide the possibility to describe individual elements of the construction or individual layers. This suits the necessity of the design team that has no intention of deciding on component details at this stage.

The designers fix the tool inputs of position map, altitude and urban density (Table 5.1), which are given to them by the project constraints of the building site. The inputs of Archisun to model surroundings' elements (in Table 5.1) enable the design team to represent existing buildings and vegetation and

[11] The useful volume corresponds to the air volume inside the building: it excludes partitions inside and between apartments, structure, floors and technical spaces.

[12] The value of the useful volume is deduced in function of program prescriptions - 24 apartments, with useful floor area of 70m^2 for each one - assuming internal floor height of 2.7m.

explore different possibilities to accommodate the building site, for instance, by planting new trees.

The assumptions on user behaviour and indoor environmental conditions are affected by projects constraints: they depend on the residential use established in the building program. The building operational settings instead are design variables, but the designers decide to fix them. At this stage in fact, control strategy is not an object of design decisions. Therefore, all variables related to the user (user behaviour, indoor conditions and operation) are fixed at this stage. The possibilities offered by Archisun to model user related factors are quite restricted. The energy assessor expresses these conditions through the input *"building use"*. Among limited list of values he chooses the option, *"permanent"* (Table 5.1). Then the tool, based on this input value, assigns a set of default values for each day of a representative week. Such tool constraints on detailed use parameters fit well with the design team intention to constrain the control strategies for the building operation.

5.4.4 Generation and evaluation of concept design alternatives

In this section we present a chronological reconstruction of the design process. We take in to account the time pressure that limits the design process and we stress the frequent shift among different design aspects that characterizes the design activity. To reproduce these circumstances we avoid recreating a design process with deep energy analyses of a wide range of alternatives, which is not realistic in current design practice. The focus is not on energy analysis in itself, but on how energy calculation is used by the design team through the design process.

The reconstruction provided in this section is limited to a segment of the concept design stage in which the design team joins for a work session (Table 5.2).

It is admitted that a large number of alternative solutions are explored by the team during concept design, but in the short segment examined, only the design solutions C1 and its further modification in another solution C2 appear. In the limited interval of time considered just one of the decisions that we have identified is involved: the definition of the building envelope opening ratio. Likewise, only some of the performance indicators addressed at this stage are involved: indoor temperature and space heating and cooling demands. These indicators are calculated with Archisun.

Segment of the design stage

Alternative design solution	Design decision	Performance indicator	Use of Archisun
	Building orientation		
	Building shape		
C1, C2	Building envelope opening ratio	Indoor temperature Space heating and cooling demand	← ←
...	Building envelope and partitions characteristics	Primary energy consumption	
Cn	Mechanical systems (heating, cooling, hot water)	Energy cost	
	Mechanical systems - in-situ renewable	Embedded energy	
	Outdoor environment - exterior space		

Table 5.2. Reconstructed segment of the concept design stage.

During the work session the design team has an open discussion supported by real time analyses, combining quantitative analyses and qualitative considerations. Energy analyses made with Archisun involve the creation and repeated modifications of the model.

This is the very beginning of the design process and they make initial explorations: they start outlining some rough solutions which help to identify important aspects for the project (such as energy, comfort and cost) and analyse them. They want to get a quick overview of these aspects and advance rapidly through different design alternatives, instead of spending much time on one. So, **the design team needs just rough evaluations to support the discussion during the work session. Their analyses are necessarily limited to few performance indicators and they are not pretended to be fully exhaustive.** For the thermal analysis, they mainly consider space heating and cooling demand. The analysis of indoor temperatures is limited at this stage to a simple evaluation of seasonal average values.

At the beginning of our chronological reconstruction, the design team makes initial considerations on multiple aspects (such as the urban regulation constraints, the access to the apartments and the local climate) and starts to outline the solution C1.

The projects constraints and an initial solution are progressively represented through an evolving sketch. The urban plan is, for the design team, the starting point for the concept formalization. Given the floor surface of the building, urban plan significantly limits the design decisions regarding the building orientation and building shape. Therefore, the designers define the form and position of the whole building volume in the project site very early in the process. The resulting building shape is a narrow compact parallelepiped. Its dimensions are strictly conditioned by the limits of 12 meters depth from the main alignment and of 4 floors' height. The orientation of the building mainly facing North and South is defined by the designers in conformity with the prescribed alignment with the street.

Then, the designers consider the access to the building from the public space. They discuss whether to use the typical solution of this region with the stairs internal to the building fabric[13]. With this configuration some apartments would have only one external facade. This suggested the designers to adopt, instead of the traditional stair case, an external access system to assure two external facades for each apartment.

During the work session they agree that this solution with narrow layout and double exposition for each apartment seems to simplify the resolution of various aspects of the design problem. The linear configuration of the volume enable a uniform solution for all apartments under different aspects: all apartments are exposed to similar conditions to exploit solar radiation and ventilation, so that similar thermal performance may be achieved; they may enjoy similar views to the exterior; and the same internal distribution may be replicated. This uniformity allows providing apartments with the same level of quality for all tenants. In addition it simplifies the design and construction process. In fact it fosters the design of uniform constructive solutions that reduce complications and costs, both in design and construction. The design team considers the idea of providing external access to the flats with a continuous balcony on the north facade. The idea raises conflictive issues associated to other design aspects, specifically privacy and security of tenants, which are questioned within the design team.

In this moment, the design team decides to deepen a design aspect that previously emerged through the design process, the thermal performance. In particular they intend to analyse the energy demand for space heating and cooling and the indoor environmental conditions. In fact, the concept solution generated so far requires special attention to the facades (with large south and north surfaces), and they consider it necessary to explore and evaluate the relation between transparent and opaque surfaces of envelope. According to the designers, an appropriate relation could be decisive for the thermal performance of the building. In particular, some questions arise: which is the trend of variation of heating and cooling demand with the variation of opening ratio? Do thermal gains prevail over losses in winter, by increasing the opening ratio? And how is it in summer? The experience of the design team is insufficient to formulate clear answers; therefore they resort to Archisun to

[13] Examples of this kind of solution may be observed in the collection of projects reported by Trilla (2006), the social housing department of the Barcelona municipality.

perform energy calculations. They expect that the results of energy calculations will help them to formulate these answers.

At this moment of the process, designers start modelling the concept solution with Archisun (Table 5.3). The boundary conditions (building location, volume, building use and so on) are introduced in the tool. Then, the description of the design solution is completed with the other input data to represent all design variables necessary for the calculation (as thermal properties and geometry of the building envelope). To create the model in Archisun the energy assessor only needs to describe the main parts of the building envelope without details and without defining the internal space organization. With this, the number of inputs introduced is limited to about 100. In that way, the time needed to crate the model is limited. The model created so far with Archisun to analyse the current design solution is described in detail in Annex 3.

Table 5.3. Synthesis of inputs of the Archisun model.
(The extended description of the inputs is reported in Annex 3)

OUTDOOR ENVIRONMENT (C)

Location

BUILDING (E)

Volume	4536 m^3

	Opening ratio (south)
C1	15%
C2	45%

	U W/m^{2}K
Facade	0.95
Roof	0.53
Floor (adjacent to interior space)	1.30

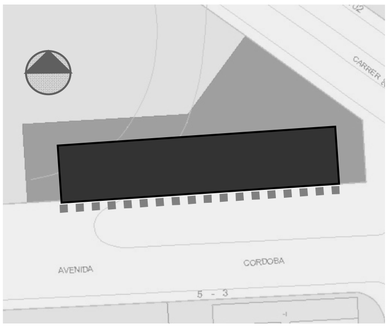
	U W/m^{2}K	Transparence (0-1)
Windows	4.40	0.55
Solar shading devices	Fix + movable	

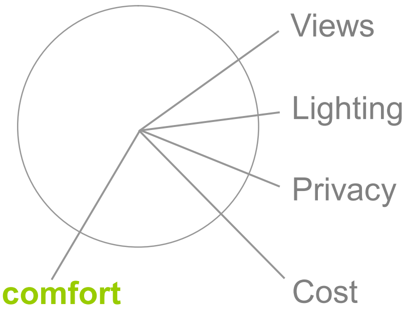
USER RELATED FACTORS (U,I,O)

Maximum occupancy	120 persons
Building use	Permanent residential
Heating set point temperatures	Variable in time (non-editable parameter)

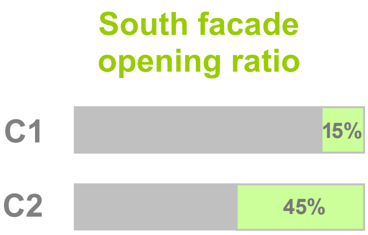
Nº inputs specified by the user	~100

Building envelope is initially characterized by 15% windows opening ratio in the south facade (C1). Then the ratio is gradually increased up to 45% (C2), to explore the effect on the performance. Average temperatures remain nearly the same, only the peak temperatures in summer days are more pronounced. The design team focuses on the energy demand. The calculation shows them irrelevant variations on space demands for heating and for cooling (less than 5% for both indicators, in Figure 5.6).





Energy & Indoor comfort



	Archisun output: Space demand [kWh/m³·y]		Indoor temperature in Winter [°C]		Indoor temperature in Summer [°C]		Cost	
	Heating	Cooling	Ti	dTi	Ti	dTi	Facade cost [€]	Budget fraction
C1	9.10	3.63	11.9	1.1	28.2	8.6 (23.9-32.5)	90 000	3%
	+4%	+0%						+2%
C2	9.50	3.62	12.0	1.2	28.1	10.6 (22.8-33.4)	140 000	5%

Ti seasonal average of indoor temperature without mechanical cooling
dTi seasonal average of daily swing of temperature without mechanical cooling

Figure 5.6. Effect of opening ratio on the building performance. The design team focuses on space heating and cooling demand. The design decision on the opening ratio requires evaluating energy demand along with other aspects such as cost, lighting, privacy and views.

To gain confidence in the model correctness, they test what happens when applying the 45% opening ratio to all facades. As expected the heating demand increases substantially (30% higher). Then, the designers turn back to C1 and C2, and observe the main heat gains and losses to better understand why south facade opening ratio has little influence on heating and cooling demands. By increasing the opening ratio, the consequent increment of solar gains is balanced by the increment of thermal losses. That occurs both in the winter, with the increment of transmission losses, and in the summer, with the increment of ventilation losses. At that point, the designers have confidence in the model and better insight into the behaviour of solution C1 (and C2). Therefore, they realize that this configuration seems to allow playing with opening ratio on the south without substantially compromising the heating and cooling demand. However they identify the problem of summer overheating, accentuated when the opening ratio increases to 45%.

To make a brief and comprehensive evaluation of this design decision possible, they have to postpone more detailed energy and comfort analyses and consider other essential aspects of the project. So they consider the effect of the opening ratio from a different perspective, shifting the attention to cost, lighting, privacy, external views and usability of the space (Figure 5.6). Cost represents a primary concern. A rough estimate of the cost of the total windows' area in the south facade shows that impact on the whole project budget is very limited[14]. Also providing the tenants with a pleasant space to live in is fundamental for the design team. They consider that limiting the openings on the north side, facing external access, and putting large openings to the south would be advantageous. They would provide an open view to the landscape and more direct sunlight inside rooms in winter. They also contemplate private balconies on this side, which may be exploited by tenants. Large openings may be combined well with private balconies. With large openings, in fact, flats' interior gains a visual and physical connection with exterior spaces of balconies. So space usability for tenants is enhanced and the limited area of the flats extends outward to balconies. At the same time the balconies provide a visual and physical filter protecting the privacy of flats from the public street.

The design team is more inclined to increase the opening ratio (solution C2), giving priority to the usability of space and the views, because they consider it important to offer a pleasant space for tenants. However they intend to revise overall design solution to enhance the comfort conditions.

In sum, the design team has so far combined energy analysis, made possible by Archisun, with other kinds of considerations. Thanks to energy calculation results, they understand more about the impact of the decision on energy and comfort. In that way, they are better informed to get an approximated but comprehensive view of the main aspects affected by their decision. So they are more prepared to decide on the opening ratio.

With the limited details of Archisun inputs and outputs the process described - the modelling process, the results' visualization and interpretation- are relatively simple and rapid for the design team. This facilitates the evaluation of energy performance together with other aspects affected by the opening ratio (such as cost, lighting, privacy, external views and usability of the space). With this tool, the consideration of all these aspects is made possible within a single work session.

Based on the reconstruction of the conceptual design stage, in Section 5.6 we are going to consider in more detail the tools features and how (and how far) they satisfy the necessities of the design team for this stage.

[14] The estimation of construction cost is inclusive of direct costs and the profit of contractors. Based on experience the design team assumes a price of 400€/m^2 for windows and 100€/m^2 for the wall. The prices are an approximation of those provided by the BEDEC prices' database of Catalonia (ITeC, 2014). The result is calculated for a south facade area of 600m^2 approximately.

5.5 DESIGN DEVELOPMENT

We have so far reported the reconstruction of the conceptual design stage. We report the reconstruction of the design development stage following an analogous structure. In Section 5.5.1 the constraints of the project are described, and in Section 5.5.2, the design decisions considered at the development stage are identified. Then in Section 5.5.3 we describe how project constraints and design decisions considered affect the definition of the energy model. In Section 5.5.4, the description provided is contextualized in a segment of the design process extracted from the design development stage, when design solution is generated and evaluated.

5.5.1 Updated project constraints at design development stage

Throughout the design process the project constraints we have described for the concept design phase have been evolving. Therefore, at the design development phase the design team partially redefine constraints: the building program is updated; the current design solution has developed according to the program; new site conditions and applicable regulation applies; and also the design goals are revised[15]. All these constraints are described through this section[16].

The program of the project during the design process undergoes some changes from its precedent formulation at the conceptual design stage and it is updated. In particular, it is decided that the two stair cases have to be separated and independent[17].

Throughout the design process the program of the project has been transposed to the design solution that is now already largely defined in its main features (from Figure 5.7 to Figure 5.9). These features, compared with the initial program, provide much more specific constraints for the design development. In fact, several design decisions have been taken since concept design stage. During the project the initial solution proposed at the concept design phase for the access to the apartments from the exterior by a continuous balcony in the north facade was discarded. In consideration of

[15] Design goals are revised at the each design stage according to the model of the design process defined by INTEND (2009).

[16] Although the design problem is more defined at this stage of the process, it is still under evolution. Therefore, also at design development stage it is reliable that the conditions described in this section are initially identified by the design team, and then adjusted throughout the design development.

[17] This restriction is inspired to the actual project, according to the affirmations of interviewed practitioners and the executive project report (Frutos, 2006b).

security and privacy aspects, the client preferred a conventional solution of two independent staircases internal to the building. Accordingly, the program of the project is adapted adding this restriction for the access to the apartments.

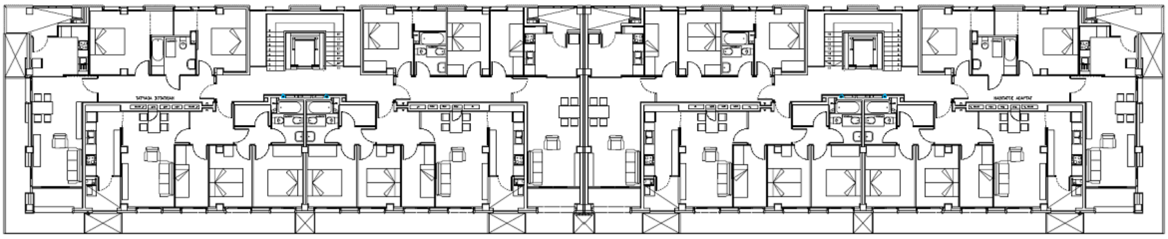
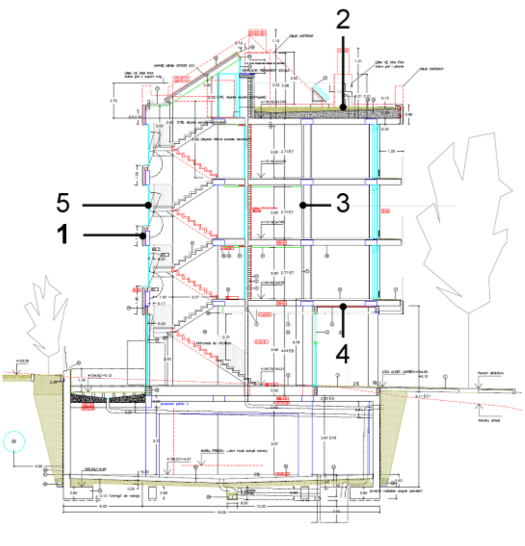


Figure 5.7. Plan of the 3th floor (adaptation of the real project, Frutos, 2006a).

Figure 5.8. South facade (adapted from: Frutos, 2007a).

Figure 5.9 North facade (adapted from: Frutos, 2007a).

At this state of the design process, the design solution defined is an elongated compact block of four floors, plus one underground floor for the garage. The block is organized in two symmetric parts. Each one is provided with an independent hall and staircase as prescribed by the program. The first, second and third floors, where the apartments are located, have the same internal distribution. Two apartments' layouts are defined: rectangular-shape (R), facing south, and L-shape (L), with north and south facades. In turn, L is divided in two types: those positioned between other apartments (Li), and those at the extremity of the block (Le), having a third facade exposed to the exterior. On top of the third floor there is a flat roof. Each staircase gives access to the flat roof and to a space dedicated to technical systems, located at the same level. The south, east and west facades are characterized by a uniform solution. In these facades all apartments are provided with long semi-continuous balconies and all openings are French windows. The north facade is provided with smaller openings and overall windows' surface is also smaller. Openings are homogeneously distributed according to a regular grid. The construction components are defined as indicated in Figure 5.10. The facade is made of concrete panels with internal insulation. The flat roof is made of concrete, with cellular concrete insulation. Inside the apartments, rooms are separated by lightweight partitions made of gypsum panels. The construction system of internal floors consists of concrete slabs. The windows have double glazing and aluminium frames with thermal brake.



1. **Facade: concrete with internal insulation**
2. **Flat roof: concrete with cellular concrete insulation**
3. **Lightweight partitions: gypsum panels**
4. **Internal floors: concrete slabs**
5. **Windows: double glazing and aluminium frames with thermal brake**

Figure 5.10. Cross section of the building (adapted from: Frutos, 2007b).

At the design development stage, some of the site conditions considered at conceptual design stage have changed. In fact, the construction of new buildings in front of the south facade was approved by the municipality. This change affects different design aspects. In fact, the environmental conditions change as the shadows of new buildings may affect thermal and lighting conditions and in addition the presence of neighbours affects acoustic levels and privacy. Perceptive conditions also change, as the views on the landscape are reduced by the volumes of new buildings.

Furthermore, the design team revises the project goals with the client, considering several design aspect. Design goals concerning the energy performance are expressed at this stage with more precision, by establishing more specific performance requirements.

First, performance requirements established by the design team for building components must be verified. The current design solution is based on some parameters that the design team previously established, such as the U of the envelope components.[18] Once established, such parameters became performance requirements. Therefore, during design development, when the precise assembly of layers is going to be decided, they aim at achieving these U values[19]. Performance requirements for envelope components are indicated in Table 5.4.

Table 5.4. Indicators and requirements: envelope components performance

	Requirement
1. Average U of each facade and the roof	</= 0.40 W/m²K
2. Average U of windows	</= 2.70 W/m²K
3. Average g of windows	</= 0.60

Also energy and indoor environment performance of the whole building have to be satisfied by the current design solution, as it occurred in the previous design phase[20]. The design team considers different performance indicators and for some of them they establish specific values as performance

[18] It is assumed that building components characteristics have been specified in the project documents delivered at the end of the concept design.

[19] The progressive definition of performance requirements throughout the design process reflects the theoretical schema proposed by Spekkink (2005): at each stage of the design process more specific performance requirements are generated by developing the design solution, and then, at the next step, when the design solution has evolved further, these requirements are verified.

[20] A similar schema to the one proposed by Spekkink (2005) is reproduced: with the transition from a design stage to the next one, building performance requirements are verified again, in addition to new performance requirements for separated components.

requirements (Table 5.5). Considering the budget of the project the design team does not establish very ambitious requirements.

Table 5.5. Indicators and requirements: comfort and energy performance of the building and the mechanical systems.

	Requirement
4. Indoor environmental comfort by zone	
Hours of overheating in summer	Operative temperature may overcome 30°C for a maximum of 5% of occupied hours ([21])
5. Energy demand for	
Space heating	</= 45 kWh/m^{2}a ([22])
6. Energy consumption by energy carrier for	
Heating (gas)	no value established as requirement
Domestic hot water (gas)	no value established as requirement
Lighting and appliances (electricity)	no value established as requirement
7. Renewable energy generation in situ	
Solar thermal for domestic hot water	</= 60% of Energy Demand for domestic hot water
8. Primary energy consumption for	
Heating, domestic hot water, lighting and appliances	</= 145 kWh/m^{2}a

The set of indicators to be verified was not decided at the beginning of conceptual design and so established for all the process. On the contrary, the identification of such indicators is a result of the process. In fact, their definition was conditioned by the design decision taken during the design

[21] The design team chooses European standards as a reference. prENrev 15251:2006 (E) proposes a maximum period of 5% of occupied hours out of Operative Temperature limit. The standard, suggests Operative Temperature limit in function of Outdoor Temperature. The norm proposes alternative levels of comfort for the specification of requirements. The strictest requirement limit in the norm is $T_{i\ max} = 0{,}33\ T_{rm} + 18{,}8 + 2$. In this formula, $T_{i\ max}$ is the limit value of indoor operative temperature and T_{rm} is the running mean outdoor temperature. This limit applies when $10 < T_{rm} < 30$ ºC. For simplification designers assumes $T_{rm} = 27$ ºC, resulting approximately a limit of 30 ºC.

[22] The value is an approximation of the requirement established in the real project (GEUMA, 2007).

process. In particular, during the conceptual design the use of mechanical cooling was excluded from the proposed design solution. At the design development stage, the designers consider it necessary to verify if this hypothesis is still valid. To do that, detailed indoor environmental comfort conditions become a fundamental incognita, which the energy assessor carefully evaluates by assigning specific requirements and then verifying them. Instead, cooling demand and consumption are omitted from the indicators analysed at this stage, because the design option of mechanical cooling was previously excluded.

Compared with the precedent design stage, the design solution is now quite defined and it is possible to make a more reliable prediction of indoor space conditions. Indoor conditions as the operative temperature may be calculated with higher temporal and spatial resolution: by hourly values and for multiple zones. As more reliable predictions are possible, the definition of design requirements may be more strict and precise, and for some requirements specific target values are fixed (Table 5.5). Verifying precise targets serves to give the client a better assurance on the quality of the project when the design process is getting to the end.

At this stage, the design team has recourse to detailed dynamic simulation with DesignBuilder as quantification method to assess summer overheating (point 1) and space heating demand (point 2). Based on the results, energy consumption, renewable energy generation and primary energy consumption are also evaluated.

Dynamic simulation is used in order to highlight the trend of the performance indicators with the variation of design solutions, so as to support design decisions. Additionally, simulation is used at this design stage to verify the compliance of specific values for some performance requirements (specified in the table).

The tool is selected mainly according to the performance indicators to be assessed at this stage and the accuracy needed to verify specific values. In fact, the calculation method implemented within DesignBuilder provides outputs required with level of time and space resolution demanded for the evaluation. It calculates temperatures with hourly resolution and for each zone, and it also provides space heating demand for each zone. The calculation method delivers quite accurate results when precise inputs are available.

Nevertheless, we will show later that several other factors have great importance in relation to the choice of this calculation method. We will highlight how they affect the evolution of the design process.

5.5.2 Object of design decision at design development stage

Also at the design development stage the design team considers some design decisions that affect energy performances of the building. The decisions contemplated at this stage are not limited to the features of the building and the mechanical systems, but also regard their operation. Provided that the main features of the design solution are already defined, most of these decisions concern design details and specifications. In particular, the design team decides on:

1. Specific solutions for building components (characteristics of layers of facades, slabs and roof; details of the windows' including glazing, frames and solar protection devices)
2. Specific solutions for mechanical systems for heating and domestic hot water (characteristics of the components of secondary systems, and plants)
3. Mechanical system used for space cooling (confirm the decision to exclude mechanical cooling)
4. Operation of the building and the mechanical system, by setting specific control strategies

The design team uses energy simulation to evaluate the decision to exclude mechanical cooling. In fact, at concept design stage, the design team assumed that no mechanical cooling system would be adopted. At current design stage in turn, the design solution is more developed and much more information exists, and then, they intend to verify their initial hypothesis of excluding mechanical cooling. They establish that, in case of excessive overheating, they will consider refining the design of building components and the control strategy, in order to improve the design solution.

Among the design decisions considered at this stage by the design team, we will focus on one of them, analysing how energy calculation is used to decision on the mechanical cooling.

5.5.3 Representing the design scenario through the energy model

The design scenario currently developed at the design development stage is represented by the design team with the energy model. In this section, we make the relation between the current design scenario and its energy model explicit. As occurred in the precedent stage, the design team translates the project constraints to specific boundary conditions of the DesignBuilder model. The project constraints that affect the creation of the model at this stage are not limited to the site conditions and the building use, but they also result from the design solution so far consolidated.

As represented in Figure 5.11, external project constraints determine, to a large extent, some of the variables that influence energy performance, namely the outdoor environment (C), the user behaviour (U) and the indoor environment quality (I). Such parameters were given at the conceptual design and they remain unchanged at the design development stage. The energy assessor has to fix the boundary conditions that define these parameters in the model, as already occurred at the conceptual design stage. In addition, most global features of the design solution, such as building geometry, have already been decided at the concept design stage, and now the energy assessor needs to fix them when creating the model. The design team wants to decide instead about more specific details of building (E_{det}) and mechanical systems (S_{det}), and then, they intend to leave these variables open when they start creating the model. Operational settings (O) were fixed at the conceptual design stage; now instead, the design team intends to also decide upon them.

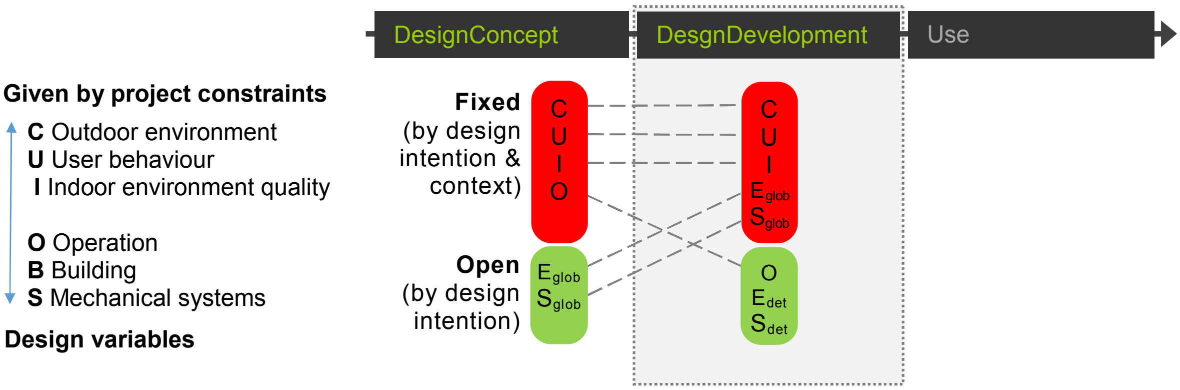


Figure 5.11. Boundary conditions are fixed by the design team for the design development stage. Open design decisions mainly regard detailed characteristics of building (E_{det}) and its mechanical systems (S_{det}), and the building operation (O).

We have described above the variables of the energy performance that the design team needs to fix as boundary conditions of the model and those variables they intend to leave open in order to test possible design options. Also the calculation tool they are going to select to create the model may impose some restrictive calculation hypotheses and boundary conditions. The design team needs a tool which prevents these restrictions by allowing them to properly represent fixed conditions, and to explore and model open design variables.

The energy assessor selects DesignBuilder, which is described in Annex 2.

In Table 5.6, the DesignBuilder inputs are shown in relation to the designers' intention: on the left the main boundary conditions in DesignBuilder are indicated; in the following column the designers' intention is expressed.

Table 5.6. The values assigned to the boundary conditions in DesignBuilder are summarized. The column Tool input shows if the modelling data are tool inputs editable by the designer, or parameters constrained by the tool. The column Design wish shows if the intention of designer is to edit/modify the data (to explore design solution) or to fix them. Besides, the column Design variable specifies if the data correspond to design variables or are given by project constraints. Variables in red are constrained by the tool (Tool input: No) and/or by the designer intention (Design wish: Fix). Variables in black are constrained neither by the tool nor by the designer intention (Tool input: Yes and Design wish: Open).

DesignBuilder modelling data		Tool Input [Yes/No]	Designer Wish [Open/Fixed]	Design Variable [Yes/No]	Notes
OUTDOOR ENVIRONMENT (C)					
Location	Bcn Airport	Y	F	N(1)	1: given by project constraints (site)
…Climate data	-	Y-N	F	N(1,2)	2: taken by tool library / manual input
…Existing surroundings data	-	Y	F	N(1)	3: already decided
…New surroundings data	-	Y	F	Y(3)	
BUILDING (E)					
…Geometry data of each zone	-	Y	F	Y(1)	1: already decided
…Geometry data of each opening	-	Y	F	Y(1)	2: such as balconies
…Geometry data of each obstruction (2)	-	Y	F	Y(1)	3: initially assumed by default
…Layers details of each component	-	Y	O	Y(3)	
…Windows glazing & frames details	-	Y	O	Y(3)	
Flats partitions properties :	adiabatic	Y	F	(1)	
…Type & properties of blinds	↔	Y	O	Y	
MECHANICAL SYSTEM (S)					
…Heating system specifications	↔	Y	O	Y(1)	1: not applicable in the model of D1
…Cooling system specifications	↔	Y	O	Y(1)	
USER RELATED FACTORS (U,I,O)					
…Occupancy data by zone	-	Y	F	N(1)	1: given by project constraints
Heating setpoint temperatures	↔	Y	O	Y-N(2)	(program prescription: zone functions)
Cooling setpoint temperatures	↔	Y	O	Y-N(2)	2: not applicable in the model of D1
...Solar shading control settings	↔	Y	O	Y-N	3: limited by project constraints (ventilation
...Ventilation control settings	↔	Y	O	Y-N(3)	range limits are imposed by regulation)

From Table 5.6, we can observe that, for all variables that the design team intends to open or fix, editable inputs are provided by the tool. The tool provides flexible inputs to model the boundary conditions they intend to fix. And more importantly, it is widely flexible to define with enough precision the building components and operational settings that the design team intends to explore at this design stage.

Hereafter, we explain in some detail how the design scenario is represented throughout the model. A complete description of the model created by the energy assessor is provided in Annex 3.

The outdoor conditions are constrained by the project site. To represent them the energy assessor introduces the location input into the model. He assumes, as an approximation, the location of the Barcelona Airport available in the library of the tool, which associates the location input with detailed (hourly) climate data series for one year.

Currently, the design team has already decided the internal distribution of different spaces and functions inside the building for each apartment. To simplify the modelling process (the model edition, the calculation process and the interpretation of results), it is decided to analyse only one apartment. They select one of the most exposed to outdoor conditions: the dwelling on the east extremity (Le) in the upper floor of the building. In addition to the south and north facades, the flat is also contiguous to the east facade and the roof, therefore it is more affected by the outdoor temperatures and intense solar radiation in summer. They decide to ignore the heat exchanges with adjacent apartments and staircase, in this way reducing the complexity of the analysis. With this assumption they can model only that apartment, ignoring other thermal zones of the building. In physical terms, that involves assuming that the partitions between apartments are adiabatic. The approximation of the physical behaviour of the building that the energy assessor intends to adopt can be properly represented by the tool (Figure 5.12). In fact, the tool is flexible in representing the envelope components according to different input options including adiabatic surfaces.

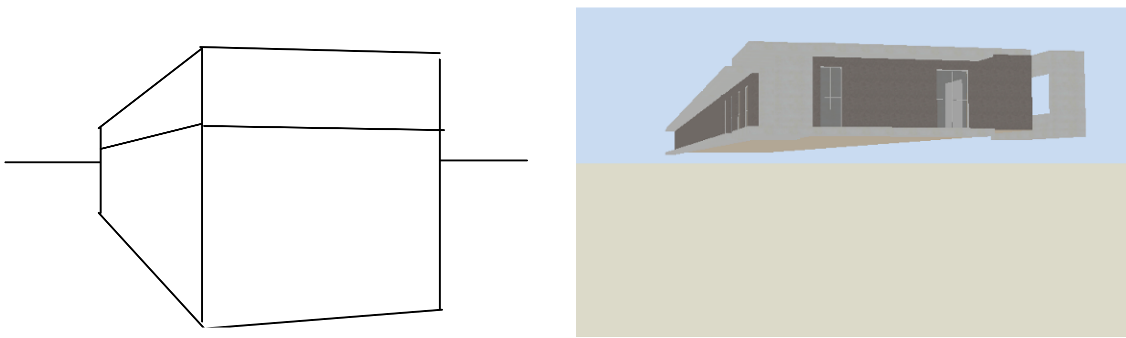
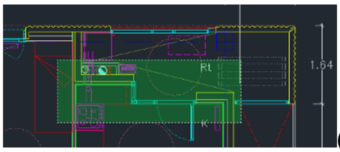


Figure 5.12. On the left, a sketch of the building volume is shown. On the right, a view from DesignBuilder shows the building abstraction made by the designer with the energy modelling tool. Only the elements of the design scenario which are required for the specific performance analysed are modelled: the apartments on the upper floor exposed to the East. The rest of the volume of the whole building sketched on the left is not modelled.

The building geometry, which at the moment is completely defined, can be conceptualized as rectangular plane surfaces. This allows the energy assessor to describe the design scenario faithfully enough and with sufficient freedom. Thus, he interprets the geometry, introducing some simplifications (as in the example provided in Figure 5.13).



(CAD)

(DesignBuilder)

Figure 5.13. The energy assessor makes an interpretation of the design scenario when he represents it with DesignBuilder: the north wall of kitchen is simplified as a single plane in DesignBuilder.

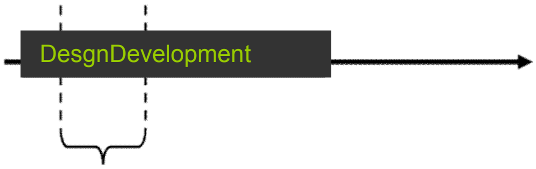
The tool enables modelling indoor conditions that respond to the plant distribution defined in the design solution. In fact, the tools allow the possibility to model particular occupancy patterns for each zone, specifying thermal loads and time schedules for people and equipments.

The tool allows some freedom to the design team to explore detailed options for solar protection and their control settings. In fact, the tool is flexible in representing different kinds of solar protection: both fixed external elements, whose geometry can be modelled, and movable shading devices of several types, internal or external to the glazing (such as blinds and curtains). Also different control strategies for the operation of solar protection may be explored by the design team for manual or automated control. These can be reproduced with several alternative input options such as time schedules, temperatures limits or solar radiation limits.

Moreover, the design team has the possibility of exploring different control strategies for natural ventilation. In fact, the tool is flexible in representing a large variety of patterns by providing multiple input options, such as detailed time schedules for the air change rates or for the windows' opening. The second option, of defining windows' opening, is associated with a more complex calculation procedure: the thermal calculation is coupled with an additional calculation module for air flow modelling which determine the air flows.

5.5.4 Development and evaluation of the design solution

In this section, we consider only a segment of the design development stage, in which the design team develops and then analyses the design solution D1. During this segment of the process just one of the decisions evaluated by the design team is addressed, regarding the exclusion of the mechanical cooling system. Likewise, only some of the goals addressed at this stage are involved, just indoor environmental comfort and space heating demand are analysed.



Segment of the design stage

Alternative design solution	Design decision	Performance indicator	Use of Design Builder
	Building components Mechanical systems (heating and hot water)		
D1	Mechanical cooling exclusion	Indoor comfort – overheating Space heating demand	← ←
... Dn	Operation – control strategies	Energy consumption (gas, electricity) Renewable energy generation Primary energy consumption	

Table 5.7. Reconstructed segment of the design development stage.

The design solution has been evolving throughout the design process. During the design development stage it has been refined, achieving a quite complete and detailed definition.

Previously, at the conceptual design stage, the idea of using no mechanical cooling was proposed. But it was never assessed in detail at that moment. In fact, at the conceptual design stage, it was not possible to verify in which zone overheating could be more extreme, simply because the design solution was too vague. Specific distribution of flats inside the block, size and position of the openings, and many other features, were not yet decided. Now, instead, the information available on the design solution is consistent and detailed enough to verify more precise performance indicators for indoor comfort, the hours of overheating.

Therefore, the design team decides to evaluate overheating using DesignBuilder. Due to the limited time available to create the model the energy assessor decides to analyse only one flat. He selects the one that is more exposed to exterior conditions. The initial intention is, first, to see if acceptable comfort could be achieved in the most sensitive ones of the flat, and then if necessary, to explore options of solar protection devices and control strategies for solar protection and natural ventilation. The design solution is represented with DesignBuilder. The edition of the model takes some time, meanwhile parallel design aspects are developed and it occurs that some design changes are made to resolve the structural aspect. Due to changes in the position of the pillars, some changes in the envelope geometry have to be reproduced in the energy model. The facade line in correspondence to the kitchen and the living room balcony is moved and also the internal partitions must be adapted. The adaptation of the model geometry is complicated by the presence of multiple zones and several openings and the balconies in the facade. All these elements are modified or re-modelled. So, the design team needs additional time in order to update the model (Table 5.8), increasing the delay accumulated during the project. Finally operative temperature in different zones is calculated.

Table 5.8. Synthesis of inputs of the DesignBuilder model.
(The extended description of the inputs is reported in Annex 3)

OUTDOOR ENVIRONMENT (C)

Location	Bcn Airport

BUILDING (E)

Useful floor area of the flat	70 m^2

	U (1) W/m^2K		U W/m^2K	SCGC -
Facade	0.33	**Glazing**	1.521	0.575
Roof	0.377	**Windows frame**	4.719	-
Floor	adiabatic			
Partition between flats	adiabatic	**Solar shading devices**	Exterior blinds	

USER RELATED FACTORS (U,I,O)

Heating set point temperatures	20ºC (average of all zones) (2)

	Summer comfort calculation		Heating demand calculation	
Solar shading control	Blind closed	9-12 & 14-18	Blind opened	always
Night ventilation	up to 4.0 ACH	18-7	-	
Minimum fresh air	11 l/s person (average of all zones) (2)		11 l/s person (average of all zones) (2)	

According to the use of each zone, different settings are used for occupancy density, internal gains from light and appliances, and natural ventilation. Beside the ventilation provided during the day in each zone and the minimum fresh air, additional night ventilation is provided in summer.

Nº inputs specified	+ Nº graphical objects created	+ Nº defaults
>150	~50	1000s

(1): obtained from inputs of each layer used in the calculation
(2): obtained from inputs of each zone used in the calculation

According to the results, all the zones of the flat Le satisfy the indoor comfort requirement established by the design team for the overheating: in summer (from June to September) the temperature never overcomes 30°C for more than 5% of occupied hours (from Figure 5.14 to Figure 5.18). Beside the requirement previously established, the energy assessor further analyses the results. In the majority of the zones the temperature overcomes 25-26ºC for about 20% of occupied hours, so they consider the level of comfort acceptable. Only in the living room -the sole zone exposed to the sun both form south and east- the temperature overcomes 29ºC for about 25% of occupied hours.

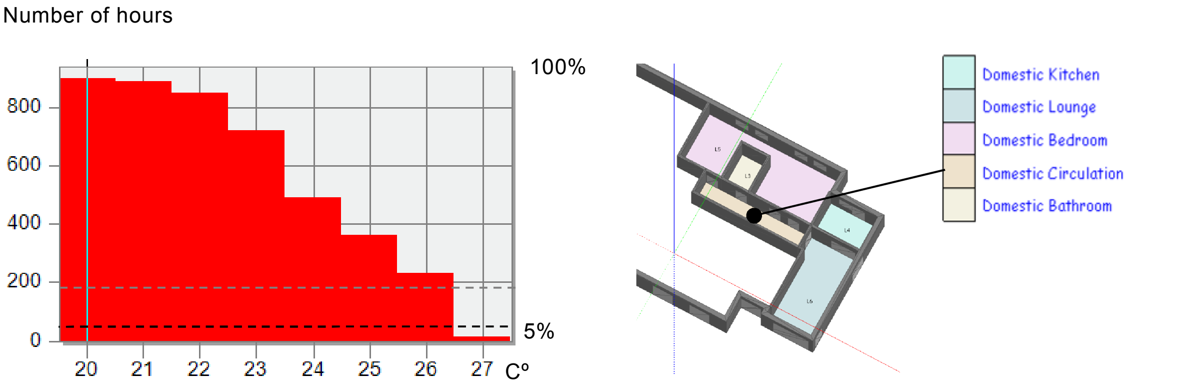


Figure 5.14. Number of occupied hours above specified temperatures in the corridor (zone L2) in the period from July to September.

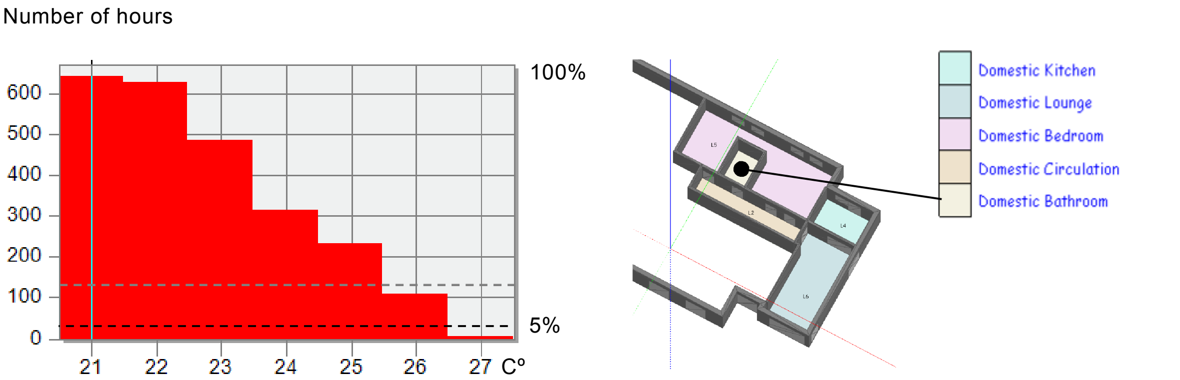


Figure 5.15. Number of occupied hours above specified temperatures in the bathroom (zone L3) in the period from July to September.

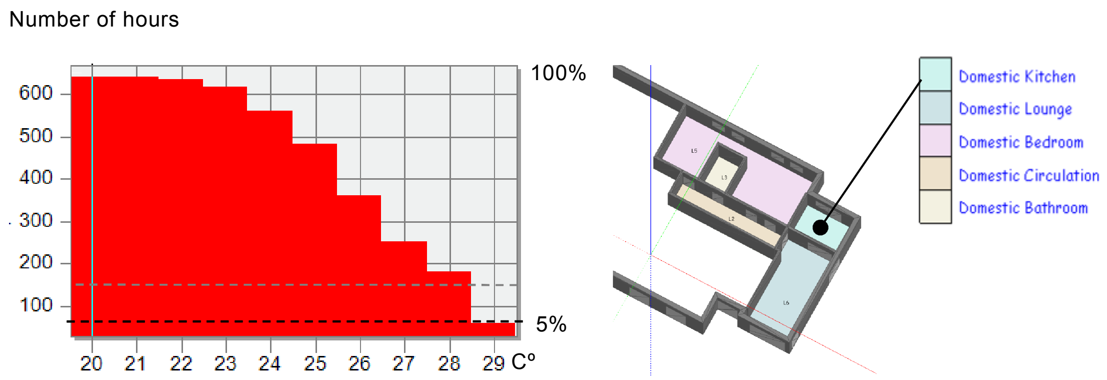


Figure 5.16. Number of occupied hours above specified temperatures in the kitchen (zone L4) in the period from July to September.

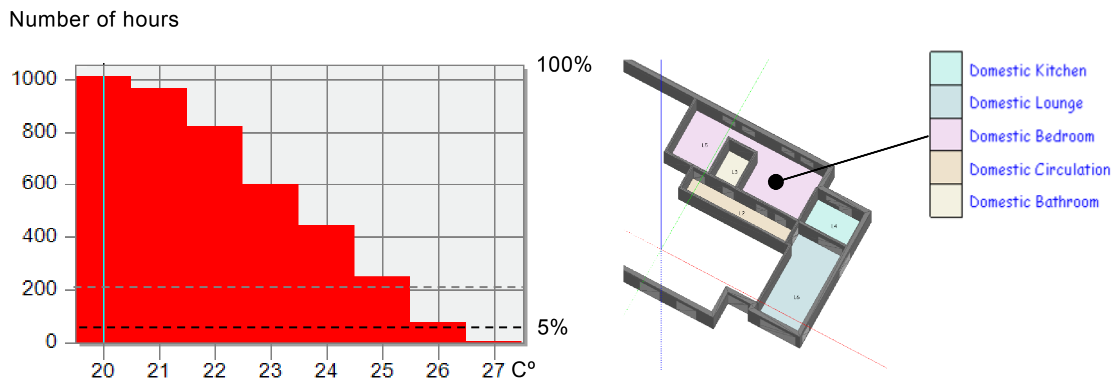


Figure 5.17. Number of occupied hours above specified temperatures in the bedrooms (zone L5) in the period from July to September.

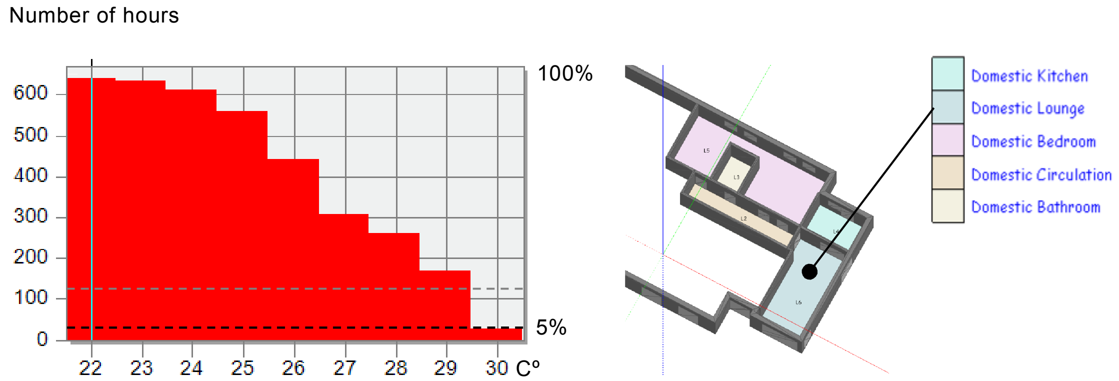


Figure 5.18. Number of occupied hours above specified temperatures in the living room (zone L6) in the period from July to September.

The energy assessor observes that the flat examined is more exposed to the sun radiation then the others. Then, he considers that the other flats are likely to have less hours of overheating and the average comfort conditions of the building will be acceptable. Based on these considerations, they agree with the client that it is not necessary to design a mechanical cooling system for the block.

In addition, considering the result of the comfort analysis and also the short time remaining before the project delivery, they agree not to explore more options for solar protection and control strategies to further improve the comfort performance.

They prefer to dedicate the remaining time to making a more comprehensive assessment of the thermal performance extending the analysis to the heating demand in winter. They exploit the considerable effort already made in creating the model to calculate space heating demand and verify the corresponding requirement. This additional analysis in terms of model edition is quite rapid for the energy assessor. He only adds the set point temperature for space heating and changes the control settings for solar shading devices.

Calculated space heating demand is 31.17 kWh/m^{2}a. Then, according to the calculation, space heating demand requirement of 45 kWh/m^{2}a is satisfied. Having achieved the main design goals the design team proceeds to prepare the final project documentation.

Table 5.9. Evaluation of the indoor comfort and space heating demand during the reconstructed segment of the design process. Summary of results.

	DesignBuilder outputs	**requirement**
Hours of overheating in summer	In all zones, operative Temperature overcomes 30°C for less than 5% of occupied hours	Operative Temperature may overcome 30°C for a maximum of 5% of occupied hours
Space Hating Demand	31.17 kWh/m^{2}a	</= 45 kWh/m^{2}a

So far we have reconstructed the design process, describing the integration of the energy modelling as a part of the process. Based on this reconstruction, we analyse how the tool used suits the project. The analysis is presented in the next sections.

5.6 SUITABILITY OF THE ENERGY CALCULATION METHODS: ANALYSIS OF THE KEY FACTORS

In the reconstruction of the design process that we have provided we have distinguished two design stages, concept design and design development, taking into account the specific energy modelling tools used at each stage.

The choice of two energy modelling tools, Archisun for the concept design and DesignBuilder for the design development, responds to the different needs of each stage. Based on the reconstruction of each design phase, we analyse how far each tool, and in particular the underlying calculation methods, suit design needs. For a systematic evaluation, we examine the ten key factors for the suitability of calculation methods defined in Chapter 4.

5.6.1 The choice of Archisun at the concept design stage

In this section we analyse Archisun suitability in this particular project for the concept design stage. Hereafter, the key factors for the choice of energy calculation methods are discussed.

- **Level of discretization** in the tool inputs is quite low. Archisun inputs require a moderate degree of detail, so that the design team may appropriately represent the objects of design decisions while keeping the global view of the design problem and solution under control. At the same time, modelling detail is limited to the essentials for the fulfilment of an acceptable accuracy.

  In particular, the inputs required to describe the outdoor environment and use related factors (operation, indoor environment quality and user behaviour) are just two: use and location. Based on these inputs, time dependent variables are determined, not as detailed hourly schedule, but as a few mean values and periodical oscillations required to describe short cycles of 14 days for each season. This fits with the need for designers to reduce the input task for constrained variables such as the outdoor environment and use. This means that they do not need to make a big effort modelling such external constraints, and they can concentrate on the design variables to shape the design solution. The approximation of the method in the representation of temporal variations aims to reproduce common use patterns in residential buildings by using a few parameters. Then these simplifications should suit the apartment building being designed in the project.

  In addition, Archisun discretizes the building as one single zone, and it simplifies mechanical systems substantially. These simplifications in the representation of the building and the mechanical systems involve the reduction of the inputs required to a few parameters. The description of the building is unified under a few inputs, for example, the orientation is assigned for the whole building volume, the opening ratio unifies the geometric definition of all openings in each facade, likewise single U and g values are provided for each facade. In a similar way a seasonal efficiency is sufficient for the definition of each mechanical system (namely, heating, cooling and hot water systems).

- **Level of complexity of calculation algorithm** implemented by Archisun is relatively low for automated calculation. This involves limiting the accuracy, but enhancing the transparency and the feedback immediacy in the analysis, provided that such immediacy is a priority at this stage.

  A substantial simplification in the calculation algorithms lies in the implementation of Fourier series. In fact, the use of this kind of mathematical function dramatically reduces the number of calculation iterations compared with more faithful modelling approaches which repeat calculations for innumerable time steps (typically hourly or sub-hourly time steps for a full year model). Moreover, the simplification of the building volume as a single zone avoids the need to integrate in the calculation algorithm the complex dynamic interaction of multiple inter-zone heat flows.

  Also the radical simplification of mechanical systems with seasonal efficiencies avoids the complexity of systems modelling. Finally, the effect of systems on the space heat balance is neglected. In fact, the calculation of building and mechanical systems is sequential and it is performed in two separate steps, avoiding iterative calculation loops between the building and mechanical systems models.

- **Responsiveness to design decisions** of the tool is appropriate for the project. In fact, the tool inputs correspond to the few main characteristics of the building and the mechanical systems that the design team needs to explore at this stage. With Archisun it is possible to represent the characteristics that are necessary in order to address relevant decisions for this stage. For instance, the percentage of openings is a calculation input of Archisun that suits design needs greatly, because the design team has precisely to decide upon the building envelope opening ratio. In other words, they have to decide the proportion between transparent and opaque envelope, independently of the composition of the facade or the design of specific windows, which initially are not relevant for them. At the concept design stage of the project, decisions are considered at the level of whole building. Archisun inputs, such as the global U of the entire envelope, respond to this necessity, and do not force practitioners to anticipate detailed decisions, such as characteristics of individual components and layers.

Moreover, Archisun outputs provide the performance indicators for the whole building and extrapolate them per season and for the whole year, as required by designers at this stage. In fact, the design team needs results to be aggregated in this way for the initial design explorations: at the moment they consider the whole building without dealing with individual flats and they need a few indicators to make rapid analyses. On the contrary, it would not be useful for the design team to extend the analyses to a multitude of disaggregated values, such as hourly values.

- **Feedback immediacy** of Archisun is high. This is favoured by the fact that the level of discretization of the model and level of complexity of calculation algorithm are relatively moderate. As the calculation method embeds several simplifications, the whole modelling process we have described is quite immediate. In fact, thanks to the relatively low detail of the tool inputs, the energy assessor is able to create the model of solution C1 in a day and to modify it in a few minutes to produce the solution C2. The automated calculation process is nearly instantaneous and the interpretation and discussion of the few output data that the model provides may be held in one session. In that way, it is possible for the design team to join together for a one-day session and repeatedly manipulate the model while discussing results.

  High feedback immediacy is fundamental at this design stage, in order to rapidly screen a large number of variations in the solution, which is yet highly uncertain and open. For this residential project the design team is relatively small and works in close cooperation. In this condition, real-time calculation offered by Archisun makes it much easier for the architect to receive the specialist feedback before moving forward and it fosters a continuous interaction between partners during the process.

- **Flexibility in design modification** of Archisun is adequate to the project for the concept design stage. The energy assessor can easily explore the kind of variations addressed at this stage. Such variations affect the whole building parameters, as the orientation and shape of the whole volume, or for instance, the opening ratio, U and g-value of an entire facade. A radical concept reformulation, like a change of the building shape, can be represented with a moderate effort manipulating few parameters without re-modelling from scratch.

  In addition, the energy assessor may adjust, with moderate effort, some boundary conditions initially set down at the concept design stage, by manipulating a few parameters of Archisun. As we observed in fact, initial constraints are likely to be reformulated throughout the process, and then these changes must be reproduced in the model modifying the boundary conditions. For example, it might occur that during the project a dispensation from the local plan would allow an increment of useful volume. This modification could be reproduced by directly incrementing the volume input and adapting the relatively small number of parameters that define the building geometry. Instead with a large set of geometric inputs, which characterize other tools as DesignBuilder, modifying the model geometry would be much harder, and possibly re-modelling from scratch would be easier.

- **Flexibility in representing design scenarios** with Archisun is acceptable. It allows modelling the concept level solutions that the design team explores to decide on building features. With the tool it is possible to faithfully represent the simple geometry outlined so far. In fact, internal residential spaces are still not defined and the access to the flats is exterior to the main volume - thus the geometric definition of the solution results in a simple parallelepiped.

  However, the tool does not allow the analysis of different internal spaces that will later appear in the design development. The energy assessor is aware of that and knows that the tool will be abandoned later in the design process if more specific analyses are required. In fact, at the design development stage internal stair cases integrated in the main building volume and specific flat zones are fully defined resulting in a more complex geometry and distribution. Detailed geometry and distribution required for a precise analysis of summer comfort cannot be faithfully represented with Archisun. This does not impede the designer in taking advantage of the tool at the concept design.

  Moreover, the low flexibility of this tool in the representation of use related factors do not affect and limit the exploration of the design solution. In fact, the design team decided that use related factors are not an object of design decisions at this stage.

- **Accuracy** of the analysis provided by Archisun seems to be acceptable for the concept design stage. We have observed that the energy assessor aims to limit the level of discretization of the model to the essentials for the fulfilment of an acceptable accuracy. We are going to explain how this can be done with Archisun. The climate and use patterns are reproduced by Archisun with a limited time resolution, but time discretization is studied for modelling common use patterns of residential buildings; in that way the tool aims at providing acceptable accuracy for residential buildings while limiting the model complexity. Likewise, the tool is based on strongly simplified assumptions intended for modelling conventional heating and cooling systems. Then, the accuracy enabled by Archisun is likely to be sufficient for a project like this one, which deals with residential use and with conventional heating and cooling systems. However, we ignore how far the simplified representation of the building as a single zone limits the result accuracy for the solution C1 and C2.

The accuracy of the prediction of space heating and cooling demand with Archisun seems to be sufficient for the conceptual design stage of the project. At this stage the accuracy of performance prediction is not the first priority. According to the design goals agreed with the client, the design team use Archisun to point out the trend of heating and cooling demand with the variation of opening ratio. Therefore, the practitioners only need the minimum accuracy necessary to correctly indicate this trend. And there is no need for higher accuracy, which is typically required to predict absolute values.

Archisun deals with the uncertainty of the variables associated with the project constraints, such as climate and user behaviour, with a deterministic approach. Archisun developers provide pre-established climate and user behaviour parameters, and embed several assumptions in the calculation algorithm instead of entrusting them to the user discretion. Therefore, consequent potential errors in the performance outputs are rigidly related with the tool and are not affected by the user subjectivity and mutable modelling assumptions[23].

Unfortunately the design team may not have any proven guaranty of the reliability of results during the design process. In fact, it is impossible for them to have documented validation of the calculation method accuracy for the specific project conditions. They can only refer to their experience and to performance data of multifamily buildings in other locations of Catalonia with a similar climate.

- **Suitability for holistic design** of Archisun is facilitated by its low level of discretization. In fact, the modelling process is quite simple and the design team do not need to concentrate too much effort on energy analysis. That means that they do not subtract the resources that are necessary to deal with other design aspects such as cost, privacy and views. A holistic design approach is also facilitated by the high feedback immediacy of Archisun, which allows a rapid shift from one problem domain to another.

  Moreover, the calculation outputs embrace a varied range of performances aspects, by analysing thermal, lighting and acoustic

[23] It is quite difficult to get general conclusions on the accuracy achieved through this approach. Its aim is to guarantee a minimum level of accuracy. In fact, if such inputs were under practitioners' responsibility, analysis accuracy would differ according to the sensibility and the experience of practitioners in energy modelling. Moreover, the energy assessor would be charged by more work when generating inputs and analysing results.

comfort, along with energy performance. Then the tool allows the design team to get an integrated analysis of these performance aspects with a single model. However, the design team does not exploit the tool for lighting and acoustic analysis to evaluate the solution C1 (and C2). Besides, other design aspects that are considered by the design team, such as cost, privacy and external views, are not covered by the tool. Therefore, the holistic view of the design problem and solution largely depends on the design team capacity to synthesize multiple aspects.

To sum up, Archisun facilitates a better understanding and control over the design problem, helping the design team to consider energy and comfort performances together with the other design aspects addressed at this stage.

- **Data coherence preservation** is facilitated by the two options provided by Archisun to define the model according to different level of detail. Low detailed inputs are intended to outline the overall solution initially, and more detailed inputs allow refining the solution afterwards. Initial data are preserved: low detail inputs are transposed with system of rules to a complete and consistent set of detailed inputs, so that the user modifies them to refine the model.

  Nevertheless, in this case study different tools are used in the design process in order to fulfil the specific needs of each design stage. Therefore, in this case, data coherence preservation does not depend simply on Archisun, and the coherence from one stage (or tool) to the next is not easily solved. In particular, the transfer of energy calculation inputs from one tool to the other is problematic. A specific limitation of this tool is the lack of transparent documentation regarding some variables in the calculation, especially user related data. Consequently, it is hard to faithfully reproduce this information in the next design stage within DesignBuilder.

- **Transparency.** The calculation method is relatively simple, enhancing the understanding of the overall physical behaviour of the building. The meaning of the opening ratio, a model parameter that is important in design decision taken at this stage, is well understood by all partners in the design team. Nevertheless, some thermal properties, such as delay and amortization factors of the envelope do not have wide use and standard definition in building physics community.

  Moreover, calculation algorithm is not totally transparent to the user. For instance, the equations that model occupants' behaviour and building operation are not clearly documented, in particular for ventilation. This limits the practitioners understanding of the design problem and their full control over the solution generated. Nonetheless, we must remark that this is not a limitation intrinsic to the calculation method, but it must be attributed to the documentation support available on this tool. For this reason, we cannot judge the calculation method non-transparent.

According to the key factors discussed so far, the choice of Archisun is satisfactory to the needs of concept design of this project. And it can provide acceptable answers to take more conscious design decisions.

5.6.2 The choice of DesignBuilder at the design development stage

Below, we discuss how appropriate DesignBuilder and its calculation engine EnergyPlus are in the project for the design development stage. Hereafter, the key factors for the choice of the calculation method are examined.

- **Level of discretization.** At this design stage the information available on the design is quite complete and also detailed. The inputs of DesignBuilder are more than sufficiently detailed to represent the design scenario, keeping to its current degree of definition.

  High discretization is possible to describe the building, including the internal spaces, the envelope and partitions. The indoor environment can be defined at the zone level. Each individual component of envelope and partition may be modelled specifying the properties of each layer of the construction. The inputs' discretization is also high for the outdoor environment data and use related factors (operation, indoor environment quality and user behaviour). Such a time discretization allows modelling hourly variations of the climate data that are available for Cerdanyola. Likewise it allows the description of control strategies, which the design team intend to reproduce.

  The detail needed to inform design decisions is also provided by the outputs of the calculation method. The operative temperature - performance variable that the energy assessor has to analyse - is provided for each zone, and hourly values are calculated. In that way he may detect hourly peaks in temperature that are relevant for comfort assessment.

- **Level of complexity of calculation algorithm.** The calculation algorithm used in DesignBuilder is very complex compared with Archisun. It includes large number of equations, and more complex solution techniques. For instance, heat conduction through building elements is modelled by conduction transfer functions. The model couples different domains of analysis. For example, thermal calculation may be coupled with a multi-zone airflow calculation module. The calculation involves several interactions between all the elements of the model, such as the heat transfers between multiple zones. The number of interaction relates to the high space and time discretization.

Due to its complexity, it would be impossible to implement this calculation method without a software application. In practice, even an expert in various domains of building physics could hardly have complete control and understanding of whole calculation process. For this, the tool is not easy to use for the practitioners involved in this project, which are not advanced users.

- **Responsiveness to design decisions.** The level of discretization permitted by tool allows faithfully representing different design options that the designers intend to address. And it provides them with relevant indicators for the performance aspect influenced by design decisions at stake.

  In particular, the energy assessor has the possibility of describing specific solar protection devices faithfully and representing different control strategies. The designers intend to explore these options in order to improve summer comfort. The model permits quantifying a relevant performance indicator for thermal comfort – the hours of overheating. Furthermore, this performance indicator is provided with the level of time and space discretization which is relevant for the analysis: hourly results are produced zone by zone. Only with a similar discretization, extreme hourly values and specific critical zones may be detected.

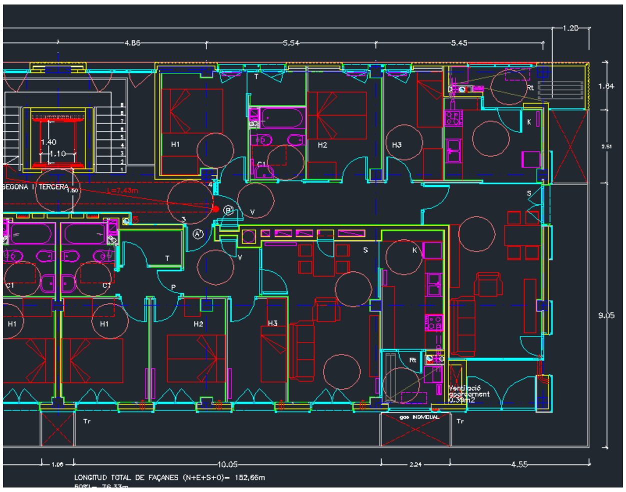
- **Feedback immediacy.** The possibility of getting prompt feedback from energy modelling is significantly limited by the tool. The lack of immediacy hinders the possibility to adapt the model to the changes that occur during the design process. Minor design changes occur at this stage, even if most major decisions have been previously taken and there are no radical reformulations of design hypothesis. Due to the complexity and detail of the information required by the model, a long time is needed to update it before providing useful feedback to inform design decisions.

  The lack of immediacy prevents the design team from investing time in a more accurate assessment, dealing with the adjustment of comfort requirement, the analysis of user behaviour, or the refinement of operational settings. In fact, having more time it could be considered with more attention whether the comfort requirement is strict enough; the occupant behaviour in relation with blinds control could be more systematically investigated, taking into consideration worse conditions. The long time spent on modelling also limits the further development of the design solution: the energy assessor makes no attempt to improve solar protection and control strategy. With the time and resources available for this project, it was impossible to conduct more accurate analysis and just a small part of the large potentials of the selected energy modelling tool may be exploited.

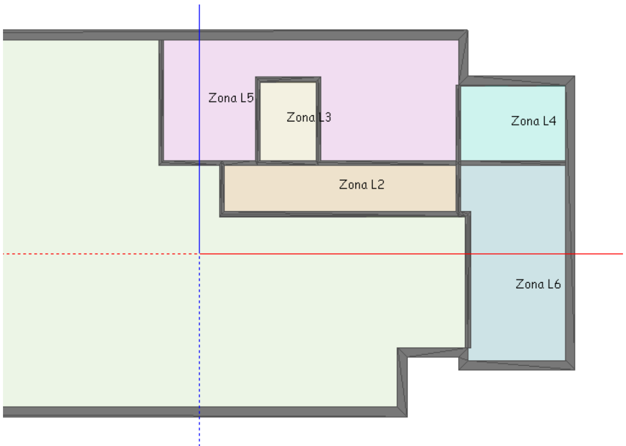
- **Flexibility in design modification.** Some changes of the building geometry have been introduced while developing the design solution. The tool is quite inflexible to reproduce the design modifications affecting building geometry. DesignBuilder in fact enables a complex definition of geometry consisting of a three dimensional system of planes and volumes, so that it is not easy to reproduce changes without a deep remodelling of building geometry. In fact, the displacement of a wall involves the modification of all connected elements to preserve geometric consistency of the building.

  This lack of flexibility in design modifications is not only dependant on the tool. It also depends on the design decisions and questions addressed, and how the energy assessor interprets a design scenario with the model to face decisions and questions. In particular, to address the issue of summer comfort, the indoor spaces that are more exposed to extreme conditions have to be identified and represented as thermal zones in DesignBuilder. The energy assessor has some freedom to decide which and how many zones have to be modelled for a relevant abstraction of indoor environment. His interpretation of the geometrical complexity affects the flexibility of the model for future design modifications. If more zones and partitions are modelled, it will be more difficult to modify the model according to mutations of the building geometry. The choice of the energy assessor to model in detail only the flat Le makes the model a little more flexible to design modifications.

- **Flexibility in representing design scenarios.** DesignBuilder provides great flexibility to the energy assessor to reproduce the design scenario. The tool enables the energy assessor to discretize indoor space with the number of zones that he wants, and so he has some freedom in the abstraction of the design solution. The energy assessor represents the design solution in the way he considers more appropriate to analyse summer overheating. Instead of modelling each room as a thermal zone, he joins together spaces that, according to his knowledge, have homogeneous thermal conditions. We show an example in Figure 5.19: the three bedrooms in the north are modelled by the energy assessor as a single zone (Zone 5) in DesignBuilder.



(CAD)



(DesignBuilder)

Figure 5.19. The three bedrooms on the north side in the CAD plan are modelled as one single zone (Zone 5) in DesignBuilder.

- **Accuracy.** The calculation method applied by the tool is potentially very accurate. The energy assessor uses it to verify specific performance goals, comparing the calculated hours of overheating with limit value fixed as requirement. The calculation method is accurate enough for this kind of verification.

  Nevertheless, the energy assessor assumes conventional hypothesis to enter design constraints of climate and user related data in the model. These design constraints are largely uncertain. As the model is very detailed the energy assessor must introduce several inputs to define these hypotheses. Therefore, despite the potential accuracy of the tool, he makes a guess on many inputs, including extended schedules of hourly values for occupancy, lighting, appliances, ventilation and blinds regulation. So, they cannot be completely sure about the outputs' accuracy. They just know that the tool makes an accurate calculation, taken for granted that these assumptions are exact. Indeed, the reliability of the analysis largely depends on the capacity of the energy assessor to make reliable assumptions.

- **Suitability for holistic design.** The design team copes with different design aspects: they analyse the energy performance, then adapt the building structure to provide more appropriate design solution and then return to update the energy analysis. That is to say that the design team have to shift the attention and distribute its efforts on all relevant design aspect that the project presents. The high level of discretization of the model and the level of the complexity of the calculation algorithm hinder the agility of the design team when they shift the attention back to energy assessment. In this sense, complexity of the tool is an obstacle for the integration of multiple design aspects.

  In contrast, even if the tool does not provide a fully comprehensive set of analyses, it gives the possibility of integrating different performance analysis, such as summer comfort and space heating demand, with the same calculation method. The integrated modelling approach offered by the tool allows preserving the consistency among different phenomena that are strongly coupled in reality.

- **Data coherence preservation.** The coherence of information between different domains is in part addressed by the calculation method, which integrates different coupled domains of analysis. However, many design aspects are not integrated within the model and much of the design information is not included in it. For instance, precise information regarding specific rooms' geometry, that is not particularly relevant for energy and comfort analyses, is not included into the model. Therefore, to preserve the consistency of the design solution the design team has to update and coordinate the information between separate models, created with DesignBuilder and the CAD application, or other digital and non-digital supports. The very large amount of data modelled with DesignBuilder makes it difficult for the design team to preserve the coherence with the information contained in other models. In fact, the probability that the practitioners make errors is quite high with such an abundance of details. On the other hand, the translation of information at different moments throughout the design process strengthens the insight of the energy assessor into the project.

  Also exploiting information that comes from the precedent design phase and has been modelled with a different tool such as Archisun is complicated. Even if Archisun and DesignBuilder mostly cover the same domains of energy analysis, the formalization and discretization of the information required by their calculation methods are very different. Nevertheless, the change in the design scale is not just an obstacle dictated by the tool set adopted, but a fact which is very inherent to the nature of the design process.

Moreover, the evolution of the design process prevents designers from using data from the Archisun model. In fact, the design scenario modelled with Archisun at the concept design phase evolved during the process and now it is quite different. This does not have to do with the tool, but with the dynamic nature of design. Several design variables have changed: from the access to the apartments to the thermal insulation. For this reason, various data of the Archisun model are not meaningful to generate the new model with DesignBuilder. And for the same reason, calculation results are not comparable, taking models created at different design stages.

- **Transparency**. The calculation method is mainly based on principles of physics, and in general, on an acknowledged research background. This fact makes the calculation method unambiguous and fosters its transparency. A detailed and unambiguous model is useful to produce precise and clear specifications that are essential, first, to inform the building construction, and second, to check the components' quality and the whole building performance.

  However, extreme complexity of the whole calculation methodology is an obstacle. In fact, with the level of knowledge on building physics that the energy assessor possesses, it is absolutely impossible to fully understand the whole calculation process. The energy assessor ignores many model inputs, outputs and calculation options of DesignBuilder, due to their large number and non-obvious meaning. Likewise, he is not able to check all default values that DesignBuilder provides for the model. Thus, there is a potential risk of misunderstanding the model. In addition, the complexity and detail of the model inputs and outputs make an immediate interpretation of results very difficult. Then it is not easy for the energy assessor to facilitate straightforward conclusions to the design partners and the client.

According to the key factors discussed, the choice of DesignBuilder for this project reaches an acceptable compromise to fulfil design needs at the design development stage. Despite the complexity of DesignBuilder, which complicates and slows the design process, the tool offers the flexibility necessary to answer the specific design questions, posed by the design team.

5.7 CONCLUSIONS

In this case study we have reconstructed an ordinary design process (in terms of building use, size, budget, design solutions). But we have introduced a differential element from many other projects: the deep integration of energy modelling throughout the whole design process (from concept design to design development). In fact, energy analysis is not relegated at the end of the process for final verifications, but it is integrated from the beginning, anticipating initial design decision.

The ordinary design process we reconstructed shows that energy modelling does not have to necessarily be regarded as a means to produce ambitious and innovative design solutions (which are far away from the normal practice). On the contrary the case shows how energy modelling may be used to design conventional solution widely used in a current projects. At concept design, the practitioners develop a conventional facade solution. To arrive at a suitable solution they have to decide on the opening ratio. The decision is apparently trivial, but its impact on energy demand is not obvious for practitioners. In this situation, they use Archisun to quantify this impact, so they become much better informed to take this decision. In sum, even for a conventional solution like the one considered, energy calculation provides valuable support.

The case study allows highlighting that the effective use of energy calculation tools occurs, integrating them timely and ad hoc throughout the design process. In particular, Archisun is exploited at the beginning of the design process, at the precise moment when the design team needs to take a conscious decision on the opening ratio. It is important that Archisun is used at the right time, to correctly orient a decision that conditions the next steps of the design process. So before making the decision, the design team is informed on its impact on the energy performance. Proceeding in this way they set the base to progress toward a satisfactory design solution (in terms of energy and comfort). In that sense, the tool is integrated timely throughout the process.

Besides, the case study reveals the difficulty in choosing calculation tools which provide a good trade-off between different factors of choice. In fact, for more than one of the analysed factors, both Archisun and DesignBuilder result in being not excellent tools, but just acceptable for the purpose of the practitioners.

That said, their use is feasible and justified by the added value that the tools bring to the project. The contribution provided by Archisun and DesignBuilder is to expand the knowledge of the design team. In fact, when they want to decide on the opening ratio and the use of mechanical cooling system, they do not know enough about the impact of these decisions on comfort and energy performance. By making energy analysis they comprehend more about the performance that they can expect from the design solution (or the alternative solutions). With this insight they can make more conscious decisions on the opening ratio and the use of mechanical cooling system. In such a way the design process is likely to be more effective in achieving performance goals.

In the case study it is observed that energy modelling requires a considerable effort, and then, it is used to address design questions and support decisions only if simpler means (such as, experience) cannot answer. Therefore, some of the decisions considered throughout the process are made with energy modelling support, while many others are not. For instance, they initially decide to give a uniform configuration for all the apartments, believing that this choice would favour uniform thermal conditions; they reach this conclusion by reasoning and they do not consider it necessary to make the effort of verifying this supposition with thermal calculations.

A distance in time separates different questions addressed with energy modelling during the design process. Indeed energy modelling is not continuous throughout the process, but punctually involved. So, it is impossible to verify in a later stage of the project lifecycle the results of performance analyses punctually made at the concept design stage. This is due to the fact that the design solution changes substantially during the process, and then, the model created with Archisun at the conceptual design stage is not comparable with the final design solution. For this reason it is impossible to validate the model of the solution under development against the performance of the real building.

It is also shown that the indicators to be evaluated, and then the tool to be used, are precisely determined by the design team during the process and not a priori. At the concept design stage, the indoor comfort is analysed using average comfort conditions obtained by the simplified calculation of Archisun as indicators. But at the design development stage, they decide to quantify a more precise indicator, the percentage of hours of overheating. This requires detailed calculation so that an advanced simulation tool, namely DesignBuilder, is used. The necessity arises during the process when they realise that overheating has to be more carefully considered and they decide to make a more detailed analysis.

In this case study, our assumption was to associate the conceptual design stage with large-scale decisions and low detail in the design proposal, and the design development stage with small-scale decisions and high resolution. In many project this is not a firm pattern. According to our assumption for this project, the progression of tools used throughout the two design stages responds to an increasing level of discretization.

The analysis proposed in the case study is the result of a careful reconstruction of the design process: how constraints initially identified evolve, when decisions are considered, and finally how energy modelling integrates into the process. Based on this reconstruction we could analyse the use of the energy modelling tools and underlying calculation methods at different stages of the process. In the reconstruction of the design process we provided hypothetical settings. The advantage of dealing with a hypothetical process has been to tailor the details of our reconstruction to the purpose of our study. In a real case instead, the process is more difficult to track (Cross, 2007) because available information is often limited to the final product of design (drawings, reports and models). So a complete reconstruction of the process often is not possible. The obvious advantage of a real case is the possibility to get tangible evidence.

In order to complement this case study a real case is analysed in Chapter 6.

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Chapter

6

Case B: design process of a residential building in Vienna

CHAPTER 6: TABLE OF CONTENTS

In the precedent chapter we have analysed Case A, investigating the use of energy calculation in a hypothetical design process. The purpose of Case B is to complement Case A, studying how energy calculation had actually been used in a real design process.

In particular the key factors in the choice of the calculation method are considered to analyse how the energy calculation method adopted was appropriate for this specific project. As in the precedent case, we intend to exemplify as far as possible an ordinary project because our aim is to consider the applicability of energy calculation in ordinary building design. For this reason the case taken represents a common situation in Austria in terms of building use, typology, functional program, size, budget and location. In cultural and geographical context of Austria, sustainability and energy efficiency have had some more penetration in design practice compared with Spain. Thus, we selected a project developed in Austria to study a real design process, assuming that in this context the deployment of energy modelling in design were less distant from ordinary design practice. However, the project was also characterised by some uncommon conditions including the fact that all the members of the design team worked in the same office. The close cooperation of different specialists facilitated the integration of different design aspects from the beginning of the project. Moreover, the project was the object of a research project involving the monitoring of the building.

The chapter is structured as follows. In Section 6.1, we specify the scope of the case study and introduce the methodology used to reconstruct the design process. In Section 6.2, we provide an overview of the project life cycle, from the design to the use, identifying the tools used at each stage for energy calculation and other building physics' analyses. In Section 6.3, we focus on the reconstruction of the design phase and we describe how energy modelling takes part in the design process. In Section 6.4, we compare the energy calculation results obtained at the design phase form energy calculation tool, OIB-hwb02h, with data from a calibrated model based on monitoring data. In Section 6.5, we analyse the tool features and results delivered by the tool and we put them in relation with the necessities of the design team. In that way, we evaluate how far the tool could meet the needs of the project. In Section 6.6, we draw the conclusions on the case study.

6.1 SCOPE OF THE CASE STUDY AND METHODOLOGY OUTLINE

We provide an a posteriori reconstruction of the design process, identifying the energy calculation tools used. Based on this, we discuss in detail the key factors for the choice of the tool in this specific design situation, in order to evaluate how far the tool and the underlying calculation method suits for the project.

To reconstruct the design process we interviewed the design team and we analysed the building site (Figure 6.1) and the project documents (Figure 6.2 to 6) including the models set up by the design team at the design phase. Then, to discuss the key factors and understand how appropriate the tool was, we compared the model used at the design phase with a tailored model calibrated with monitoring data.

Figure 6.1. Aerial view of the site before the construction, adapted from www.bing.com [2012 09 18]

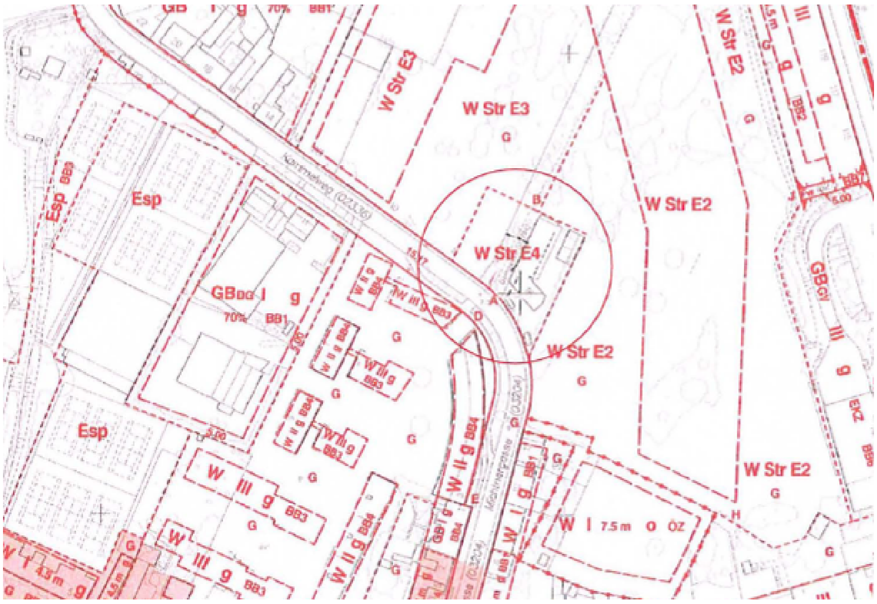

Figure 6.2. Urban regulation plan, in force at the design phase (2007).

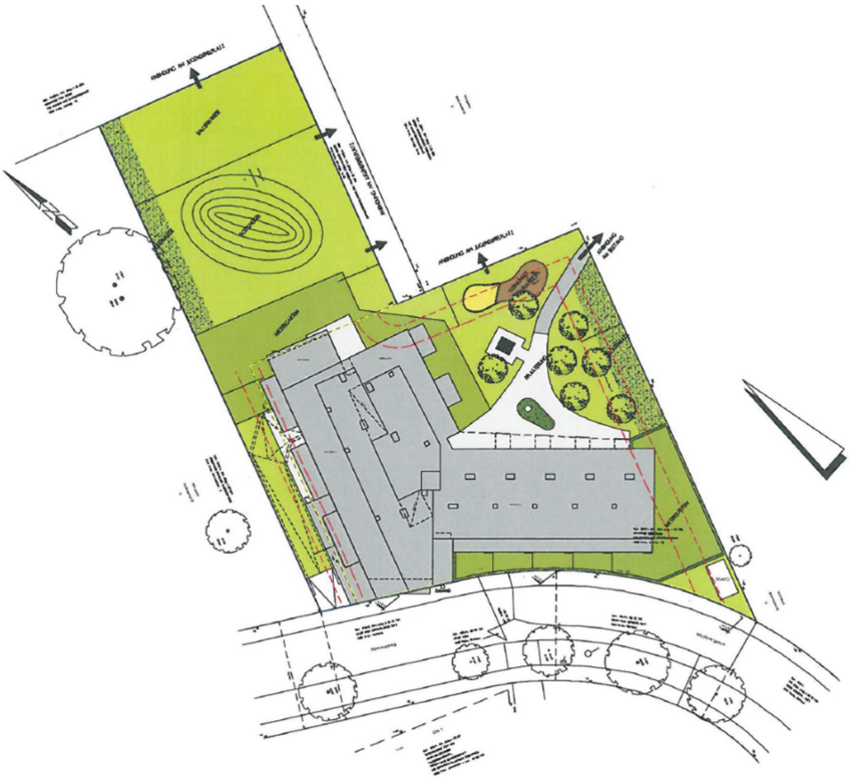

Figure 6.3. Plan of the building site with urban alignments. State of the project at the end of the design phase (2007).

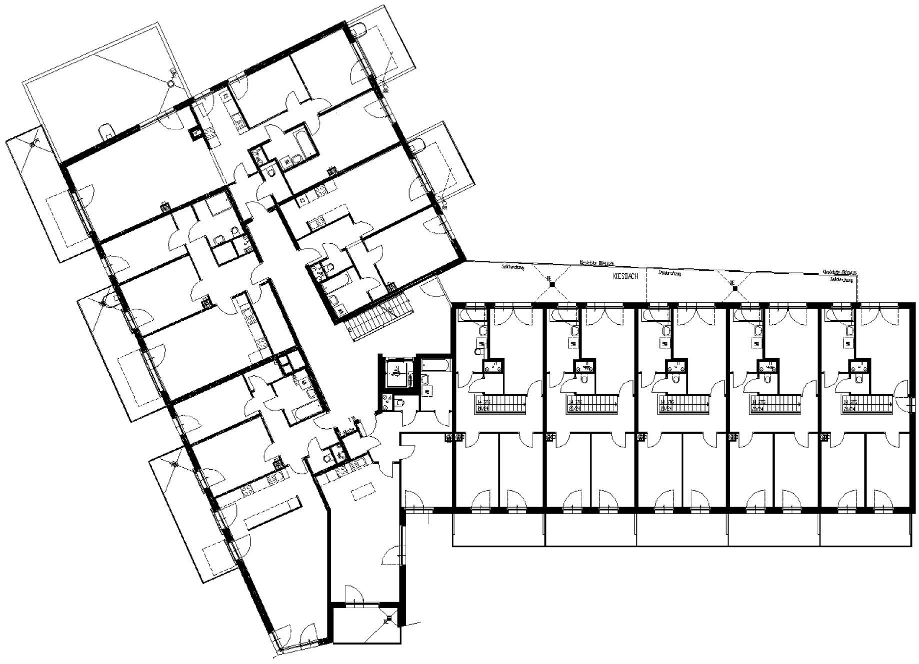

Figure 6.4. Plan of the 5th floor. State of the project at the end of the design phase (2007).

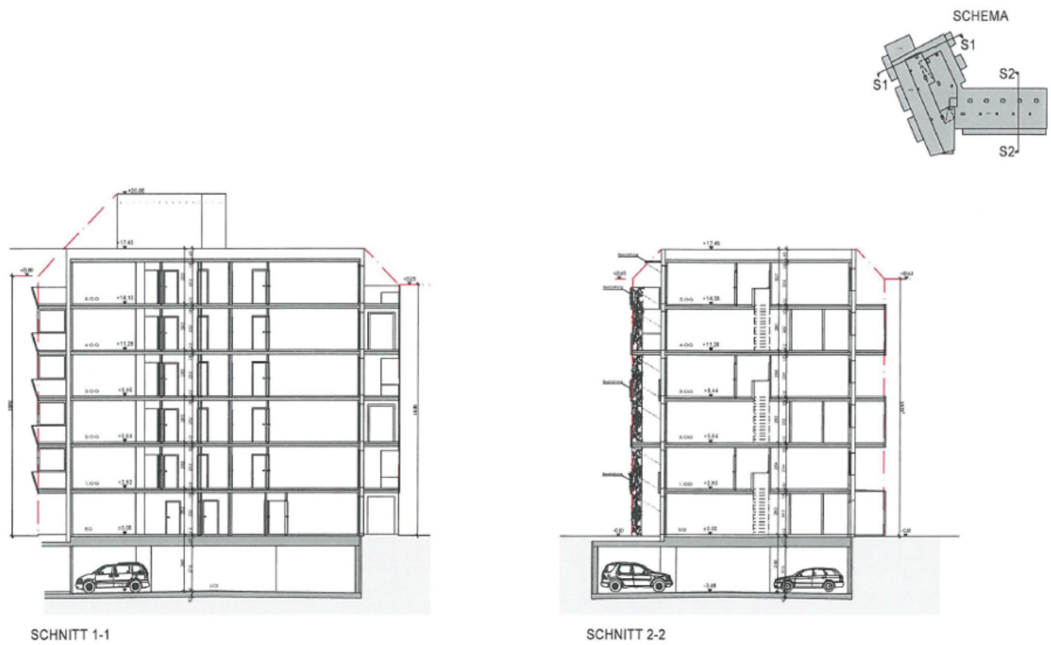

Figure 6.5. Main vertical section. State of the project at the end of the design phase (2007).

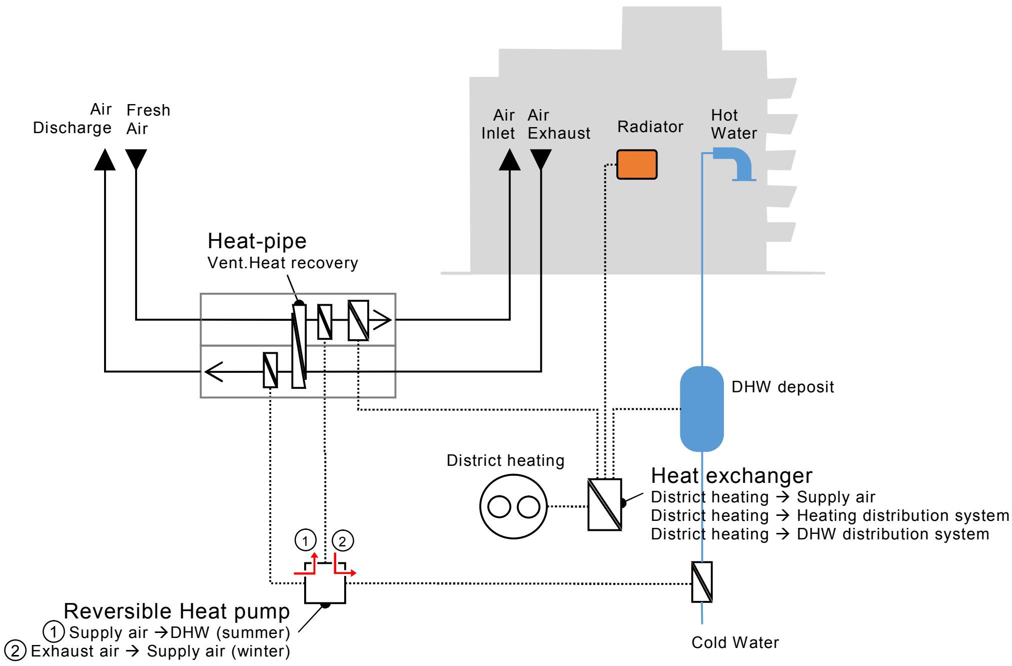

Figure 6.6. Schema of the mechanical systems: the ventilation system with heat recovery, the heating and the hot water systems alimented by the district heating. State of the project at the end of the design phase (2007).

6.2 OVERVIEW OF THE PROJECT LIFE CYCLE

The project life cycle was reconstructed. The identification of different phases is based on interviews and dates reported on delivered documents and models. During the design phase the design team developed a proposal to submit to the public authorities of Vienna in order to get the Wohnfonds Wien funding for residential projects (wohnfonds_wien, 2012). The project was submitted in 2007 and the grant was received in 2008. As the designers affirmed, the land was granted with specific conditions such as limited construction costs, affordable rents, inclusion of social housing in the apartment building, and integration of several innovative technologies. The technologies proposed by the design team for the building included the green shading to the facade, the use of a heat pump for heat recovery in the ventilation system, and the monitoring of domestic hot water, cold water, electricity, and heat consumption from district heating.

The building was erected between the autumn of 2008 and spring of 2010. Currently the building is occupied. Before the building came into operation, several aspects were assessed by the design team including cost, structure and building physics. Regarding building physics, the heating need, thermal comfort (summer overheating), and acoustical comfort were calculated. These different aspects were quantified separately with different tools. The tools OIB-hwb02h and ArchiPHYSIK were used at different phases to calculate heating demand: initial calculations were made at the design phase with the OIB-hwb02h tool and energy certification requirement were verified at a final stage with ArchiPHYSIK. Two in-house Excel tools for acoustic insulation and summer overheating were used to fulfil building performance requirements. The tool Aterm was used to consider thermal bridges to fulfil performance requirements and provide inputs to ArchiPHYSIK (Figure 6.7)

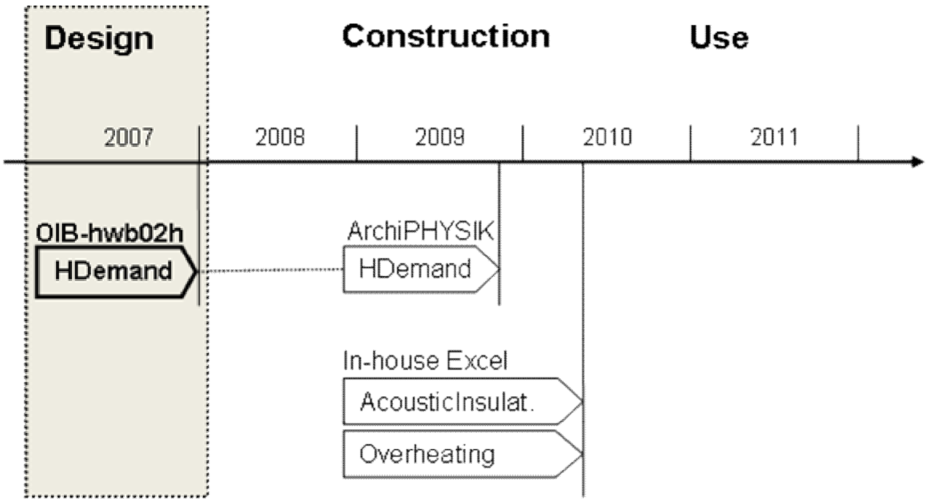

Figure 6.7. Chronological reconstruction of the project from the design phase to the operation phase. Main tools used in each phase are indicated. The reconstruction is based on interviews and dates reported on delivered documents and models.

The investigation focuses on the design phase starting at the beginning of the design process and ending with the submission of the project to Wohnfonds Wien in December 2007. In particular, how energy calculation tools are used in this phase is considered.

6.3 DESIGN PHASE

According to the interview, the different specialists integrated in the design team started working closely together from the beginning of the project. The team initially included the architect, the cost assessor and the structural engineer. Then the building physics' assessor – in charge of the energy and comfort assessment[1] – was also implicated.

The building physics' assessor intervened at the design phase making energy calculations. The OIB-hwb02h tool (OIB-382-010/99, 1999) was used with the scope of verifying the heating demand goal previously agreed with the client.

The **OIB-hwb02h calculation method** quantifies the space heating demand of a single zone according to a simple quasi-steady-state approach. It calculates the heat balance over the whole heating season, as a steady-state method. But a gain utilization factor is introduced in the equation to reproduce dynamic effects. Total heat transfer by transmission and ventilation are obtained in function of the number of heating degree days in the heating season. Total heat gains are obtained in function of the accumulated solar radiation and internal heat gains over the whole season (OIB-382-010/99, 1999).

The outputs are calculated for the whole building and are provided on annual base. They are limited to the space heating demand and the different terms the heat balance (of transmission, ventilation, solar radiation and internal sources).

A more extended description of the OIB-hwb02h tool, including the underlying calculation method, the inputs and the outputs, is reported in Annex 2.

6.3.1 Project constraints at the design phase

Different kinds of constraints affected the design of the building, including the architectural program, the characteristics of the site, the urban regulation and also the energy performance requirements established by the design team and the client.

The building program consisted of a residential building combining 48 apartments and a children's group home. The program also provided for bicycle and pram storage, a garbage room, an underground garage, space for common activities, rooms for technical services, storage lockers, a laundry room, and cleaning services. The gross conditioned floor area was 5300 m² approximately.

The project was sited in a residential neighbourhood. New residential strips surround a park on two sides, and the project site was located on the third side facing the street (Figure 6.1). The public park was intended for use primarily by the tenants residing in the new residential buildings surrounding

[1] Different from the other case study, in this one we do not refer to the figure of the energy assessor, but to the building physics' assessor, as the same professional was in charge of the energy assessment as well as thermal and acoustic comfort assessments.

it. The form of the site, and the distance and volume limits imposed by the zoning regulations provided some constraint to the building shape and volume (Figure 6.3). Then the building resulted in a quite compact shape, broken in two perpendicular volumes. The connection to the district heating installed in the urban area was available at the project site.

The design team confirmed energy performance requirements with the client: **the space heating demand could not be greater than 20 kWh/m²a**. According to the interview, the client sought a low energy building, but was conservative with the space heating demand as it was feared that it would be too difficult to reach the lower energy standard of passive houses (15 kWh/m²a).

6.3.2 Object of design decision

Main design decisions affecting the energy performance of buildings were addressed through the design phase. According to the interview, they emerged at different points during the design process:

1st. The building shape and opening ratio of the facades were considered.

2nd. The values of envelope components characteristics were decided with assistance from the space heating demand calculation.

3rd. The decision between natural ventilation and mechanical with heat recovery options was attained using the space heating demand calculation. In the calculation, only the heat recovery portion of the mechanical ventilation system was modelled.

Other decisions were addressed although it was not possible to reconstruct at which point of the design phase these decisions were taken. They include:

- The solar protections were considered proposing a green facade made with climbing plants
- The mechanical systems for space heating and domestic hot water were considered, proposing to aliment them with the district heating and to install radiators.

As specified some of these design decisions (2 and 3) involved the use of space heating demand calculations with the OIB-hwb02h tool.

6.3.3 Expressing the design scenario through the energy model

Before the design solution was modelled, some variables influencing space heating demand were already fixed and some were still open:

- Design variables such as envelope components characteristics and ventilation heat recovery were open to explore the design solution.
- Design variables such as building volume, building shape, and windows ratio had already been fixed by the design team.
- Finally, variables out with design control such as outdoor environment and use conditions were necessarily fixed. They were determined by the design team based on the project constraints of the site and the architectural program.

Through the inputs provided by the tool it was possible to explore open design variables mentioned above, namely:

- U and g-values inputs enabled defining building envelope components characteristics.
- The input of heat recovery efficiency was used to define ventilation system heat recovery.

Through the inputs provided by the tool it was also possible to specify fixed variables:

- The inputs of gross conditioned floor area and volume, windows number and dimensions enabled defining the building shape, volume and windows ratio
- Building location and use inputs enabled defining outdoor environment and use conditions respectively, as the calculation method provides standard climate conditions and internal gains based on location and building use inputs

Detailed values assigned in the model are reported in Annex 3. Other design variables could not be represented by the tool inputs, such as, the shading factor from the green facade, and the mechanical systems for heating and ventilation, except the ventilation heat recovery.

6.3.4 Chronological reconstruction: generation and evaluation of the design solution

The uncommon organization of the design team allowed the integration of different design aspects from the beginning of the project. The first proposal based on urban planning regulations was outlined by the architect together with the cost assessor and the structural engineer. The shape of the building and window-wall ratio were decided evaluating different design aspects including space distribution, form, structure and cost.

Therefore, the energy assessment of the first proposal was conducted to verify the fulfilment of the space heating demand requirement. The design solution was modelled with the OIB-hwb02h calculation tool.

Default values for envelope components were initially used and then modified to explore different options to fulfil the space heating demand. Triple glazing was hypothesised; however, as the cost was higher than increasing the insulation thickness, thicker wall insulation was chosen. The decision was reproduced in the model reducing the U of the facades[2] from about 0.35 W/m^2K up to 0.15 W/m^2K. As the design requirement was still not achieved, mechanical ventilation with heat recovery was introduced, but the measure was insufficient.

Design requirement was achieved by supplementing a heat pump to increase the heat transfer between the exhaust and supply air (Figure 6.8). The decision to introduce the heat pump was reproduced in the model increasing the heat recovery efficiency from 50% to 75%. That way, the contribution of the heat pump was included in the calculation of space heating demand by reducing the ventilation heat transfer. A reduction of space heating demand to 19.79 kWh/m^2a resulted from the calculation. The calculation results are shown in Table 6.2.

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[2] In the project documentation that we had access to, the exact value initially established by the building physics' assessor was not available. The practitioners reported in the interview that the values prescribed by technical regulation were used in absence of different values. We take as reference the minimum values required for external wall, 0.35 W/m^2K, indicated by the regulation in force at the time of the project (OIB-300.6-038/07, 2007).

Table 6.1. Synthesis of inputs of the OIB-hwb02h model.
(More extended description of the inputs in Annex 3)

OUTDOOR ENVIRONMENT (C)

Location Vienna

BUILDING (E)

Gross conditioned floor area 5295 m^2

	Area m^2	**U** (1) W/m^2K
Facade	2367	0,15
Roof	901	0,17
Floor/Partition to unconditioned space	939	0,18

	Area m^2	**U** W/m^2K	**g of glazing** -
Windows	641	1.30	0.55

USER RELATED FACTORS (U,I,O)

Heating set point temperatures 20ºC
Internal loads 3 W/m^2
Natural Ventilation and infiltration 0.2 ACH

MECHANICAL SYSTEMS (S)

	Flow rate ACH	**Heat recovery efficiency** -
Mechanical ventilation	0.4	50% - 75%

(1): average (weighted by areas) of the U values used in the model for different components

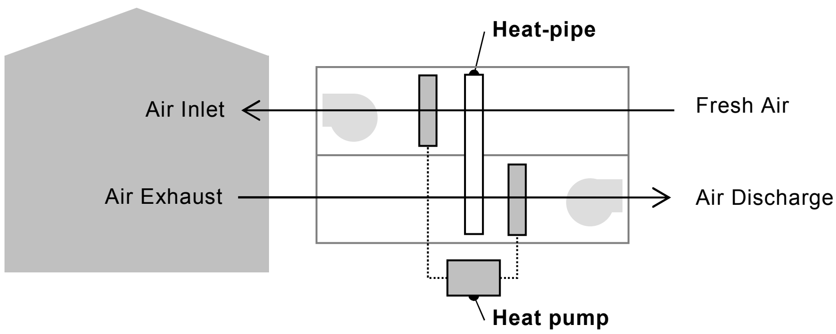


Figure 6.8. Schema of the mechanical ventilation system with heat pump for heat recovery modelled with the OIB-hwb02h calculation tool.

Table 6.2. Space heating demand calculated by the OIB tool for the solution with heat recovery and the improved solution with the heat pump.

	As Design 2007 V1	**As Design 2007 F**	**Requirement**
	Heat recovery	Heat recovery with heat pump	
OIB-hwb02h input Heat recovery efficiency	50%	75%	
Space Heating Demand	25,58 kWh/m²a	19,79 kWh/m²a	< 20 kWh/m²a

The implementation of a reversible heat pump was also intended to provide the possibility of some cooling to the supply air in summer by taking advantage of the same mechanical ventilation system.

During the design phase, the design team also decided to use the district heating to aliment space heating and the hot water production. Moreover a green facade was considered to achieve summer comfort parameters. The energy consumption of mechanical system and the effect of the green facade on comfort performances were out of the analysis enabled by the OIB-hwb02h tool, and therefore, they were not quantified with the tool.

6.4 COMPARISON OF THE DESIGN MODEL WITH A MODEL CALIBRATED WITH MONITORING DATA

To evaluate the choice of the OIB-hwb02h tool, at the design phase, we based it on the data obtained from analysis of the performance of the occupied building. We used a calibrated model as a reference, which was created at the TU Wien[3] and based on monitoring data from 2011.

Note that the monitoring data were collected when the mechanical system started functioning. At that moment, the initial control settings of the mechanical system including the control of the heat pump had to be tested and adjusted. For a more precise analysis data should be collected over a longer period.

The model As Operation 2011 F indicates the actual performance of the building with the heat pump and it is calibrated with the monitoring data. By modifying this model, the model As Operation 2011 V1 is created to represent the actual building behaviour as if it was without heat pump. In Table 6.3, the

[3] The calibrated model was created at the Research Centre for Building Physics and Sound Protection of the Technical University of Vienna.

results of these two variants are presented, comparing data extrapolated from the occupied building and the results obtained by the building physics' assessor at the design phase.

Table 6.3. Performance indicators of the model variants at the design phase (As Design 2007 V1 - As Design 2007 F) compared with the corresponding variants calibrated with the monitoring data of 2011 (As Operating 2011 V1 - As Operating 2011 F). Indicators not assessed by the calculation at the design phase are highlighted in grey.

	As Design 2007 V1	**As Design 2007 F**		**As Operating 2011 V1**	**As Operating 2011 F**	
	Heat recovery	Heat recovery with heat pump	variation	Heat recovery	Heat recovery with heat pump	variation
Space Heating Demand	25,58 kWh/m²a	19,79 kWh/m²a	-23%	16,79 kWh/m²a	13,73 kWh/m²a	-18%
Energy Consum.						
District Heating	n.a.	n.a.	n.a.	61,39 kWh/m²a	56,49 kWh/m²a	-4,90 kWh/m²a
Electricity	n.a.	n.a.	n.a.	18,37 kWh/m²a	29,79 kWh/m²a	+11,42 kWh/m²a
Energy Cost						
District Heating	n.a.	n.a.	n.a.	4,30 €/m²a	3,95 €/m²a	-0,35 €/m²a
Electricity	n.a.	n.a.	n.a.	3,12 €/m²a	5,06 €/m²a	+1,94 €/m²a
Total	n.a.	n.a.	n.a.	7,42 €/m²a	9,01 €/m²a	+1,59 €/m²a

The indicators calculated with the calibrated model encompass space heating demand, energy consumption and energy cost indicators. Space heating demand is calculated as it was done at the design phase, incorporating the heat contribution of the heat pump in the ventilation heat transfer. Energy consumption from district heating includes the heat supply for different uses: hot water; space heating delivered by radiators; and space heating delivered by mechanical ventilation. Electricity consumption includes the alimentation of fans and pumps in hot water, heating and ventilation systems; the household consumption; and the common consumption for the whole building. Energy cost includes the direct cost of energy for the district heating and the electricity.

The introduction of the heat pump for heat recovery entails a reduction of the ventilation heat transfer. As a result, according to the calibrated model space heating demand is reduced by 18%, concurring with the results of the OIB-hwb02h model (23%) used at the design phase.

However, considering the other indicators of energy consumption, the advantage of the heat pump is not evident. In fact, while the district heating supply for space heating decreases, producing a slight reduction of the total consumption for district heating, electricity consumption increases. In terms of direct energy cost there is an increment, as the additional cost for electricity is higher than the saving in district heating.

In sum, the apparent advantage of the heat pump indicated by space heating demand is questioned when energy consumption is analysed. The analysis of real data clearly shows that the space heating demand calculation is not significant to evaluate the impact of the heat pump, and the calculation of consumption is essential.

6.5 KEY FACTORS IN THE CHOICE OF THE ENERGY CALCULATION METHOD

In this section, the key factors for selecting the OIB-hwb02h tool during the design phase are discussed. In particular the calculation method lying behind the tool is considered, rather than its implementation as a software application.

- **Level of discretization**. From the information available, we are not able to reconstruct exactly the information available and its level of details when the model was initially set up. Nevertheless, from the model data (such as location of individual windows on each facade and their dimensions) we can deduce that the design of the building envelope was developed at least at the level of specific elements modelled. Moreover, as deduced from the interview, the level of detail of the model reflects the time available for the building physics' assessor to provide feedback to the design team in a reasonable time. As the building physics' assessor explained during the interview, the OIB-hwb02h tool was chosen because the heating energy demand could be calculated with a relatively small number of input data. For the same reason they decided not to use a complex simulation tool. With OIB-hwb02h, the number of inputs necessary to describe the exterior climate and use-related factors was very limited. In fact, for the quasi-steady-state calculation few constants were needed as inputs; it was not necessary to specify any time schedules (such as occupancy schedules). That was fitting with the need of designers to simplify the input task. In addition, the OIB-hwb02h tool represents the building as a single zone. That way the task of modelling a multifamily building with apartments of different sizes and layouts is substantially simplified. In turn, the accuracy of results is not affected in a relevant way by the fact that space heating demand is averaged for all apartments.

- **Level of complexity of calculation algorithm**. The calculation method is considerably simple compared with advanced simulation tools. In fact, the calculation is limited to space heating, and in particular to analysis is space demand. The consideration of a single energy use, the exclusion of comfort aspects and mechanical systems modelling, considerably reduce the boundaries of the analysis compared with more complex calculation methods (such as EnergyPlus). Being limited to the space demand calculation, the calculation method does not need the complexity that more advanced tools require for solving simultaneously building, mechanical systems and plants. Moreover, the use of a quasi-steady-state calculation method represents a drastic simplification of real phenomena compared with advanced simulation tools. The extension of the entire calculation process is dramatically reduced compared with the number of iterations required for a faithful modelling approach, which entails repeating the calculations for numerous time steps. Furthermore, the simplification of the building volume as a single zone eludes the need for modelling multiple inter-zone heat flows. The simplicity of the calculation algorithm was commensurate to the quick response time and the transparency needed by the design team.

- **Responsiveness to design decisions**. The tool was selected because it calculates the performance indicator that the design team intended to analyse: the space heating demand. The design team also chose a calculation tool that could support their decisions on construction components. In fact, the thermal properties of construction components (such as U and g-values) could be represented faithfully using the model. The calculation method illustrates the impact on the space heating demand produced by variation in the thermal properties that are explored by the design team. Based on the calculation results, the values of the components thermal properties could be defined.

  Through the design evolution, the design team started by considering, beyond the construction components, the ventilation system. The first proposal of using mechanical ventilation with heat recovery could be modelled, but the variant with the heat pump to improve heat recovery could not be modelled faithfully. It was necessary to compare it to an equivalent mechanical system (see discussion about flexibility in representing design scenarios).

  Moreover, the OIB-hwb02h model could only quantify space heating demand, which was not significant to evaluate if heat recovery with a heat pump improved the building energy performance. The introduction of a mechanical system, namely the heat pump, necessarily involves an impact in terms of energy consumption. In fact, the heat pump has a direct consumption of electricity and it acts by reducing the heat consumed from the district heating. So to evaluate its impact it would have been essential to quantify heat and electricity consumption.

  In sum, the OIB-hwb02h calculation method was suitable to evaluate the initial decision on construction components but it was not appropriate to evaluate the introduction of the heat pump for heat recovery.

- **Feedback immediacy**. Sufficient immediacy in the feedback of energy assessment was imperative for the different partners to work in coordination on different design tasks, and to develop the design phase according to the time and budget available. The tool provided rapid feedback on different options assessed. From the interview, we deduce that the time necessary to get and introduce the information needed to build (or modify) the model, to run the calculation, to process and analyse the result, and to discuss them was acceptable in comparison with time available. Nevertheless, the work flow was lowered by the need to replicate each option within different tools.

- **Flexibility in design modifications.** At the beginning of the design process, components characteristics were evaluated and the two hypotheses on heat recovery from ventilation were modelled. Throughout the design process, modifications to the design solution were reproduced editing the model as the design evolved. Introducing the heat recovery into the model was simple. In fact, the model inputs already defined remained unchanged; simply an additional input was assigned: the heat recovery efficiency. Other design modifications would not have been reproduced in such a direct way with this tool. For example, rotating the building to modify its orientation is possible but very unhandy in this model. Instead of directly modifying one angle parameter, it is necessary to modify the orientation of every single envelope surface modelled. The level of detail of that model, which represents individual windows, requires 65 inputs for modifications, one for each window.

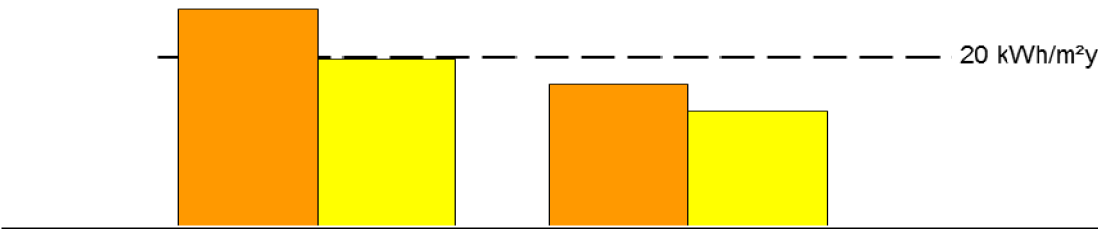
- **Flexibility in representing design scenarios**. The tool was initially flexible enough to represent all different envelope variations evaluated and the first hypothesis of heat recovery.

  Nevertheless, when the heat pump was introduced for the heat recovery the model was unable to represent it. To emulate the heat pump effect in the calculations, the efficiency of heat recovery was increased from 50% to 75%. The model did not represent the actual design solution, but an equivalent solution intended to produce similar performance.

  This kind of assumption is often made by practitioners. In this situation, the competence and experience of the energy assessor plays an essential role in detecting misleading results and avoiding incorrect interpretations. In this particular case, the assumption of the building physics' assessor to emulate the heat pump was probably a hazard. In fact, a heat pump for heat recovery in a centralized mechanical ventilation system of an apartment building was uncommon in Austria (Feist, 2004), and the design team had no previous experience of this kind of application of heat pumps. Therefore, they could not actually know whether the result of the model would have been reliable or not, thus, the utility of the model for this design decision was questionable.

- **Accuracy**. To evaluate the accuracy of the results obtained from the model created at the design stage, we compare its results with the results of the analysis of the occupied building (Table 6.4). It is necessary to take into account that the monitoring data from the occupied building had been gathered when the mechanical systems started functioning and control settings had to be adjusted. So the considerations suggested by this comparison should be corroborated by monitoring data from a longer period.

Table 6.4. Space Heating Demand of the model variants at the design phase (As Design 2007 V1 - As Design 2007 F) compared with the corresponding variants calibrated with the monitoring data of 2011 (As Operating 2011 V1 - As Operating 2011 F). The option exceeding space heating demand limit is shown in grey.



	As Design 2007 V1 Heat recovery	**As Design 2007 F** Heat recovery with heat pump		**As Operating 2011 V1** Heat recovery	**As Operating 2011 F** Heat recovery with heat pump		**Requirement**
Space Heating Demand	25,58 kWh/m²a	19,79 kWh/m²a	-23%	16,79 kWh/m²a	13,73 kWh/m²a	-18%	<20 kWh/m²a

At the design stage, the design team introduced ventilation heat recovery (As Design 2007 V1). The OIB-hwb02h model indicated that the space heating demand was above the upper limit of 20 kWh/m^2·a. So heat recovery was improved with the introduction of the heat pump (As Design 2007 F). With the improvement, the model indicated that the requirement was achieved. In contrast, according to the analysis of the occupied building the design requirement is achieved for both options, the building without heat pump (As Operation 2011 V1) and with heat pump (As Operation 2011 F).

This suggests that with the OIB-hwb02h model accuracy it is only possible to make a conventional verification, based on simplified calculation assumptions[4] which has no pretentions to reflect the real

[4] Simplified calculation assumptions lie in the simplified structure of the quasi-steady-state calculation method and the standard boundary conditions for climate and use. An additional simplified assumption is introduced by the building physics' assessor that decided to emulate the heat pump effect by increasing the efficiency of heat recovery.

building performance. While the model accuracy is insufficient to predict the real building performance and verify if the two heat recovery options satisfy the requirement.

In addition, it is interesting to consider the impact produced by the heat pump according to the design model (-23%) compared with the analysis of the occupied building (-18%). The percentage variation shown by the design model is coherent with the analysis of the occupied building. This suggests that the accuracy of the design model is sufficient to indicate the approximate variation of heating demand associated with this design decision.

- **Suitability for holistic design.** The design team needed to balance time and human resources between energy analysis and other essential aspects of the project. The design was initially developed evaluating primary design aspects such as the building cost and structure. Then building physics' assessment was integrated, including the use of the energy calculation tool OIB-hwb02h. The choice of a relatively simple calculation method responded to the moderate priority of energy in particular beside the cost assessment. The various aspects were developed collaboratively, as all consultants were working in the same office.

  Energy performance was modelled separately from other performance aspects: the OIB-hwb02h tool is based on a dedicated calculation method only for space heating demand calculations, and it does not integrate multiple analyses. However, the moderate complexity of this calculation method could foster the shift of attention required during the design process between the energy assessment and other design aspects. The integrated development of the project was possible mainly through the collaboration of the different specialists. The simplicity of the tool played an important role in order to make collaboration effective. The moderate level of discretization of the model, feedback immediacy and the low level of complexity of calculation algorithm were determinant. In fact, it was important for the building physics' assessor to provide rapid feedback to the design partners and to bring understandable results for discussion. In this way, the simplicity of the calculation method facilitated the integration of multiple design aspects.

- **Data coherence preservation**. Throughout the project, information was produced using different dedicated models for energy, summer thermal comfort, thermal bridges and acoustics analyses. Furthermore, two different tools were used to calculate energy performances: OIB-hwb02h during the design phase and ArchiPHYSIK during the construction phase. The use of separate tools required translating information several times between the OIB-hwb02h model and other models. It is evident that this increases the risk of inputs' errors. It is also evident that the different inputs' formats of each tool had favoured inconsistencies and asynchronies though different representations during the design process. In this case study, specific inconsistencies existing between each model have not been investigated. However, it must be noticed that inconsistencies between the different models were acceptable as long as they would not affect model outputs' accuracy needed to answer design questions. The translation of information several times through the design process probably also provided a benefit for the project, by strengthening the insight of the project matured by the building physics' assessor and other members of the design team.

- **Transparency**. The calculation method was transparent enough for the needs of the project. In fact, it is very simple and based on widely used magnitude, the degree days. In particular, the hwb02h method had broad diffusion in Austria and the building physics' assessor was familiar with it. Therefore, results could be easily interpreted and the physical meaning of the project model was easily understood by the building physics' assessor and communicated to the design team. Nevertheless, when the later decision on the heat recovery with heat pump was considered, the calculation method was not providing any significant help to understand the behaviour of the new design solution proposed. In fact, the crude reduction of its characterization to one efficiency value provided a very poor representation of the design option. In particular, the attempt of emulating the heat pump effect by altering the efficiency of heat recovery with a fictitious value involved a non-transparent use of the method. The building physics' assessor could not compensate for the limitation of the calculation method: based on his knowledge and experience he had no proven guaranties that the increment of the heat recovery efficiency to 75% could correctly reproduce the impact of the heat pump.

6.6 CONCLUSIONS

The specific goal established in the project for the space heating demand was formally achieved: according to the calculation, the requirement of space heating demand was satisfied. The OIB-hwb02h calculation method was the instrument for this verification.

The calculation method only enabled a formal verification, based on conventional calculation assumptions without pretention to predict the real building performance. The analysis of the real data suggests that the model was not capable of ensuring that real building performance reaches the requirement.

It is evident that the choice of the calculation method was not secondary. According to the analysis of the ten key factors, the tool supported the practitioners during a part of the design process, but it was not appropriate throughout the whole process. At the beginning, it was adequate to support the decisions on building construction properties, but later it gave insufficient information to support the decision on the heat recovery in the ventilation system.

When designers addressed the decisions about building construction properties, an appropriate trade-off could be found in the choice of the tool. In particular, the OIB-hwb02h method calculated the space heating demand, which is a representative indicator of the effect of building construction properties on thermal performance. At the same time, the immediacy of the calculation feedback was acceptable, so they could progress timely in different aspects of the project. In addition, the tool was transparent for the building physics' assessor.

Later, when the mechanical ventilation system was considered, the calculation method offered the immediacy needed by the designers. However it was not flexible in representing the option of the heat recovery with the heat pump. In addition it was unable to quantify additional performance indicators necessary to evaluate the impact of the heat pump. Clearly, a more comprehensive range of indicators not calculated by the OIB-hwb02h method was needed to make a well informed decision on the heat recovery. In that sense the model capacity to enhance the knowledge of the design team was limited. Possibly, a better trade-off could have been achieved with a different tool, but it was not trivial to satisfy conflicting needs. In fact, the use of a more complex tool, flexible in representing alternative heat recovery options and to quantify more indicators, was difficult to conciliate with the necessary immediacy in energy analysis. It would have been complicated to dedicate more time and effort to a complex energy analysis against the necessity to examine and resolve other fundamental aspects of the project such as cost and structure.

A paradox may be observed in the project, which is contradictory with an effective use of energy calculation within a design process. In fact, the calculation supported decisions on which the design team had more experience, namely, the definition of construction components. In turn, the tool was weaker where more answers were really needed: on innovative elements of the project, such as the uncommon mechanical ventilation system. There are two explanations. First, the design process was constrained by time and budget limitations. Knowing that it is more complex and demanding to model mechanical systems than building envelope, designers decided not to model the mechanical systems. A second reason may exist. Possibly the calculation method was chosen with the initial purpose of defining construction components. Then, design evolution led to address the option of the heat pump to improve heat recovery. Often a particular decision emerges throughout the process (Cross, 2007, pp. 65-79), and so, it is possible that this option was not contemplated when the calculation method was chosen. Because of that the selected method was poorly suited to analyse the heat pump.

The case study shows the difficulty to fully support different questions throughout the whole design process with a single tool. Although no radical changes occurred, the design process evolved: throughout the process different decisions had been considered, the need of new indicators had risen, and information demand had increased. Therefore, the OIB-hwb02h calculation method that initially offered an acceptable trade-off became inadequate during the process evolution.

The case study also shows that the use of energy modelling is not necessary to address any design decision or for any question related with energy performance; but it can be exploited when the experience is insufficient to provide satisfying answers. For example, the building shape and opening ratio of the facades were decided at the beginning of the project before using the OIB-hwb02h tool.

The need for further investigation emerges from the case study. In the project, an important barrier to an energy-conscious design approach and to the use energy modelling tools was extra time and cost. In ordinary projects like this, it is not clear how this financial necessity has to be covered. The problem of extra cost of sustainable design may involve economic, political and ethical considerations that are out of the scope of this dissertation. Yet, this kind of considerations is needed for a feasible application of energy modelling in design.

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Chapter

7

Discussion and general conclusions

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Throughout this chapter we articulate a general discussion and the conclusions of the whole thesis according to the following structure. In Section 7.1, we point out the results achieved through the shift of research perspective proposed in the thesis and we highlight essential reasons for the scarce application of energy calculation in design. In Section 7.2, we examine in more detail the results obtained, exposing all the main outcome of the thesis, then we provide some additional considerations. In Section 7.3, based on the results of the research, we answer the issues raised in the introduction of the thesis. In Section 7.4, we identify some open problems that might require future research.

7.1 A DIFFERENT RESEARCH PERSPECTIVE. RESULTS

We have highlighted that most analysed literature has investigated the energy calculation in building design from the specialist perspective of engineering and building physics. Thus, we have proposed a different point of view from the perspective of building design. Accordingly we began our study from the analysis of the design process. Through this change of perspective we have achieved the following results:

1. We have identified several implications of the use of energy calculation in the design, which enable a better understanding of how and how far energy calculation may be effectively exploited in ordinary design.
2. Based on the first result, we have filled a research gap providing a systematic analysis of the key factors in identifying suitable calculation methods for a design team in a particular project and design stage. The influence of these factors has been illustrated and tested in two case studies.

Without making some previous assumptions about the nature of building design, it would not have been possible to arrive at these conclusions concerning the use of energy calculation methods and their suitability in building design.

To better understand the potential of energy calculation in design, first it has been essential to comprehend the reasons for its limited application. The limited application of energy calculation in design has been highlighted in existing literature, mainly in the fields of engineering and building physics, but not all reasons for this have been analysed in depth. According to our study some reasons are tightly routed into the nature of the design process. In particular, having analysed the crucial match of calculation method features with the necessity of practitioners, we have seen that achieving this match is far from obvious. There is no calculation method that can provide an adequate response for the needs of each particular project, and for all phases of the design process. This is due not only to the complexity of energy modelling, but also to the complexity of design practise. In fact, the evolution of any design process is largely implicit, unpredictable and difficult to structure in advance. The information necessary for the energy calculations is conditioned by the progress of the design process. Because of this, it is not easy to integrate the energy performance with other aspects that arise through the process. In the end, each design process is a unique case, and for this reason it requires calculation methods that provide specific capabilities.

7.2 HOW FAR ENERGY CALCULATION MAY BE EXPLOITED IN DESIGN. SYNTHESIS OF THE MAIN OUTCOMES AND ADDITIONAL CONSIDERATIONS

In this section we synthesize our understanding about how and how far energy calculation may be exploited in design. In particular, the main outcomes reported in the next sub-sections concern: the methodologies to integrate energy calculation in design; the choice of suitable calculation methods; the need to align the use of energy calculation to the general scope of all design processes; the underestimated limitations for the use of energy calculation in design; and the need of a range of competences within design teams.

In addition, within this section, some conjectures stimulated by the results of our work are included, because they are important to set the base of future research. In particular, we discuss the necessity of a culture based on shared values and basic knowledge on the environmental issues, as a condition to improve energy efficiency. Moreover, we consider the risks associated to the use of energy calculation in absence of this cultural framework.

7.2.1 Design methodologies for the integration of energy modelling

From our analysis, it is still not clear how effective it is to proceed in energy modelling according to structured and established performance assessment methods through the design process. Certainly, energy assessors must proceed rigorously to manage the complexity of energy modelling into the articulated and changing context of a design process. However, they must also be flexible to adapt to unpredictable circumstances that are likely to arise throughout the process. In light of these considerations, the main challenge for research is not delivering design methodologies to design teams, but to enable them to tailor existing calculation methods to their own practice. That means studying how design teams work, to understand how they may fully exploit the vast pool of existing calculation methods by adapting the methods to their working practice. From that perspective, the correspondence between the necessities of practitioners and the features of the calculation methods is fundamental. We have investigated such a connection, which enables the choice of suitable calculation methods. The outcomes achieved are presented next.

7.2.2 The choice of suitable calculation methods in design

According to our research, the selection of the calculation methods is fundamental for an effective energy assessment in design. In other words, it is necessary to find calculation methods that facilitate the decisions that are made throughout the entire design process and that affect the energy performance. At the same time, it is essential to select calculation methods that do not hinder the progress of the design process nor induce to penalize other design aspects. For an adequate choice it is necessary to match the features of calculation methods with the necessities of practitioners, which are specific to each project and design stage.

It is evident that there are no optimal calculation methods for a particular design situation. In a favourable case, it is possible to find more than one appropriate calculation method. Whereas, in other situations, hardly any suitable calculation method can be found, and it is necessary to evaluate the building energy performance based on experience or rules of thumb.

Through our investigation we have been able to understand some of the difficulties inherent to the identification of proper energy calculation tools which can be successfully deployed throughout the design process. In fact, it is not easy to fully satisfy all design needs with an appropriate trade-off among all the key factors in the choice of calculation methods. For instance, prevalent needs, like immediate analysis feedback and equilibrated allocation of resources to achieve a holistic solution, may require sacrificing the accuracy of energy analysis, as shown in the two case studies. As a consequence, in many design situations, the calculation method that one can select from the existing ones is just an acceptable choice.

We have observed that finding suitable calculation methods is made more complicated due to the unpredictable evolution of the design process. If a tool has been selected at the beginning of the process, it is difficult to know how far it will fulfil the necessities that emerge later in the process. In fact, it often occurs that a calculation method does not satisfy the rise of new design needs. For example, if a new design option arises which cannot be modelled with the already selected tool and analysed with its underlying calculation method, then it might be necessary to change the tool. For example, in Case B, the calculation method initially used to decide on building components becomes inadequate to evaluate alternative options for the ventilation heat recovery. Using a progression of tools is not a simple solution. In fact, energy modelling is already very demanding when a practitioner is working with a single tool. If, in addition, it is necessary to change between different tools, then it becomes even more arduous. In short, the unpredictable evolution of design processes is an obstacle to the use of energy calculation methods.

In conclusion, practitioners must cope with the dynamic nature of the design process. So it is important to consider that it is not necessary to carry energy modelling on continuously through the whole design process, and analyse the design solution whenever it changes. Often it is sufficient to make energy calculations only when they are required to answer a few crucial design questions arising at specific moments of the design process. For instance in Case A, both energy modelling tools, Archisun and DesignBuilder, appear in the design process only when they are needed to evaluate specific design decisions. First Archisun is used to decide on the opening ratio and later DesignBuilder is used to verify that space cooling is not necessary.

For the identification of suitable calculation methods, we stress that energy modelling is not restricted to advanced energy simulation. It is necessary to also acknowledge the role of simple calculation methods, despite their limitations. For design applications, a broad view of energy modelling, from simple calculation methods to complex ones, is required. The calculation tools considered in the case studies are representative of this variety. The OIB-hwb02h tool is based on a simple quasi-steady-state method for space heating demand calculation. In contrast, EnergyPlus offers a more complex simulation approach, enabling sub-hourly calculation steps, simultaneous solutions for multiple building zones, systems and plants, and coupled analysis of various domains. It is essential to have a broad view taking into account the variety of existing calculation methods, in order to find an appropriate modelling approach in each design situation. Advanced simulation methods allow analysis of most design scenarios including buildings with complex behaviours, but as we have shown, several limitations exist for their application. If we consider simple modelling approaches, their capability to analyse physical phenomena is especially limited in buildings that have complicated behaviour. In spite of this, the role of simple calculation methods seems particularly relevant in ordinary design practice, which is characterized by strongly limited resources. The importance of these barriers has been confirmed by practitioners in the interviews we carried out for the case studies.

To take advantage of energy calculation for the design of energy efficient buildings, practitioners and researchers must understand the importance of each key factor in the choosing of calculation methods. Clearly, this is not a sufficient condition for the design of efficient buildings, but it is fundamental in order to exploit existing tools.

7.2.3 Aligning energy calculation to the generic objective of design

Besides discussing the different kinds of calculation methods that one can select, it is necessary to make some considerations that affect every calculation method applied in a design context.

We remark that any energy model requires an exhaustive and consistent description of the object being analysed, that is to say, the design team has to specify all values required to provide such a description for all inputs for the calculation. During a design process and especially at the initial design stages, it happens that the definition of a design scenario being analysed is partial. However, it is impossible to obtain the outputs from the calculation without filling the information gaps between the design scenario and its model. Practitioners must work to close in this gap. So, to get the output from the model, the design process has to adapt to the inputs demanded by the calculation method being used. The contradiction between the partial definition of the design scenario and the complete specifications required by the energy calculation method lies in the diversity of the primary objectives of design and energy calculation methods. The design of a building aims for a final design solution and it is not important if tentative solutions analysed during the process are vague and incomplete. In contrast, the purpose of an energy calculation method is the analysis of the building behaviour, which requires a complete description of every design solution to be analysed.

A full understanding of the generic objective of design is fundamental for the effective exploitation of energy modelling in design. The aim of the design of any building is to achieve a satisfying solution with the limited resources available for the project. In ordinary design practice resources are especially limited. That means that the purpose of a design process is not to carry out an extensive exploration of all possible design options, neither to produce an accurate model, nor to pretend to gain a deep understanding of the physical behaviour of the building. A complete achievement of all these purposes is probably unfeasible in a real design process. Most importantly, pursuing those objectives is essentially useless, unless a satisfying design solution is achieved. Therefore, the degree of accuracy and the detail of the analysis must be aligned to the project circumstances to ensure that an appropriate solution may be produced within project limitations. In short, to exploit energy calculation methods their use must adapt to the aim of design.

In both case studies, it has been shown that the final goal of design determines the use of energy calculation. In Case A, the necessity to conclude the design process with a satisfactory solution leads the energy assessor to a very limited use of EnergyPlus compared with its potential. While in Case B, the need to find the final design solution within a limited time is determinant for the choice of the simple calculation approaches provided by the OIB-hwb02h tool.

7.2.4 Underestimated limitations to the use of energy calculation in design

Often, the severe limitations that hinder the use of energy calculation tools in building design are not sufficiently considered in literature.

A fact that is often underestimated is the reluctance of design teams to attain to strictly established design methodologies that integrate energy modelling in design. In fact, it is difficult to adapt predefined and rigidly structured procedures to the complex and unpredictable evolution of a design process.

Likewise, the limited resources and time available compared with those required for energy modelling are often underestimated. A considerable amount of time and intellectual resources are spent by design teams to cope with the complexity of the design process. Then, often the available resources are too limited for design teams to use complex calculation methods in a proper way. When the effort of practitioners is absorbed by over complex analysis approaches, it becomes extremely difficult to keep a clear view of all design aspects throughout the whole design process.

Another limitation comes from the need to balance the allocation of resources between energy modelling and other design tasks, in a way to achieve a satisfactory solution under all relevant design aspects.

A further limitation, of which practitioners also might not be fully aware, derives from the need to synchronize energy modelling and other design tasks to ensure the progress of the design process.

The analysis of a real example in Case B has shown that the limitations associated to resource allocation and synchronization of design tasks are fundamental reasons for the energy assessor to select a simple calculation method.

The following limitation has been also detected. The potential that lies in the theoretical possibility to choose from a wide range of existing calculation methods is limited in practice. In fact, practitioners tend to be reluctant to use many different tools, due to the inherent costs and the difficulties of the learning process. For this reason, an energy assessor usually prefers to use one or only a few tools. In turn, no single tool and underlying calculation method are suitable for the extreme diversity of the design situations that may arise in his professional activity. This problem is even likely to occur during the same design process, in which a single tool is not capable of answering all the questions that arise. This is exactly what happens in Case B. Then, the limited number of tools that a practitioner currently uses is an obstacle for the broad application of energy calculation. This obstacle is only partially mitigated by the flexibility of some calculation methods which enable the analysis of quite diverse design scenarios.

A further limitation affecting energy modelling in building design needs to be underlined. Unfortunately, there is no absolute guarantee of reliability of results when applying a calculation method to a specific building design. In fact, each building design scenario is unique, therefore it is not possible to have calculation methods which have been validated for any possible design scenario. So, there is no absolute certainty on the results provided by a tool, and how they should help to enhance the performance of a building. In these circumstances, the competences of the energy assessor, who should provide a critical interpretation of the results based on the knowledge of the energy domain, are absolutely necessary. This is the best and only guarantee of a reliable analysis that contributes to an effective enhancement of building performance.

7.2.5 The need for a range of competences within the design team

Besides the limitations mentioned so far, some important obstacles to the application of energy modelling has to do with the competences of practitioners. An appropriate range of competences in design teams is necessary to achieve effective use of energy calculation in design. The possession of these competences by the members of a design team is not necessarily obvious.

First of all, the energy assessor must possess a range of different competences. A theoretical background building physics is paramount. Then, understanding the transposition of physical phenomena in terms of models is necessary. That means, having some notions about the different modelling approaches that exist. In addition, a deeper knowledge of the specific calculation methods that a practitioner normally uses is essential. Besides the insight into the calculation methods, practical skills and confidence with the use of the calculation methods (and the corresponding implementation tools) are also needed. The energy assessor should also have, in some degree, other competences possessed by the rest of the design team.

A design team would need to have a theoretical background in design, including the multiple disciplines required to analyse all aspects of a design problem. At the same time, design team members must possess practical skills in design tasks and have confidence with the design practice to manage the design process and use design tools.

The simultaneous presence of all these competences in current design practice is not to be taken for granted: often only partial and unconnected knowledge and skills are present in a design team. In particular, if we focus on the energy assessor, a profile that combines all the competences we have mentioned is probably lacking in the majority of projects.

7.2.6 The need for a culture based on common knowledge and ethics

The existence of appropriate competences within design teams might provide a sufficient framework to make the use of energy calculation in design technically feasible. However, the application of energy calculation is not a goal in itself. It is a means -unquestionably not the only one- to reach the ultimate goal of reducing the environmental impacts associated with the energy use of buildings. To achieve this goal, having appropriate competences within design teams is not enough. Such competences have to stand on a broad knowledge and ethical framework that is not circumscribed to design teams, but also involves other stakeholders of the building sector and, more generally, society as a whole. We outline this framework hereafter.

To start with, practitioners have to employ energy modelling as a driver of the design process with the genuine intention of pursuing an energy efficient solution. This means applying energy calculation tools according to an ethical position, taking responsibility for the environmental impact of design decisions. This is not the case when energy modelling tools are used in a project as mere instruments of marketing or regulation compliance, without the commitment to reduce the energy consumption of the building.

A successful design practice oriented to energy efficiency seems to be possible only when all stakeholders of the building sector (from the client, to the constructor, to the users) adhere to the same values of respect for the environment. This is unlikely to happen unless a large part of society shares this ethical position. It is difficult to foresee an ethical change in this direction without a diffuse consciousness about environmental problems. This means that basic knowledge of these problems has to be shared among the design teams, the other agents of the building sector and the rest of society.

In summary, the consolidation of this broad knowledge and ethical framework is fundamental. Only in this cultural context, energy calculation could have wide application in current design practice in a way that is truly oriented to the improvement of the energy performance of buildings.

In most countries, the process of construction of this cultural setting still seems uncertain and far from its completion.

7.2.7 Risks of pushing the use of energy calculation without appropriate knowledge and ethics

At present, we are assisting a transition towards more restrictive regulations on energy performance of buildings. Along the way, we are witnessing an increasingly aggressive appetite among investors for the business of sustainability and building energy. These trends are actually pushing the use of energy calculation tools. However, without a solid knowledge and ethical framework design teams (and the building sector in general) will not be prepared to integrate energy calculation tools in design practice.

We foresee a high risk of an indiscriminate use of energy calculation tools that might lead to misuse of these tools, resulting in a possible deterioration of building performances. This risk essentially relates to the lack of consolidated competences within design teams.

An additional risk is reducing energy calculation tools to an instrument for the compliance of conventional verification procedures, something which is far from the purpose of understanding the energy behaviour of buildings. Even worse, energy calculation may be used in design as a fashionable and purely cosmetic gadget for marketing purposes.

Such occurrences might undermine confidence in the use of energy calculation among those practitioners and clients that are not experts in building physics. Moreover, such misuses are likely to discredit energy assessment and sustainable design practices among other stakeholders of the building sector and society in general.

The identification of these risks confirms that the construction of a knowledge and ethical framework that boosts sustainable design appears essential.

7.3 ANSWERING RESEARCH QUESTIONS

In the precedent section we have summarized our insights about how and how far energy calculation may be exploited in design. Based on these ideas, we may answer the research questions initially formulated in the introduction. Hereafter we report the questions and synthesize the answers we have achieved:

- In ordinary design practice, is it possible to take advantage of energy calculations within the design process to improve the energy performance of buildings?

As we have observed, an effective exploitation of energy calculation seems possible but it is far from being trivial. In brief, this is due to the difficulty of finding an acceptable trade-off to satisfy all design needs that characterize each project. For this reason, the use of energy calculation may be circumscribed during a design process to inform specific design decisions and to answer questions that cannot be answered based on experience or rules of thumb.

- What kind of calculation methods may be adopted?

Nowadays, it is possible to select from a large variety of existing calculation approaches. The kind of calculation methods that is more appropriate differs substantially from one case to another because each design process is unique. In each case, it is possible to evaluate the suitability of calculation methods being used, examining the necessities of the design team during the design process.

- What kind of calculation methods may be adopted in each phase of the design process?

Suitable calculation methods also differ substantially depending on the specific necessities of each design stage. For instance, there is the necessity to deal with different amounts of information at each stage; likewise the frequency of the changes in the design solution differs at each stage. Thus, to identify proper calculation methods, it is fundamental to examine the design needs that emerge at each design stage.

7.4 FUTURE RESEARCH

The work carried out in this thesis raises several issues that are open for further investigation.

- More research is needed on case studies. In particular, it would be necessary to examine the range energy related questions considered in a design process to observe which ones and how many are answered with the aid of energy modelling tools. It would be useful to track the activity related with energy modelling throughout a design process to enhance the understanding on the continuity/discontinuity of energy modelling into the process, its synchronization with other design activities and the relation among energy and other aspects of the design problem. Furthermore, it would be important to quantify the allocation of resources among energy modelling and other design tasks, both in terms of cost and time.

- The relative scarcity of real examples of effective exploitation of energy calculation in ordinary design practice posed a challenge to this research. For future studies in this line, the analysis of other available case studies and the direct observation of real projects would be challenging but surely enriching.

- One of the main motivations behind the work we have carried out is the concern about the environmental impact of buildings. In this regard, the scope of the energy calculation methods considered in our work is clearly narrow and partial (Figure 7.1). From an environmental perspective it would be essential and urgent to extend the investigation to a wider range of quantification methods. It would be necessary to integrate the whole life-cycle-analysis of buildings in design, taking into account all the main environmental impacts. A particular attention must be paid at present to the impacts associated to the climate change, which at present is a major threat to humanity.

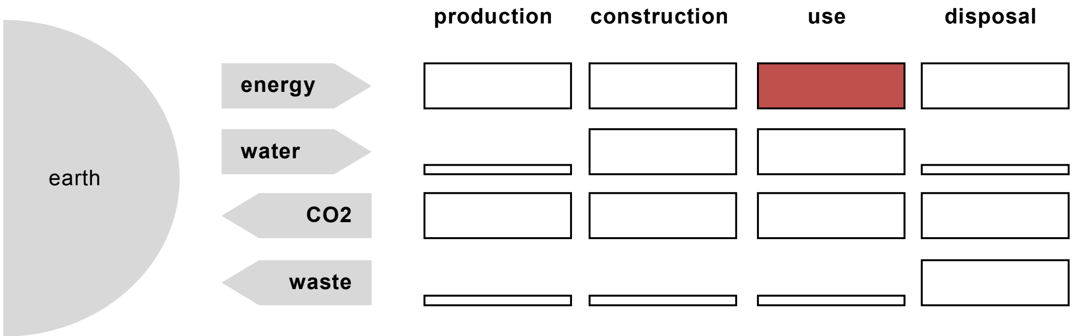


Figure 7.1. Main indicators of environmental impact for life cycle analysis of a building. The calculation methods considered in this thesis only analyse energy associated to the building use.

- A large obstacle which hinders the use of energy calculation methods in design is that their application increases the cost of the design process, as highlighted in Case B. It is not clear how the cost increment might be assumed and who should assume it. Answering this involves economic, political and ethical considerations. Such considerations overcome the limits of the technical disciplines associated to building design and involved in this research. However they cannot be eluded. For the environment preservation, it is urgent to deal with the assumption of these costs.

- In some cases, energy calculation methods may provide uncertain benefits for the improvement of the energy performance of a single building. This partially depends on the lack of accuracy in the predicted performances of the building. It is not clear how far this lack of accuracy really affects predicted performances at the scale of the building sector. In order to evaluate the benefits of using energy calculation in design, it would be necessary to expand this study by taking into account the scale of the whole building sector.

- We have pinpointed the need for a range of competences within design teams to enable them to make effective use of energy calculation. It seems urgent and necessary to build this range of competences within practitioners. Research is needed in this area, which also involves changes in the education in architectural and engineering schools.

- We have also stressed that it is a priority to prompt the creation of a broad knowledge and ethical framework that enables sustainable design practices. The establishment of this context would allow and stimulate practitioners to use energy calculation methods as an instrument to design energy efficient buildings. Our research cannot be dissociated from this complex and urgent challenge. Future research should foster the cultural transformation necessary to enable sustainable design practices. This requires a multi-disciplinary approach which takes into account the relation between ethics, education and society.

- There is an urgent need to understand, and promptly prevent with appropriate measures, the potential risks associated with the misuse of energy calculation in building design.

- Even though our study has focused on the energy performance domain, currently being a primary subject matter for research in the field of performance based design, some of its outcomes might be exploited for further investigations in other performance domains.

- In building design, there is an increasing concern for sustainability and in particular for energy performance. Energy assessment might have a considerable influence in the future transformations of design practice, which would affect the design process. Its increasing importance should be taken into account in design studies. We intended to contribute to this line of research, investigating the integration of energy modelling in the design process from the design perspective. However, more research based on a deep knowledge of the design nature is needed to progress on this line.

Annex 1

Survey on the use of energy calculation tools

ANNEX 1: TABLE OF CONTENTS

1.1 INTRODUCTION

A simple form has been prepared and submitted to different design firm to obtain information on the use of energy calculation tools in their professional practice. Different Spanish and Italian firms, that offer energy and environmental assessment of buildings, are considered. The information obtained from each design firm is provided in a separate form.

The aim of the forms was to collect information on the routine practice of each firm. For that reason, we asked the design firms about their practice in general, to avoid instigating them to focus on their most exceptional projects, which practitioners might be inclined to present.

1.2 FORMS

The following forms (from Table 1.1 to Table 1.5) show the use of energy calculation tools at different phases of the building project life cycle. The number and definition of stages is limited to three. The first two concerning the building Design include Concept design and Design development. The third concerns the building Use.

Some comments are provided regarding the deployment of each tool for each phase. Following questions were suggested to the practitioners to stimulate comments: How often is the tool used? For which scope is it used? Why this tool? For which building type is it used?

In the forms, we intend to provide the original contribution of practitioners. Although, translations and minor editorial adaptations have been made on the original forms filled in from practitioners.

Table 1.1. Use of energy calculation tools at Abac.

Design firm	Abac		

Tool	Design phases		Use phase
	Concept design	Design development	Control/Mainten.
EnergyPlus	Yes	Yes	
	Building indoor environment analysis	Compare passive solutions validate natural ventilation	
Ecotect		Yes	
		Compare and validate solar protections performance	
DOE2		Yes	
		Analyze final energy consumption	
Electric analyzer			Yes
			Get information about the building electric performance

Table 1.2. Use of energy calculation tools at Trama Tecnoambiental.

Design firm	Trama Tecnoambiental		

Tool	Design phases		Use phase
	Concept design	Design development	Control/Mainten.
Ecotect	Yes	Yes	
	Design of the general building form	First light, thermal and acoustics calculations	
Archisun	Yes		
	General consumption estimation		
Trnsys 16		Yes	Yes
		Detailed thermal calculations	Check efficiency of systems control
Radiance		Yes	
		Detailed light calculations	
Envi-Met		Yes	
		Detailed environment edition	
DaySim		Yes	
		Detailed light calculations	

Table 1.3. Use of energy calculation tools at Oriole Vidal Ingenieria SLP.

Design firm	Oriole Vidal Ingenieria SLP

Tool	Design phases		Use phase
	Concept design	Design development	Control/Mainten.
EN13790 simple hourly method		Yes	
		How often? Exceptionally For which scope? To calculate the demand of specific solutions Why this tool? For its simplicity and because it's semi-dynamic For which building type? Small building units of any type	
PHPP	Yes	Yes	
	How often? Sometimes For which scope? To evaluate the impact of different construction improvements (insulation, solar protection, window-type changes...) Why this tool? For its completeness and because it's semi-dynamic For which building type? Small and medium buildings (housing, schools, ...)		
Mc4Suite		Yes	
		Always used. Load calculation for system dimensioning, but also to evaluate the impact of different design strategies (insulations, protections …) and the final building load.	
Lider		Yes	
		Often used. To calculate de goodness of a design, both passive and active, and to compare different strategies (solar vs. district heating….). To comply with the regulations.	
Calener		Yes	
		Often used. To calculate de goodness of a design, both passive and active, and to compare different strategies (solar vs. district heating….). To comply with the regulations.	
Trnsys	Yes	Yes	
	Very seldom. External assessment. Evaluation of the impact of bioclimatic strategies.		

Table 1.4. Use of energy calculation tools at Societat Organica.

Design firm	Societat Organica		
Tool	**Design phases**		**Use phase**
	Concept design	**Design development**	**Control/Mainten.**
DesignBuilder - EnergyPlus	Yes	Yes	Yes
	In rare cases we use this tool at conceptual design phase. This occurs in case of a decisive choice for the whole project in the first design phases (for example, about an atrium or a large parieto-dynamic wall)	We use this tool to evaluate the state of the project and the strategies of reduction of energy demand.	We use this tool to evaluate the state of the existing building and the strategies of reduction of energy demand.
EnergyPlus	No	Yes	Yes
		We use this tool in case a detailed definition of some systems not provided for by Design Builder is needed	
Archisun	Yes	No	No
	We use this tool when we need rough indications at the very beginning of the project, for example, to study the building mass. Instead, Archisun is not useful if you need to define different zones		
Ecotect	Yes	Yes	Yes
	We use this tool often at conceptual design phase. We don´t use it for the calculation of energy demand. Instead, we use it for lighting analyses and design of solar protections.	We use this tool to evaluate the state of the project regarding lighting conditions and the design of solar protections.	We use this tool to evaluate the state of the existing building regarding lighting conditions and the design of solar protections.
Lider	No	Yes	Yes
		We use this tool almost exclusively for normative scope.	
Calener	No	Yes	Yes
		We use this tool almost exclusively for normative scope.	

Table 1.5. Use of energy calculation tools at Prodim

Design firm	Prodim

Tool	Design phases Concept design	Design phases Design development	Use phase Control/Mainten.
Reference performance values from precedent works	Yes		
	How often? Each project For which scope? To define the order of magnitude of plants, air conditioning systems, etc. They are also useful to have in mind the big numbers which characterize each project. They allow keeping under control the following design stages.		
Edilclima, MC4 (software based on technical regulation)	Yes	Yes	
	How often? Often For which scope? The tool is used to refine the quantification made by reference performance values	How often? Each project For which scope? The tool is used for the heating system dimensioning. For simple building, it is also used for the cooling and air conditioning system dimensioning. A normative tool is always used for documenting the conformity to the low.	
DesignBuilder - EnergyPlus (software for the simulation of the dynamic behaviour of building envelope)		Yes	
		How often? The tool is used when the building has a complex architectural design For which scope? The tool is used for buildings with complex forms, large glazed surfaces. It is used when important elements surrounding the building have to be precisely analyzed to consider the influence of shading on solar gains in summer. In our experience on these buildings, this tool is more reliable for dimensioning the cooling system than tools as Edilclima, etc.	
EnergyPlus (software for the simulation of the dynamic behaviour of building envelope and mechanical systems)		Yes	
		How often? In our company, the use of EnergyPlus is very limited because it is very onerous in terms of hours of work. Until now the tool was used only when the building has a complex architectural design and very innovative system types For which scope? The use is used to analyze very innovative systems such as: mass activation systems, seawater-source heat pumps, bioclimatic greenhouse with the function of solar collector in winter and thermal solar chimney in summer.	

1.3 SUMMARY

From Table 1.6 to Table 1.8, the results of the survey are summarized.

Table 1.6. For each tool the indications of different firms are presented. When the same tool is used by different firms, a separate line appears for each firm.

Tool	Design phases		Use phase	N° phases (Design phases -All phases)
	Concept design	Design development		
Archisun	Yes			1
Archisun	Yes	No	No	1
Calener		Yes		1
Calener	No	Yes	Yes	1-2
DaySim		Yes		1
DOE2		Yes		1
Ecotect		Yes		1
Ecotect	Yes	Yes		2
Ecotect	Yes	Yes	Yes	2-3
Edilclima, MC4	Yes	Yes		2
Electric analyzer			Yes	0-1
EN13790 simple hourly method		Yes – rarely		1
EnergyPlus		Yes		1
EnergyPlus	Yes	Yes		2
EnergyPlus	No	Yes	Yes	1-2
DesignBuilder - EnergyPlus	Yes – rarely	Yes	Yes	2-3
DesignBuilder - EnergyPlus		Yes		1
Envi-Met		Yes		1
Lider		Yes		1
Lider	No	Yes	Yes	1-2
Mc4Suite		Yes		1
PHPP	Yes	Yes		2
Radiance		Yes		1
Reference values from precedent works	Yes			1
Trnsys	Yes	Yes		2
Trnsys		Yes	Yes	2-3
	10 cases	22 cases	7 cases	

In Table 1.6 it is shown that some of the tools are used by different practitioners. Often they agree on the phase when each tool is used. Nevertheless, some firms are more restrictive in its application to a specific stage, while other firms are less restrictive and they use the same tool in more stages.

The use of energy calculation tools prevails in later design stages (Table 1.6). In this, the five firms selected reflect a trend observed in precedent studies mentioned in Chapter 3.

In Table 1.7 and Table 1.8, it is shown how often a firm declares that the use of a tool is restricted to one single phase or is extended to different phases. In Table 1.7, only the Design phases are accounted for: in the prevalent situation – 17 cases – the use of a tool is restricted to one single phase, while in 8 cases the same tool is used at different phases.

Different firms make use of Archisun and DesignBuilder (with EnergyPlus as the core of the simulation engine) during the Design phases. Archisun is used exclusively at initial design phases. DesignBuilder is rarely used at initial design phases, in prevalence it is used at final design phases.

Table 1.7. Use of a toll in individual phases or in different phases, considering only Design phases (Concept design and Design development)

	The same tool is used in	
	1 phases	2 phases
Considering Design phases: Concept design + Design development	17 cases	8 cases

Table 1.8. Use of a toll in individual phases or in different phases, considering Design phases and Use phase.

	The same tool is used in		
	1 phases	2 phases	3 phases
Considering Design phases + Use phase	15 cases	8 cases	3 cases

Annex 2

Energy calculation tools

ANNEX 2: TABLE OF CONTENTS

2.1 INTRODUCTION

In the case studies presented in this thesis different energy calculation tools have been considered:

- Archisun 3.0 (in Chapter 5)
- DesignBuilder V 2.4.2.026, with EnergyPlus v6 as a simulation engine (in Chapter 5)
- OIB-hwb02h (in Chapter 6)

These energy calculation tools are described in this Annex.

2.2 ARCHISUN

Archisun is a software application implementing a simple dynamic calculation method.

The software was developed within the framework of a European Commission Thermie programme (DIS-1277-97-ES) by the Architecture and Energy group (AiE), School of Architecture of Barcelona, Technical University of Catalonia (UPC), with the collaboration of the Catalan Institute of Energy (ICAEN), the Technical University of Milan, the University of Hannover, and A.N. Tombazis and Associates.

2.2.1 Type of analyses provided

The tool provides the analysis of thermal comfort and energy consumption for heating and cooling. Moreover, energy consumption is calculated for non-thermal uses including hot water, lighting, cooking and others. Also some indications on acoustics and visual comfort condition are provided.

2.2.2 The calculation method

The thermal calculation method at the core of the tool is described by Serra (2000) and Lopez (2006). It permits the user to analyse a single zone, which may represent the whole building or a part of it. The heat loads calculation is based on the heat balance and transfer equations. The model (Figure 2.1) takes into account direct solar contributions to the interior of the building (I_d), solar contributions on the opaque part of the envelope (I_i), internal loads and heat generation (D), heat transfers from the interior directly to the exterior (ventilation - G_v and transfer through glass surfaces - G_{dt}), and heat transfers from the interior through solid walls to the exterior (G_{it} and G_{et}). The thermal inertia of the building envelope (m_p) and the interior thermal masses (m_i) is also accounted for, considering the effective thermal mass associated to rapid temperature variations[1].

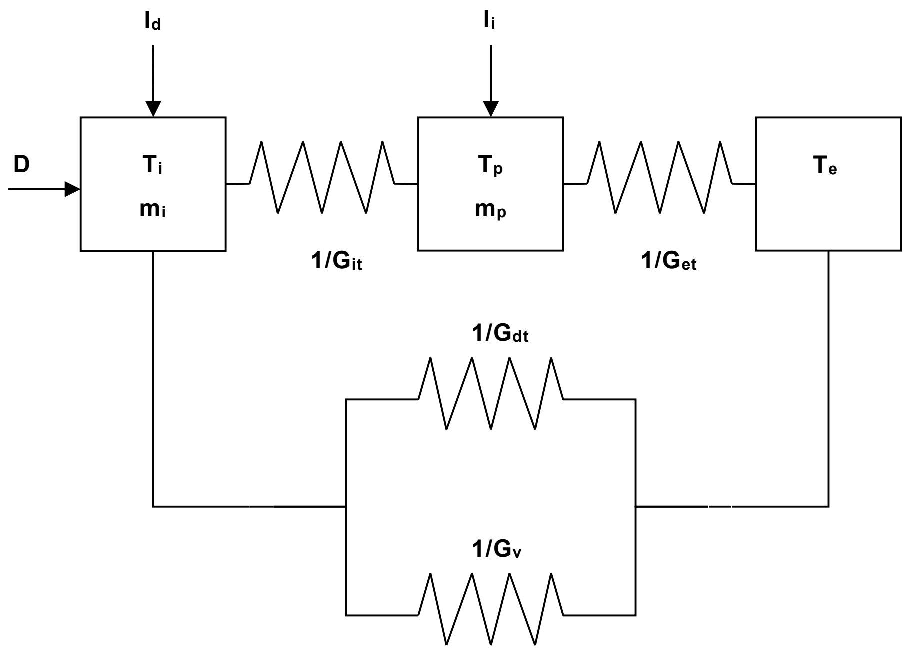


Figure 2.1. Schema of the thermal calculation model (adapted from Serra, 2000).

[1] Quantity, unit and definition of each term are indicated in the help file of the tool (Archisun 3.0, 2013)

The thermal calculation is based on periodic functions by mean of Fourier series. Given the building characteristics, the outdoor temperature and radiation, and the building use, the indoor temperature and the energy balance are determined applying the inverse Fourier transform.

The values of the parameters introduced in the basic equations are obtained as a function of the building characterization and the climate defined by the user.

Calculations are made for four typical periods (of two weeks) corresponding to each seasons. In each period, it is possible to model the dynamic responses of buildings to sequential fluctuations in climatic variables, as well as weekly and daily cyclical patterns of use. For each period, the evolution of the indoor temperatures and different thermal loads is obtained. Based on thermal loads determined for each period, annual energy performances are extrapolated.

After the calculation of the heat demand for space heating and cooling, the tool calculates the consumption according to the efficiency of each mechanical system (heating, cooling and hot water systems). For this calculation the dynamic behaviour of mechanical systems is neglected assuming constant efficiencies.

The approximation of building behaviour with periodic variations, the extrapolation of results from typical periods and the reduction of mechanical systems to constant efficiencies are the main simplifications this allow reducing substantially the complexity of the calculation method.

2.2.3 User inputs

For a typical Archisun model from 10s to 100s of inputs are required: we estimated that the number of inputs to be specified ranges from about 50 to more than 1500, varying according to the inputs' options and the details that the user adds to the model. The user inputs, described by Serra (2000) and Lopez (2006), are presented in this section.

General inputs are provided by the user in the main screen (total volume of the building, building use and number of occupants). Then the user accesses five groups of inputs, called: *"location"*, *"environment"*, *"shape"*, *"skin"* and *"interior"*.

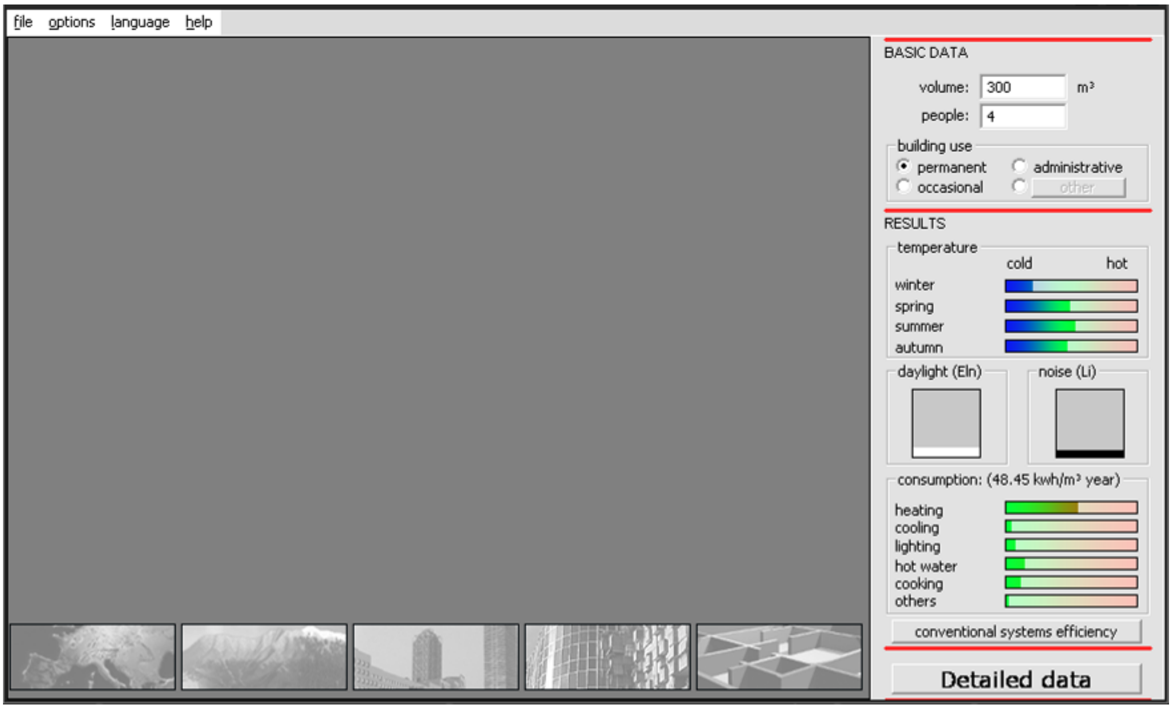


Figure 2.2. Main screen.

In the definition of the *"location"*, the user introduces these inputs: the position on the map, the height above sea level and the urban density. In function of the map position the tool defines a climate zone, sea distance and height above sea level (the last parameter can be changed by the user). Average data for the climate zone are established according to the tool library. A correction is made to the average data for the climate zone. The correction depends on the altitude, distance from the sea and the urban density. The user has also the option to enter specific climate data.

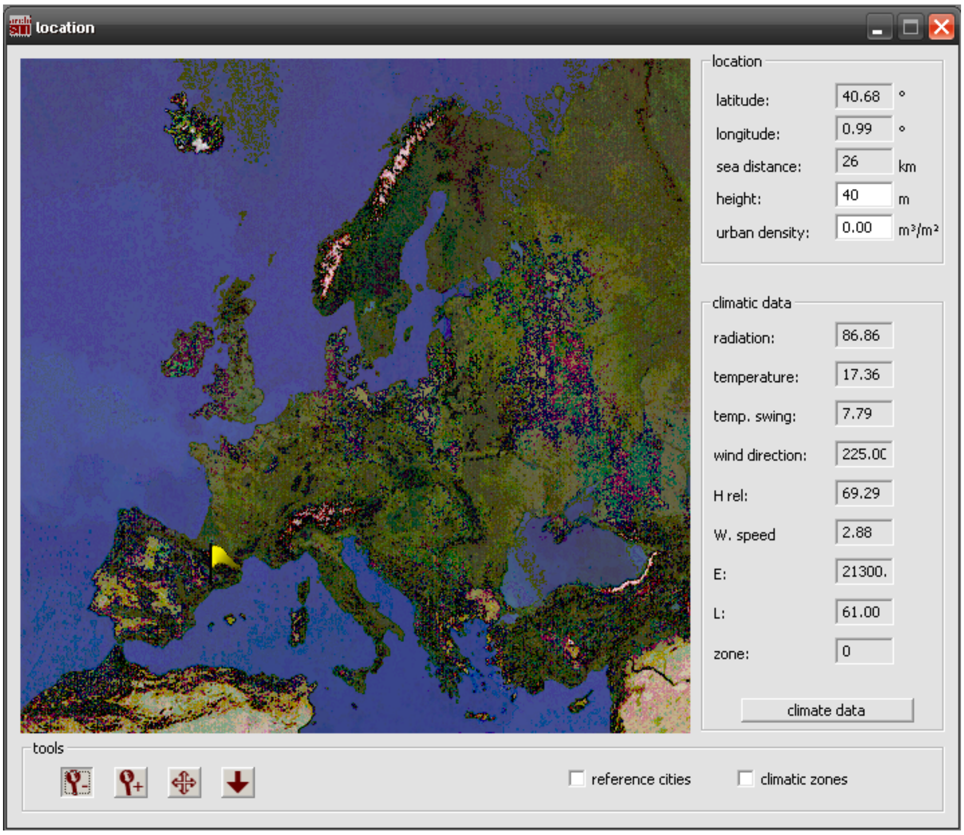


Figure 2.3. *"Location"* screen.

In the definition of the *"environment"*, data of the building surroundings can be introduced to alter the effect climate on the building. The obstruction of solid objects as vegetation (deciduous or evergreen), and the presence of water are described. Graphical information is entered on a diagrammatic plan. The correction of climate data in function of the surroundings affects: average temperatures, temperature oscillations, effective solar radiation reaching the building, relative humidity, intensity and direction of wind, and background noise level in the building site.

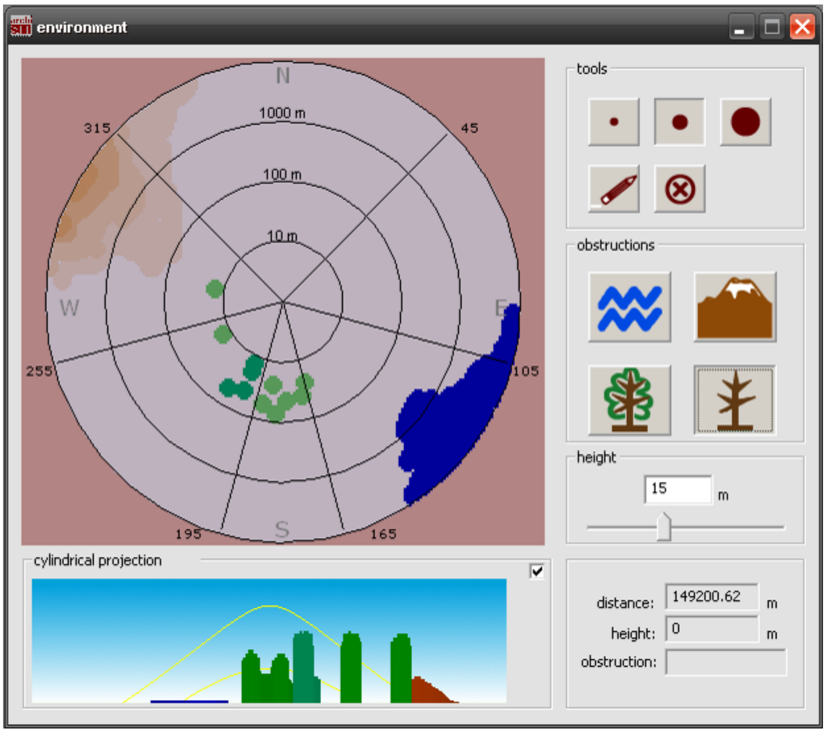


Figure 2.4. *“Environment”* screen.

In the definition of the building *“shape”*, general descriptive terms of the building are provided. The aim of this group of inputs is addressing the first level of design approximation, with *“descriptive terms”* and *“without attempting to fix values”* (Serra, 2000). The inputs introduced by the user include slenderness, lengthening, orientation, compactness and porosity. This set of parameters determines a specific geometric definition for the building that can be modified when further details for the skin are provided.

In the definition of the building *“skin”*, it is possible at different levels of abstraction: two options are provided by Archisun. Low detailed inputs allow outlining the design scenario, and more detailed inputs permits the user to refine it later. Archisun transposes low detail inputs into a complete and consistent set of detailed inputs’ values according to a system of rules.

At the most detailed level, different surfaces are identified by orientation, by adjacency conditions (to the exterior, the interior or the ground) and by type of surface (opaque, transparent and special surfaces). For each surface, the values of specific characteristics may be introduced. These characteristics include heat loss coefficient, mass, solar radiation absorption, solar protection factors, transparency, and equivalent opening for air infiltration, among others.

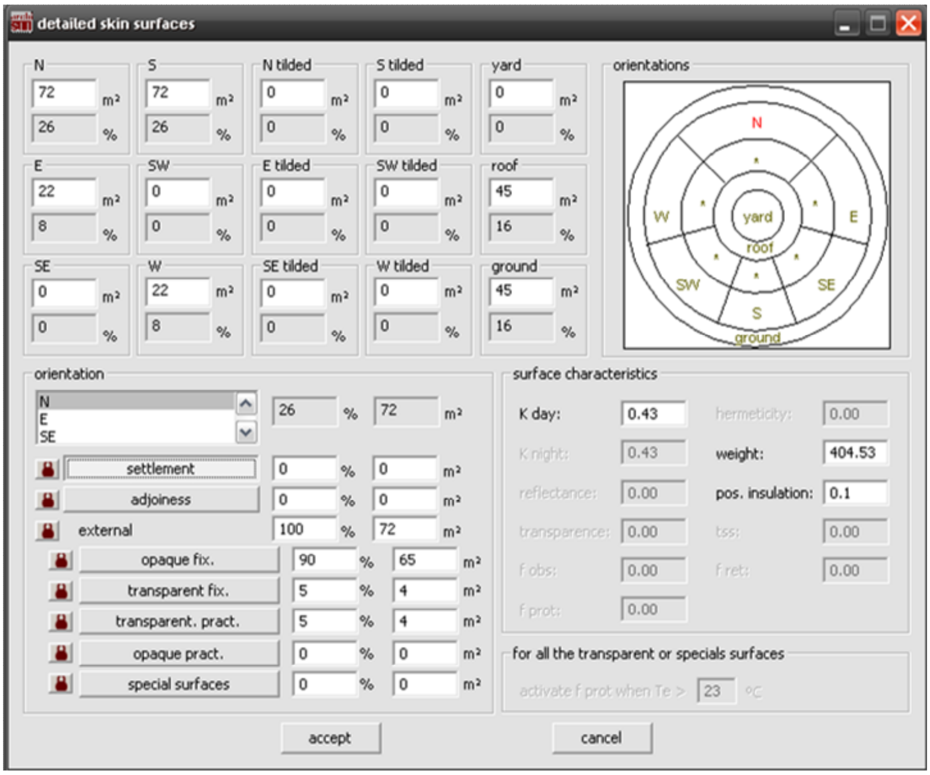


Figure 2.5. *"Detailed skin surfaces"* screen. In the upper part of the screen, areas are indicated for each orientation. In Orientation – lower left part of the screen, each orientation may be selected to specify corresponding sub-surfaces' areas. Each sub-surface may be selected to specify corresponding characteristics at the right.

The parameters defining the building interior include the main internal characteristics of the building that influence the thermal dynamic response and the cross ventilation in the building.

To calculate the energy consumption, the user can further indicate the efficiency of mechanical systems. For each system (including heating, cooling, and domestic hot water), the user can select the conventional system type provided by the tool or specify the efficiency value. In order to calculate the space heating or cooling demand, the user has to introduce an efficiency of 1 for the corresponding (heating or cooling) mechanical system.

2.2.4 Results

Indoor temperatures in free running conditions[2] are expressed as average value (Ti) and average daily variation (dTi) for each season (Figure 2.6). In addition, outdoor environment conditions are reported, including temperature average value (T) and average daily variation (dT) of the season. Also temperature evolution for the typical period of each season is provided.

Annual energy consumptions for each energy use (including space heating, space cooling, hot water, lighting, cooking and others) are expressed in relation with the conditioned volume by kW/m^3 y.

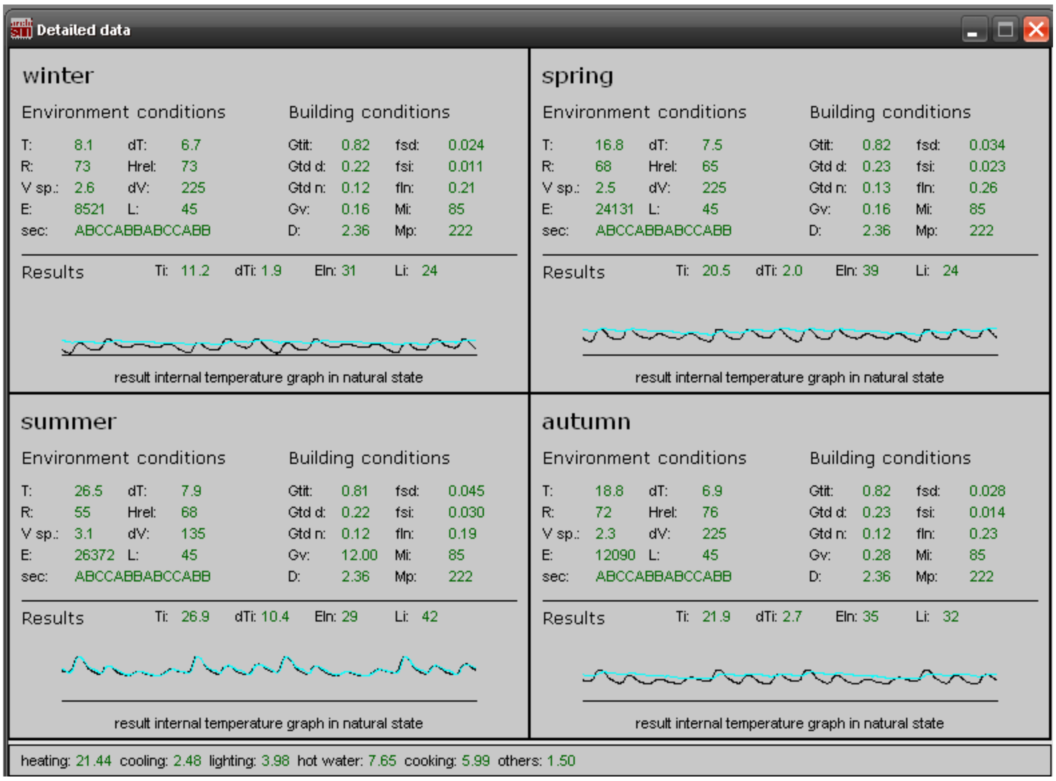


Figure 2.6. *"Detailed data"* screen of calculation results.

[2] The values of internal temperatures when no mechanical systems are operating.

Table 2.1. Symbols and quantities in the *"Detailed data"* screen of calculation results (form Archisun 3.0, 2013)

Gtit	*Indirect thermal transmission coefficient [W/m³Cº], expressing the* [...] *power passing through opaque openings, per one degree difference between interior and exterior, and per volume unit, in the considered season.*
Gtd d	*Direct day transmission thermal coefficient [W/m³Cº],expressing the* [...] *power passing through non-opaque openings, per one degree difference between interior and exterior, and per volume unit, in case of lack of mobile insulating disposal, in the considered season*
Gtd n	*Direct night transmission coefficient exchange [W/m³Cº], expressing the* [...] *power passing through non-opaque openings, per one degree difference between interior and exterior, and per volume unit, in case of mobile insulating disposal, in the considered season*
Gv	*Thermal ventilation coefficient exchange [W/m³Cº], expressing the* [...] *power which external air entrance represents, replacing interior air, per one degree difference between interior and exterior and per volume unit, in the considered season*
D	*Internal gains [W/m³] expressing the energy loose by different causes, such as metabolic rate of people energy load, artificial lighting, electrical household appliances, etc., excluding thermal control systems*
fsd	*Direct solar* [transmission] *factor [m²/m³], expressing the radiation* [...] *getting right into the interior. Given as equivalent* [...] *south oriented surface, without obstructions and with a* [transmission] *rate equal to 1; in m² of surface per volume unit for the considered season*
fsi	*Indirect solar* [transmission] *factor [m²/m³], expressing the radiation getting right into the interior through opaque openings. Given as equivalent* [...] *south oriented surface, without obstructions and with a* [transmission] *factor equal to 1; in m² of surface per volume unit, for the considered season*
fln	*Natural light factor expressing, for the considered season, the rate of interior surfaces which can be supposed illuminated with an accepted level of natural light*
Mi	*Interior thermal mass [kJ/m³Cº] expressing, for the considered season and per volume unit, the capacity of the interior of the building to accumulate thermal energy, for the daily and* [...] *variation cycles whose thermal behaviour is calculated*
Mp	*Skin thermal mass [kJ/m³Cº] expressing, for the considered season and per volume unit, the capacity of the skin to accumulate thermal energy, for the daily and* [...] *variation cycles*
Ti	*Interior temperature [Cº] expressing, for the considered season, the interior mean temperature resulting from the exterior climate conditions and the thermal characteristics of the building*
T	*Average temperature of the season [Cº] expressing the exterior mean temperature resulting from the location and environment conditions*
R	*Daily average of total solar radiation of the season on a vertical South facing surface without obstructions (daily total value divided into 24 h) [W/m²]*
W speed	*Wind average speed of the season (daily total value divided into 24 h) [m/s]*
E	*Daily average total illuminance of the season on an horizontal surface (daily total value divided into 24 h) [lux]*
sec	*Sequence of 14 days with the three types of days (type A (clear), B (cloudy) and C (overcast) given the average climate characteristics for the considered season*
dTi	*Daily average of the interior temperature swing of the season [Cº] expressing the typical variation of the interior temperature, caused by changes in the exterior climate conditions and building characteristics*
dT	*Daily average of the exterior temperature oscillation of the season [Cº], expressing the typical exterior temperature swing caused by changes in the climate conditions*
Hrel	*Average relative humidity of the season [%] expressing the humidity rate of the exterior air, for the average temperature conditions, depending on the location and environment of the building*
dV	*Predominant wind direction [º] in the considered season, according to the location and environment conditions*
L	*Average sound level of the season [dBA], expressing the exterior allowed sound level according to the location of the building*

2.3 DESIGNBUILDER

DesignBuilder is a software application implementing a complex simulation engine.

The core of the simulation engine implemented for energy calculation is provided by EnergyPlus, which is based on a dynamic calculation method, combining several calculation modules. The aim of the developers of EnergyPlus, as a simulation tool, was to faithfully reproduce the physical behaviour of real buildings. For this reason, the calculation method is mainly based on the application the principles of building physics. EnergyPlus was developed by the US Department of Energy and *"it has its roots in both the BLAST and DOE–2 programs"* (US Department of Energy, 2012b, p. 1).

DesignBuilder provides an interface to run the EnergyPlus calculation engine. It also integrates some additional calculation options that are not included in the EnergyPlus calculation engine, such as a simple calculation mode to model mechanical systems.

For Case A, we used the software realise DesignBuilder V 2.4.2.026 which runs EnergyPlus 6.0. An overview of the tool is presented in this Annex based on detailed documentation available (US Department of Energy, 2012a, 2012b and 2013; Crawley, 2001; DesignBuilder, 2013).

2.3.1 Type of analyses provided

"EnergyPlus is an energy analysis and thermal load simulation program" (US Department of Energy, 2012b, p. 1). Since the first release it has integrated other domains of analysis that are coupled with the thermal domain such as lighting, moisture transfer, emissions production and solar radiation (id. pp. 1, 2). In later developments other domains had been integrated such as natural ventilation coupling a multi-zone airflow simulation with the thermal simulation.

2.3.2 The calculation method

An overview of the computational bases of the tool is presented in this section focusing on the thermal analysis, which represents the core the tool.

At the level of building, it is possible to divide the indoor space into different zones. In this way, the interaction of multiple zones is taken into account in the calculation of space heat loads. The space heat loads calculation is based on the heat balance equations of each thermal zone and each surface element separating the zones. The fundamental assumption for space heat balance is that each zone is characterized by a uniform temperature (Crawley, 2001, p. 323).

To extend the analysis to systems, and plants, different calculation options exist in DesignBuilder: it is possible to perform a simple calculation based on constant seasonal efficiencies or to simulate building systems according to simultaneous solution schema of EnergyPlus. In the first case, the system analysis is conducted after space heat loads calculation and the results have no influence on the thermal conditions of the zone. With EnergyPlus calculation option instead, the calculation of heat loads is coupled with secondary systems and plants. In fact, in order to faithfully reproduce real phenomena, *"all three of the major parts* [of the model]*, building, system, and plant, must be solved simultaneously"* (US Department of Energy, 2012a, p. 6). At each time step, a zone heat balance updates the zone conditions and determines the heating or cooling loads. This information is used to determine the system response. This response is returned to zone heat balance calculation influencing zone conditions. Similarly, the system response provides inputs to the plant simulation and results are returned to the calculation of systems (Crawley, 2001, p. 321). In that way, all calculation steps (building, system, and plant analyses) are linked by successive iteration loops in simultaneous solution scheme (Figure 2.7).

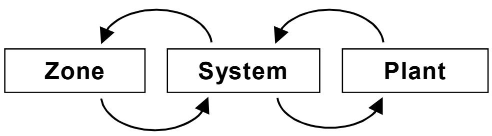


Figure 2.7. Schematic of simultaneous solution scheme (adapted from US Department of Energy, 2012a, p. 7).

A complete analysis of the model is made over a specified period, for instance one year, which is divided in a number of time steps. For each time step, a calculation iteration is made. Based on the results a new iteration is made for the following time steps. The frequency of the time steps, typically hourly or sub-hourly, is defined by the user. However EnergyPlus may vary automatically the time steps used for different parts of the model -building, system, and plant- to ensure solution stability (US Department of Energy, 2012b, p. 1).

The calculation method admits alternative options to model particular phenomena, or parts of the energy system. So that the user may select the calculation approach that is more appropriate for each case. For example, natural ventilation may be simplified introducing airflow rates as boundary conditions or it can be modelled integrating in the calculation process a multi-zone airflow calculation module coupled with the thermal calculation. In the second case, the zone thermal conditions are influenced at each time step by the airflows between zones, and vice versa, thermal conditions influence zone pressure conditions for airflow calculations.

2.3.3 User inputs

Compared with Archisun, DesignBuilder requires a larger set of inputs to create the data model necessary for the calculation. The number of inputs is extremely variable depending on the complexity of a building and the way it is modelled. A business-as-usual approach for modelling the whole energy consumption of a typical residential building may require 1000s of inputs[3]. The tool provides several templates and defaults to define different parts of the model in order to facilitate the model generation. In that way, it is possible for the user to enter or modify detailed inputs, but it is not necessary to introduce all the inputs required for the calculation.

In the first screen of DesignBuilder interface the user indicates the location. Based on it, the tool creates the *"site"* and identifies the associated climate data from the tool library for the calculation.

Figure 2.8. New project data screen

In the Layout (*"Modelo"*) panel, a new building may be created: a 3D editor is used to specify the surfaces that define the building geometry.

[3] New (2012, p. 2) considers a *"business-as-usual approach for modeling whole building energy consumption"* of a typical residential building in the United States, which is a single family house. He affirms that using EnegyPlus about *"3000 inputs"* are needed.

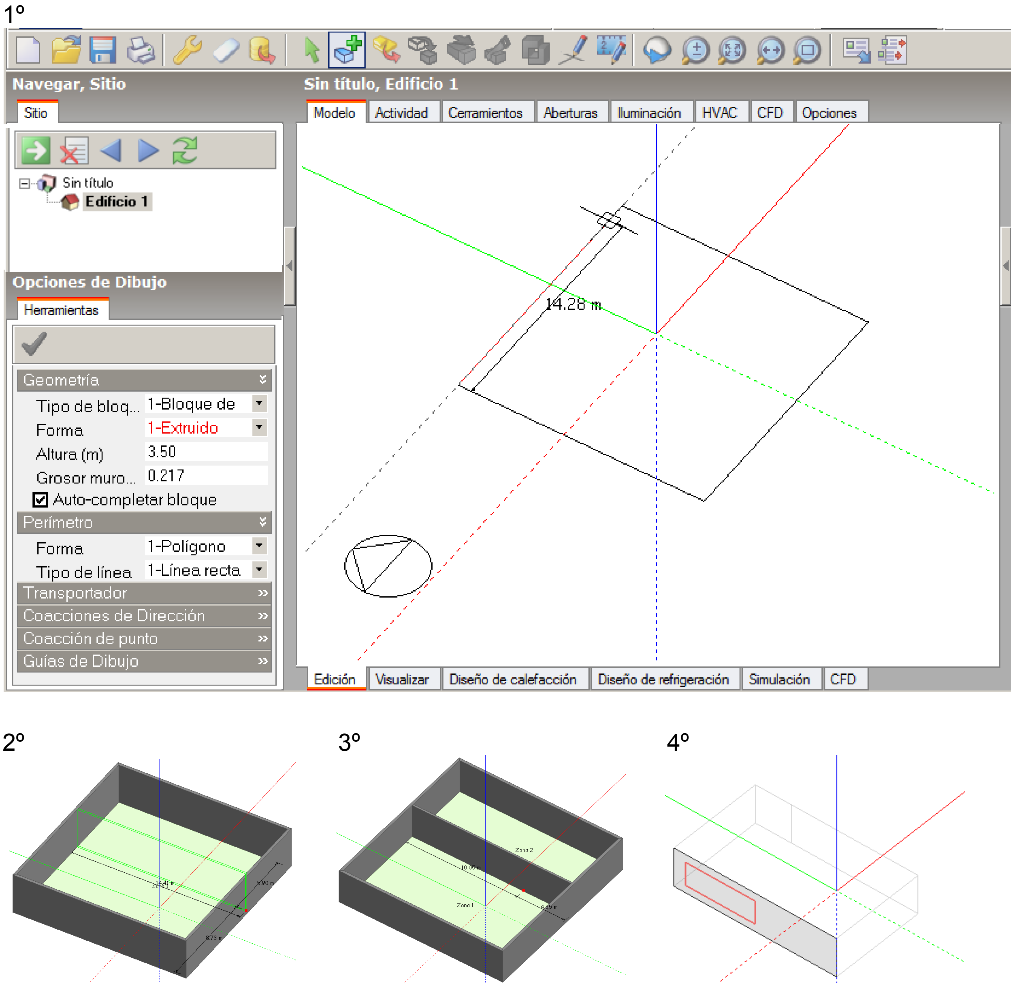
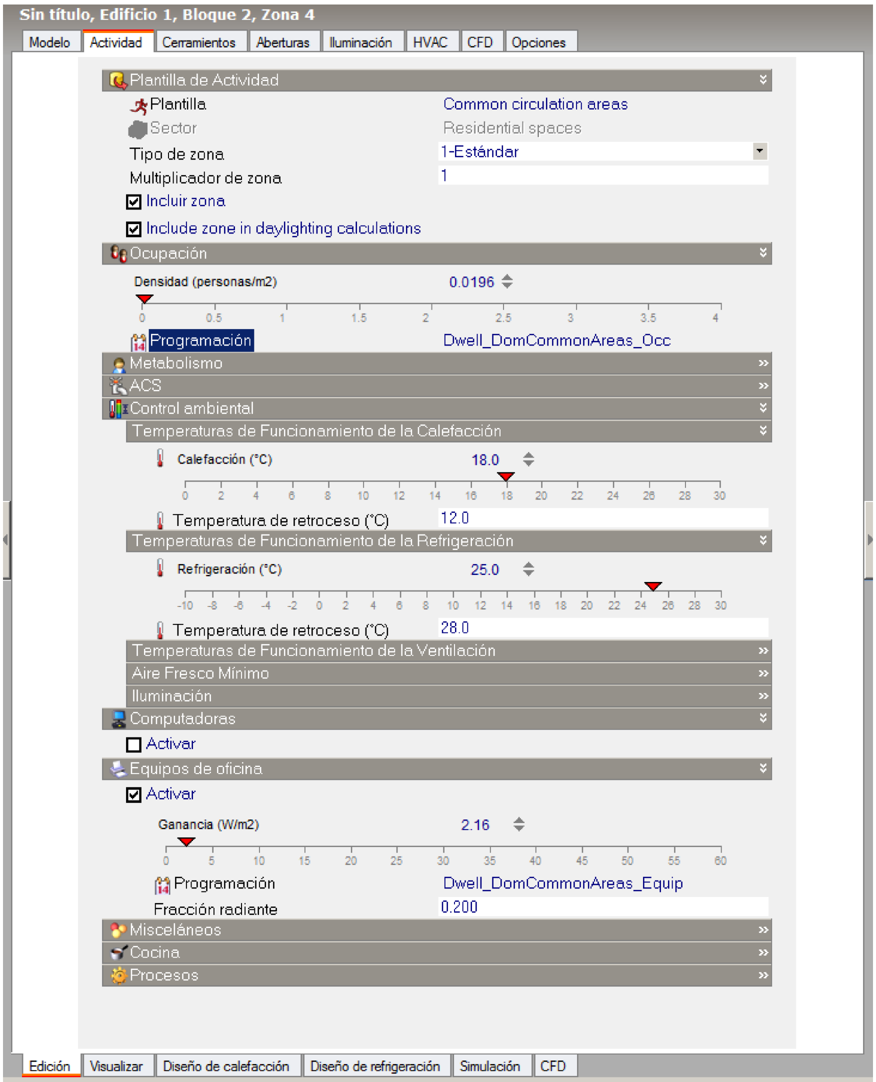


Figure 2.9. For 3D geometry edition of building blocks (1º - 2º), partitions between zones (3º), openings (4º), etc., Layout (*"Modelo"*) panel in the Edition screen.

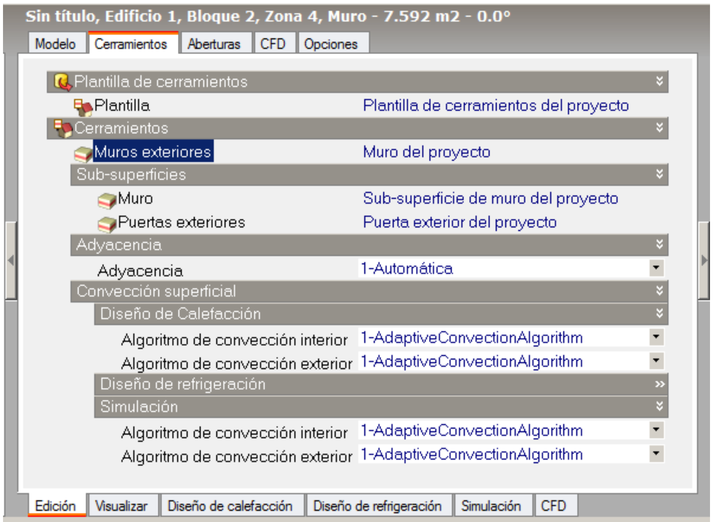
In the Activity panel (*"Actividad"*), several inputs concerning the building use are provided for each zone, including the occupancy profiles, metabolic activity, control settings for heating and cooling systems (such as set point temperatures), for natural and mechanical ventilation and infiltration, and appliances. Different option may be selected to model heat gains according to different levels of details in the input data. Time dependent inputs such as occupancy profiles and set point temperatures may be defined according to different options, which include from simplified to detailed schedule. Time schedules express the temporal variations of parameters. For instance in Figure 2.10, the schedule on the left provides, in each line, a time interval followed by a fraction of 1. This variable fraction multiplies a fixed value of occupation density (reported in the centre of the figure) to express the temporal variations of occupation density.



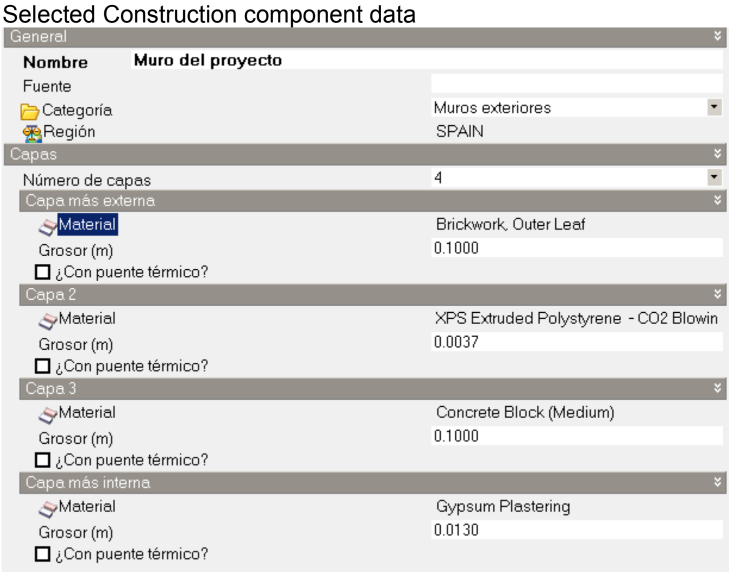
Schedule:Compact,
Dwell_DomCommonAreas_Occ,
Fraction,
Through: 31 Dec,
For: Weekdays SummerDesignDay,
Until: 07:00, 0,
Until: 08:00, 0.5,
Until: 09:00, 1,
Until: 10:00, 0.5,
Until: 17:00, 0,
Until: 18:00, 0.25,
Until: 19:00, 0.5,
Until: 20:00, 0.75,
Until: 22:00, 1,
Until: 23:00, 0.75,
Until: 24:00, 0.25,

Figure 2.10. Main inputs of the Activity panel (*"Actividad"*) in the Edition screen. Occupancy schedule is shown at the right.

Entering from the Construction panel (*"Cerraminetos"*), the user can select, modify, or create opaque construction components (such as external walls, roofs, floors, and internal partitions). Also characteristics of individual layers may be specified (such as thickness, conductivity, density, specific heat). Different options may be selected to model internal and external surfaces convection.



└► Selected Construction component data



└► Selected Layer data

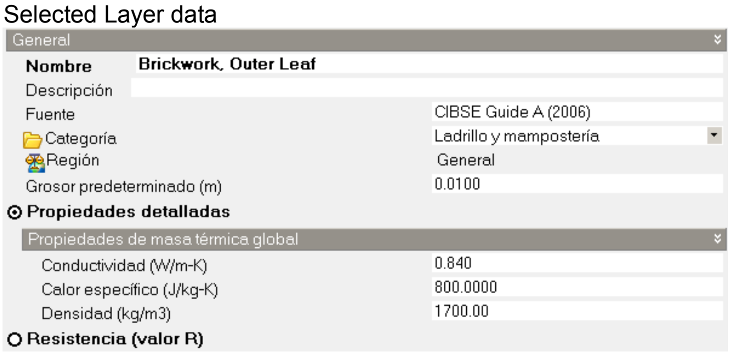


Figure 2.11. Main inputs for thermal calculations of an external wall component and its individual layers, Construction panel (*"Cerraminetos"*) in the Edition screen, partial views of Construction component and Layer edition screens.

In the Openings panel (*"Aberturas"*), the user defines different kinds of openings such as exterior and interior windows, doors, skylights and vents.

For each window, several inputs are defined such as glassing type, dimension of window sill, flange and frame. Also glassing details may be specified (selected, modified, or created) according to different options to model their thermal and optical behaviour. Type and position of the solar protection are defined. Details of glassing and solar protection may be specified (selected, modified, or created) according to different options to model their thermal and optical behaviour. Control settings for movable solar protections may be defined according to numerous options such as solar radiation, light intensity, temperature and detailed schedule among the others.

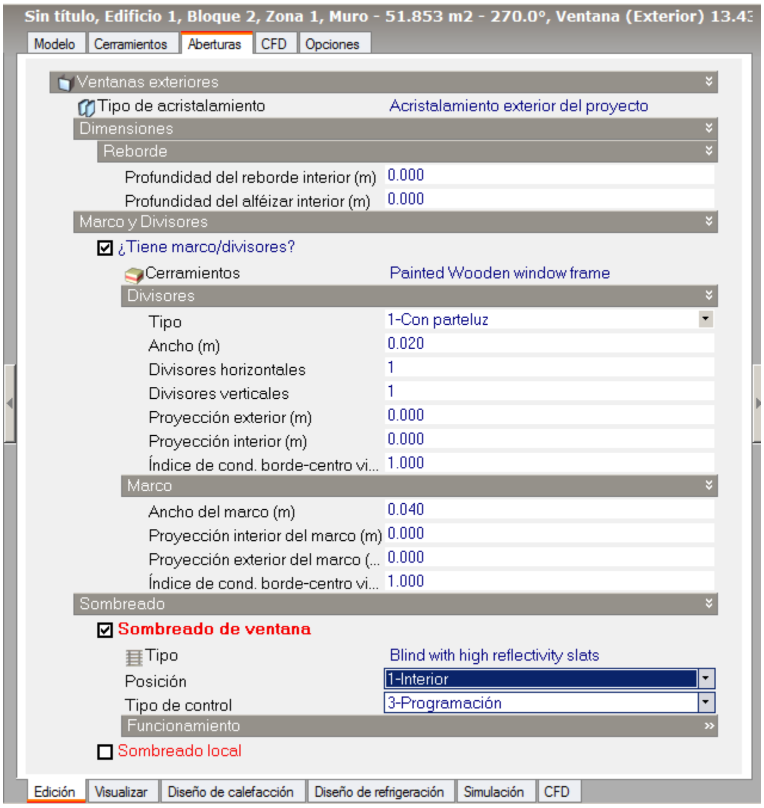


Figure 2.12. Main inputs of the Openings panel (*“Aberturas”*) in the Edition screen.

In the Lighting panel (*“Iluminación”*), inputs are provided for lighting calculations and to determine internal gains for thermal calculations.

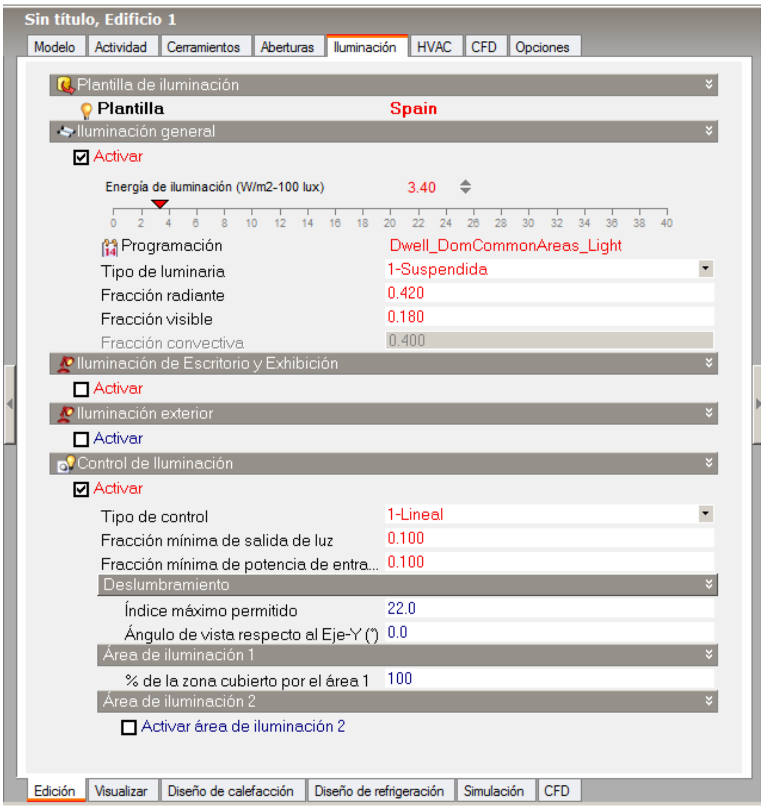
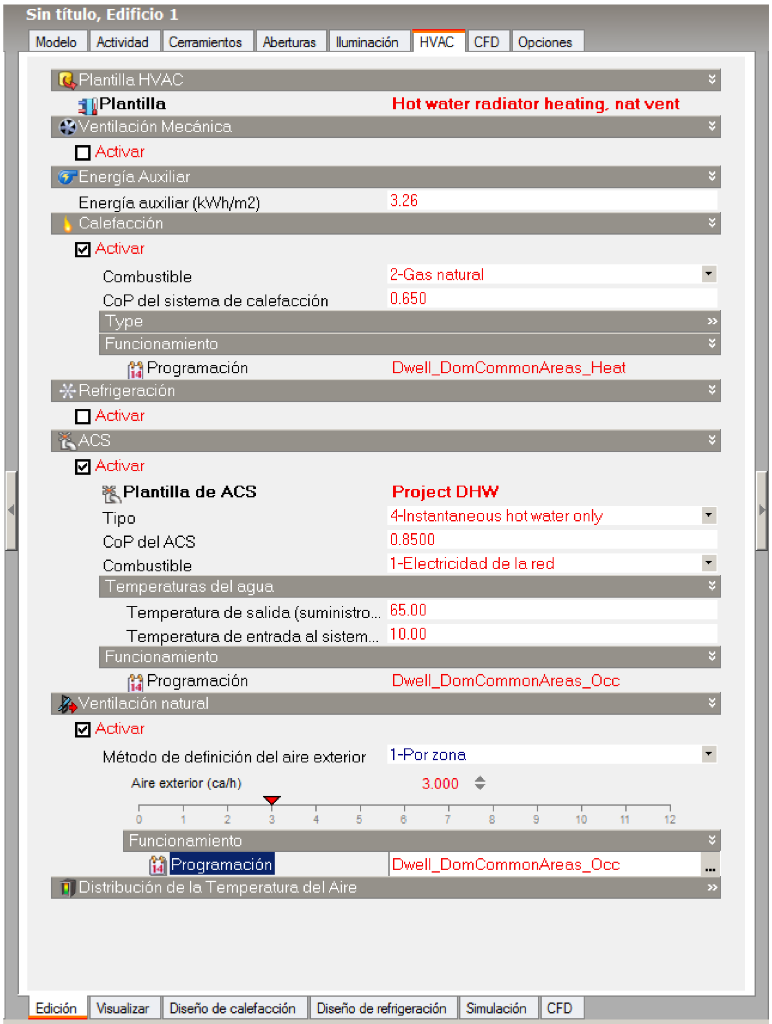


Figure 2.13. Main inputs of the Lighting panel (*"Iluminación"*) in the Edition screen.

In the HVAC panel, numerous inputs are provided to model heating cooling ventilation and domestic hot water systems. Also natural ventilation inputs are provided. Two options may be selected to model mechanical systems: according to simplified inputs with seasonal efficiencies, or by a detailed definition of systems. Two options may be selected to model natural ventilation, airflow rates may be defined as user inputs or calculated in function of wind and stack effects based on user inputs about location, openings and their operation.




```
Schedule:Compact,
Dwell_DomCommonAreas_Occ,
Fraction,
Through: 31 Dec,
For: Weekdays SummerDesignDay,
Until: 07:00, 0,
Until: 08:00, 0.5,
Until: 09:00, 1,
Until: 10:00, 0.5,
Until: 17:00, 0,
Until: 18:00, 0.25,
Until: 19:00, 0.5,
Until: 20:00, 0.75,
Until: 22:00, 1,
Until: 23:00, 0.75,
Until: 24:00, 0.25,
```

Figure 2.14. Main inputs of the HVAC panel in the Edition screen. The schedule defined by the user for air change by natural ventilation is shown at the right.

Different calculation routines may be invoked for different purpose such as heating or cooling systems design, or energy performance simulation. In the Simulation options, several inputs have to be specified such as the limits of the period analysed in the simulation, the length of each calculation time step, and the selected option to model solar radiation inside and outside the building.

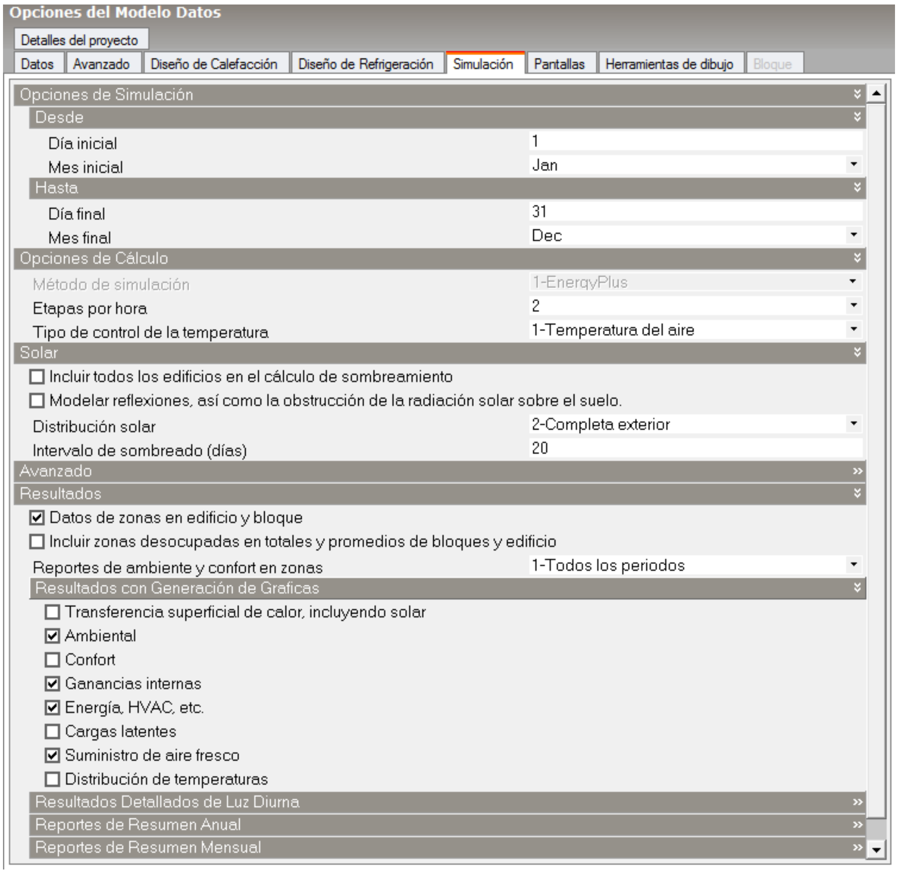


Figure 2.15. Main inputs in the Simulation options panel (*"Simulación"*).

2.3.4 Results

According to the selected options, a range of simulation results may be produced for thermal comfort and energy analysis. Also lighting and multi-zone airflows' analysis may be provided.

Thermal conditions of each zone at each time step are calculated including indoor air temperatures, radiant and operative temperatures, humidity, (sensible and latent) heat loads (from Figure 2.16 to Figure 2.18). Energy consumptions for different uses (heating, cooling, ventilation, hot water, lighting and appliances) are provided.

Based on detailed simulation results for each zone and time step, the tool also calculates aggregated results. They include monthly and annual energy performance (such as space heating and cooling demand and energy consumptions), and frequency distributions of indoor temperatures for each zone. In addition, based on detailed results, a comfort analysis module enables calculating different comfort indicators (such as hours of discomfort and Predicted Mean Vote - PMV).

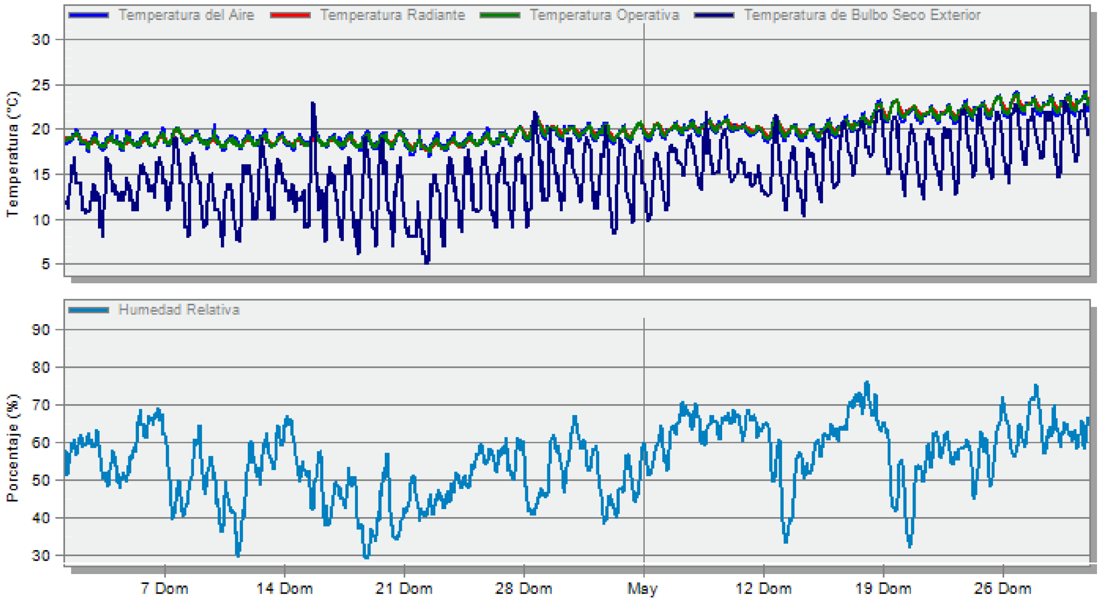


Figure 2.16. Simulation hourly results of indoor air temperatures, radiant and operative temperatures and relative humidity in a building zone over a period of two months (April and May).

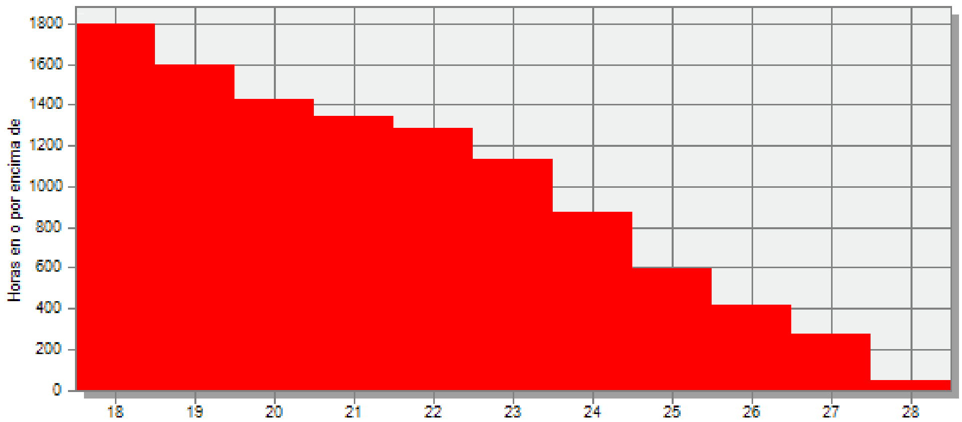


Figure 2.17. Frequency distribution of operative temperature in a building zone during the period from April to September, showing the number of hours when operative temperature is higher than a given value.

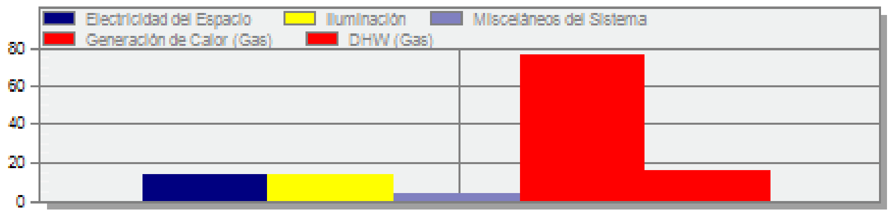


Figure 2.18. Aggregated annual values of fuel consumptions expressed in kWh/m^2 including in the following order electricity for appliances, lighting and auxiliary energy, and gas for space heating and domestic hot water.

2.4 OIB-HWB02H TOOL

This tool is a software application implementing a simple quasi-steady-state calculation method. The calculation method is implemented in Excel.

The OIB-hwb02h method was established by Austrian regulation (OIB-382-010/99, 1999) for the purpose of the building energy certification. Overtime, the regulation has changed and the method is not applicable anymore for this purpose. So, in Case B, the OIB-hwb02h was used as a calculation method independently from the certification purpose.

2.4.1 Type of analyses provided

OIB-hwb02h calculation method is circumscribed to the thermal domain. No comfort analysis is provided; the method is limited to a simple energy analysis, only providing the calculation of space heating demand.

2.4.2 The calculation method

The calculation of space heating demand of the zone (Q_H) is based on energy balance of the building (1). A quasi-steady-state method is used. It calculates the heat balance over the whole heating season, which is a sufficiently long period of time to take dynamic effects into account by an empirically determined gain utilization factor.

(1) $Q_h = (Q_T + Q_V) - \eta \times (Q_i + Q_s)$ (kWh/a)

Total heat transfer by transmission (Q_T) and ventilation (Q_V) are obtained in function of the heating degree over the whole heating season.

Total heat gains from the sun (Q_i) and internal sources (Q_s) are obtained in function of the accumulated solar radiation and internal heat gains for the whole season. The heat gains are reduced by applying the gain utilization factor (η). The utilization factor takes into account that only part of the internal and solar heat gains is utilized to decrease the energy need for heating.

The calculation is carried out for a single zone, which represents the building or the part of the building that is analysed.

Climate data of the heating season used to calculate the terms of the energy balance are provided by the tool library (including standard climate data for each region of Austria and specific climate data of each location).

Klimadaten für Österreich											
PLZ	Ortsname	Seehöhe m	$HGT_{12/20}$ Kd/a	HT_{12} d	θ_e °C	θ_{ne} °C	I_S kWh/m²a	$I_{O/W}$ kWh/m²a	I_N kWh/m²a	$I_{horizontal}$ kWh/m²a	Land
1010	Wien-Innere Stadt	170	3319	204	3,73	-13	351	211	144	357	W
1020	Wien-Leopoldstadt	170	3319	204	3,73	-13	351	211	144	357	W
1030	Wien-Landstraße	170	3355	205	3,63	-13	366	221	150	373	W
1040	Wien-Wieden	170	3361	206	3,68	-13	368	223	151	377	W
1050	Wien-Margareten	180	3398	208	3,66	-13	373	226	154	383	W
1060	Wien-Mariahilf	180	3386	207	3,64	-13	371	225	152	380	W
1070	Wien-Neubau	200	3419	209	3,64	-13	376	228	155	387	W
1080	Wien-Josefstadt	205	3400	208	3,65	-13	364	221	150	374	W
1090	Wien-Alsergrund	164	3297	203	3,76	-13	348	210	142	354	W
1100	Wien-Favoriten	212	3463	210	3,51	-13	378	230	156	390	W
1107	Wien-Oberlaa	200	3417	208	3,57	-13	373	226	154	383	W
1110	Wien-Simmering	175	3387	207	3,64	-13	371	225	152	380	W
1113	Wien-Kaiserebersdorf	160	3357	205	3,62	-13	366	221	150	373	W
1120	Wien-Meidling	190	3414	208	3,59	-13	364	221	150	374	W
1130	Wien-Hietzing	190	3415	209	3,66	-13	366	222	151	377	W
1140	Wien-Penzing	210	3474	211	3,54	-13	372	226	153	384	W
1147	Wien-Hadersdorf	230	3611	218	3,44	-13	391	241	164	409	W
1150	Wien-Rudolfsheim-Fünfhaus	200	3428	209	3,60	-13	366	222	151	377	W
1160	Wien-Ottakring	215	3416	208	3,58	-13	364	221	150	374	W
1170	Wien-Hernals	200	3421	209	3,63	-13	366	222	151	377	W
1180	Wien-Währing	200	3355	206	3,71	-13	356	215	146	364	W
1190	Wien-Döbling	200	3355	206	3,71	-13	356	215	146	364	W
1192	Wien-Neustift	264	3502	212	3,48	-13	371	226	154	384	W
1195	Wien-Nußdorf	170	3309	204	3,78	-13	351	211	144	357	W
1200	Wien-Brigittenau	170	3308	204	3,78	-13	351	211	144	357	W
1210	Wien-Floridsdorf	164	3300	203	3,74	-13	348	210	142	354	W
1216	Wien-Stammersdorf	172	3373	205	3,55	-13	353	213	145	360	W
1220	Wien-Donaustadt	160	3348	205	3,67	-13	353	213	145	360	W
1226	Wien-Breitenlee	160	3379	206	3,60	-13	356	215	146	364	W
1227	Wien-Süßenbrunn	160	3449	209	3,50	-13	363	220	149	373	W
1228	Wien-Eßling	157	3372	205	3,55	-14	353	213	145	360	W
1230	Wien-Liesing	210	3446	210	3,59	-13	369	224	152	380	W
1237	Wien-Kalksburg	300	3617	218	3,41	-14	401	248	168	420	W

Figure 2.19. Climate data of different location in Austria (*"Klima"*)

Standardisierte Klimadaten										
Wohnbau-förderung (WBF)	Seehöhe m	$HGT_{12/20}$ Kd/a	HT_{12} d	θ_e °C	θ_{ne} °C	I_S kWh/m²a	$I_{O/W}$ kWh/m²a	I_N kWh/m²a	$I_{horizontal}$ kWh/m²a	Land
Burgenland	-	3494	210	3,36	-13	383	234	158	395	B
Kärnten	-	-	-	-	-	-	-	-	-	K
Niederösterreich	227	3403	207	3,56	-13	371	225	152	380	NÖ
Oberösterreich	-	-	-	-	-	-	-	-	-	OÖ
Salzburg	-	-	-	-	-	-	-	-	-	S
Steiermark	-	-	-	-	-	-	-	-	-	St
Tirol	-	-	-	-	-	-	-	-	-	T
Vorarlberg	-	-	-	-	-	-	-	-	-	V
Wien	-	3235	208	4,45	-12	356	210	150	368	W

Figure 2.20. Standard climate data (*"Klima Standard"*) for different zones

2.4.3 User inputs

The inputs are introduced in different sheets:

- General information (*“Allgemeine Angaben”*)
- Technical information (*“Technische Angaben”*)
- Components (*“Bauteile”*)
- Calculations (*“Berechnungen”*)
- Window types (*“Fenstertypen”*)
- Window surfaces (*“Fensterflächen”*)
- Door surfaces (*“Türflächen”*)
- Transmission heat transfer coefficients (*“Leitwerte”*)

In General information (*“Allgemeine Angaben”*) postcode of the location (PLZ) is selected. Based on that, the tool identifies the corresponding climate data from the tool library.

Allgemeine Angaben		
Gebäudeart:		olw rgwpñmg
Erbaut im Jahr:		
Standort:	Straße	
1010	PLZ, Ort	1010 Wien-Innere Stadt (W)
	EZ	
	Kat. Gem.	
	Grst. Nr.	
	Geo. Länge	
	Geo. Breite	
Eigentümer/Errichter:	Name	
	Straße	
	PLZ, Ort	
Energieausweis ausgestellt durch:	Name	
	Straße	
	PLZ, Ort	
	Tel	
	GZ	
	Bearbeiter	
	Datum	
	Korrektur	

Figure 2.21. General information (*“Allgemeine Angaben”*).

In Technical information (*"Technische Angaben"*), building use, gross conditioned floor area and volume, weight of building construction, ventilation mode (natural or mechanical), ventilation heat recovery efficiency, and calculation options for thermal bridges and windows are defined for the whole building.

Technische Angaben	
Bauvorhaben:	

Gebäude		
Gebäude-widmung:	◉ Einfamilienhaus	20 °C qi = 3,0 W/m²
	○ Zweifamilienhaus	
	○ Reihenhaus	
	○ Mehrfamilienhaus	
	○ Krankenhaus	
	○ Pflegeheim	
	○ Bürogebäude	
	○ Schule	
	○ Sonstige	
Bauweise:	◉ schwere Bauweise	ETA = 1,00
	○ mittelschwere Bauweise	
	○ leichte Bauweise	

Abmessungen	
beheiztes Brutto-Volumen des Gebäudes V_B in m³	
beheizte Brutto-Geschoßfläche BGF_B in m²	

Transmissions- und Lüftungswärmeverluste		
Fenster:	◉ U-Wert laut Prüfbericht	für die solaren Gewinne gilt Ag = 0,7 * Aw
	○ U-Wert-Berechnung	
Wärme-brücken:	◉ Leitwertzuschläge pauschal	
	○ Leitwertzuschläge gemäß EN ISO 10211-1 in W/K	
Lüftung:	◉ Fensterlüftung: Luftwechselrate in 1/h	0,40
	○ mechanische Lüftung	
	maschinell eingestellte Luftwechselrate >= 0,4 in 1/h	
	Nutzungsgrad der Wärmerückgewinnung η_{WRG} in %	
	Nutzungsgrad des Erdwärmetauschers η_{EWT} in %	
	Luftwechselrate infolge von Ex- und Infiltration n_x in 1/h	
	Luftwechselrate n in 1/h	0,40

Heizungstechnische Anlagen

Warmwassertechnische Anlagen

Figure 2.22. Technical information (*"Technische Angaben"*).

In Components (*"Bauteile"*), opaque envelope is described specifying each type of construction component (*"Bauteile 1", ..., "Bauteile n"*). The user has two options: to specify each layer defining thickness and conductivity, or to introduce the U of the construction component.

Bauteile							
Bauvorhaben:							

Bauteil 1							
◉ U-Wert laut Gutachten gemäß EN ISO 6946 in W/m²K							
○ U-Wert-Berechnung gemäß Schichtaufbau							
Nr.	Schichtaufbau von innen nach außen	Dicke cm	Anteil 1 %	Anteil 2 %	λ 1 W/mK	λ 2 W/mK	d/λ m²K/W
1							
2							
3							
4							
Wärmeübergangswiderstände $R_{si} + R_{se}$ in m²K/W							
Wärmedurchgangswiderstand R_T' in m²K/W							
Wärmedurchgangswiderstand R_T'' in m²K/W							
$R_T = (R_T' + R_T'') / 2$ in m²K/W							
Wärmedurchgangskoeffizient U_i in W/m²K							
Temperaturkorrekturfaktor f_i							

Figure 2.23. Components (*"Bauteile"*).

In Window types (*"Fenstertypen"*), each type of window is characterized by U and g-value.

Fenstertypen (-konstruktionen)	
Bauvorhaben:	

Fenster F1	
U-Wert des Fensters U_w laut Prüfbericht in W/m²K	
U-Wert der Verglasung U_g in W/m²K	
U-Wert des Rahmens U_f in W/m²K	
Wärmebrückenzuschlag ψ_g in W/mK	
Gesamtenergiedurchlaßgrad g	

Figure 2.24. Window types (*"Fenstertypen"*).

In Window surfaces (*"Fensterflächen"*) and Door surfaces (*"Türflächen"*), the geometry of windows and doors shapes is detailed

Fensterflächen												
Bauvorhaben:												
Anzahl	Fenster F1 - F10	in Bauteil 1 - 24	j	S	b m	h m	A_w m²	f_g	A_g m²	A_f m²	l_g m	U_w W/m²K

Figure 2.25. Window surfaces (*“Fensterflächen”*).

Türflächen					
Bauvorhaben:					
Anzahl	Türen T1 - T6	in Bauteil 1 - 24	b m	h m	A_d m²

Figure 2.26. Door surfaces (*“Türflächen”*).

For each opaque envelope component, gross areas (including windows) are specified by the modeller in the sheet Transmission heat transfer coefficients (*“Leitwerte”*). Net areas and U-values are reported in the same sheet.

Leitwerte						
Bauvorhaben:						
Bauteile						
	Bezeichnung	A_{brutto} m²	A_i m²	U_i W/m²K	f_i	$A_i * U_i * f_i$ W/K
1						
2						
3						
Fenster						
	Bezeichnung		A_i m²	U_i W/m²K	f_i	$A_i * U_i * f_i$ W/K
F1	nom finestra?			1,000	var.	
F2					var.	
F3					var.	
Türen						
	Bezeichnung		A_i m²	U_i W/m²K	f_i	$A_i * U_i * f_i$ W/K
T1					var.	
T2					var.	
T3					var.	

Figure 2.27. Transmission heat transfer coefficients (*“Leitwerte”*).

2.4.4 Results

In the results, the Space Heating Demand obtained from the zone heat balance is expressed for one year and for one unit of gross floor area.

The different terms of the energy balance are also reported: the total heat transfer by transmission (Q_T) the total heat transfer by ventilation (Q_V) the total solar heat gains corrected by the utilization factor ($\eta \cdot Q_i$) and the total internal heat gains corrected by the utilization factor ($\eta \cdot Q_s$).

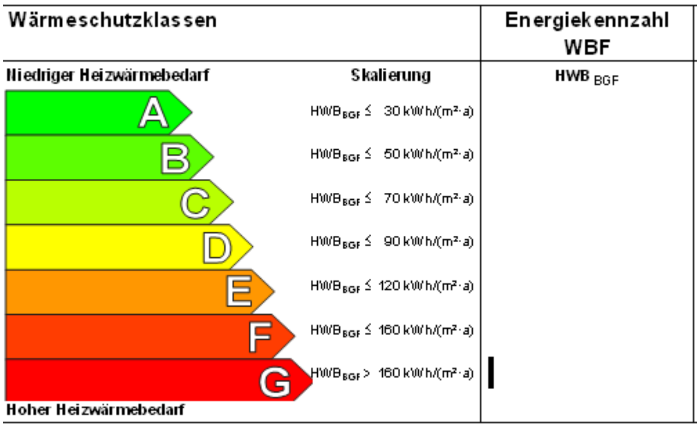


Figure 2.28. Rating of building in the energy certificate, specifying the Space Heating Demand expressed for one year and for one unit of gross floor area (HWB_{BGF}, in sheet *"EA1"*).

	Ergebnisse	WBF	Standort	
1	Leitwerte $L_e + L_u + L_g$			W/K
2	Leitwertzuschläge $L_\psi + L_\chi$			W/K
3	Transmissions-Leitwert L_T			W/K
4	Lüftungs-Leitwert L_V			W/K
5	Heizlast P_{tot}			W
6	Transmissionswärmeverluste Q_T			kWh/a
7	Lüftungswärmeverluste Q_V			kWh/a
8	Passive solare Wärmegewinne $\eta \times Q_s$			kWh/a
9	Interne Wärmegewinne $\eta \times Q_i$			kWh/a
10	**Heizwärmebedarf Q_h**			**kWh/a**

Figure 2.29. Specification of the climate conditions and the different terms of the energy balance (Q_h, Q_T, Q_V, $\eta \cdot Q_i$, $\eta \cdot Q_s$, in sheet *"EA2"*).

2.5 SUMMARY

The main features of each tool presented in this Annex are summarized from Figure 2.30 to Figure 2.32. In each figure, the flow chart of the energy calculation is schematized. It focuses on thermal calculation indicating the different steps of performance analysis with corresponding inputs and outputs. Below, in each figure, the different domains analysed by the tool, such as thermal, fluid-dynamic, lighting, acoustic, are indicated. The range of analyses enabled by each calculation tool, in black, is bounded by a dot line.

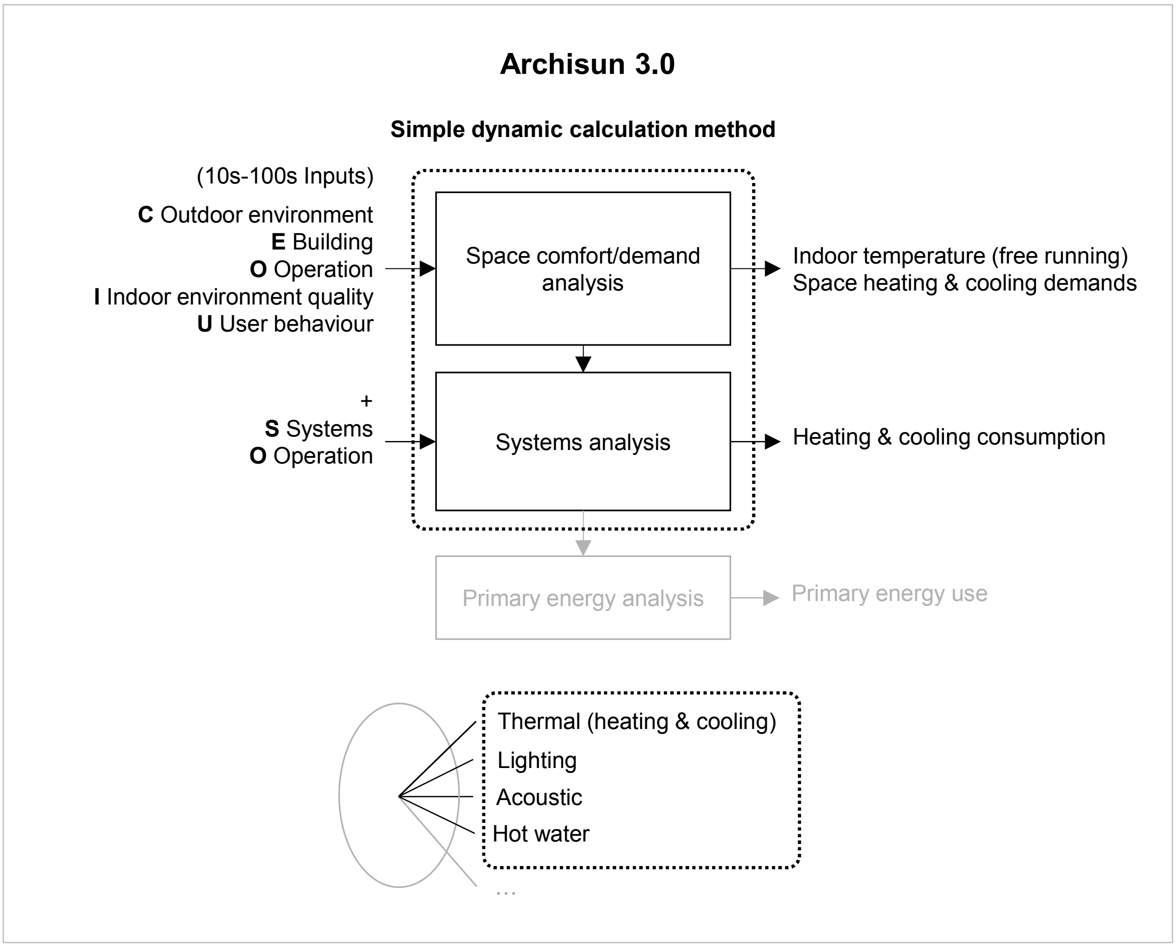


Figure 2.30. Summary of Archisun features.

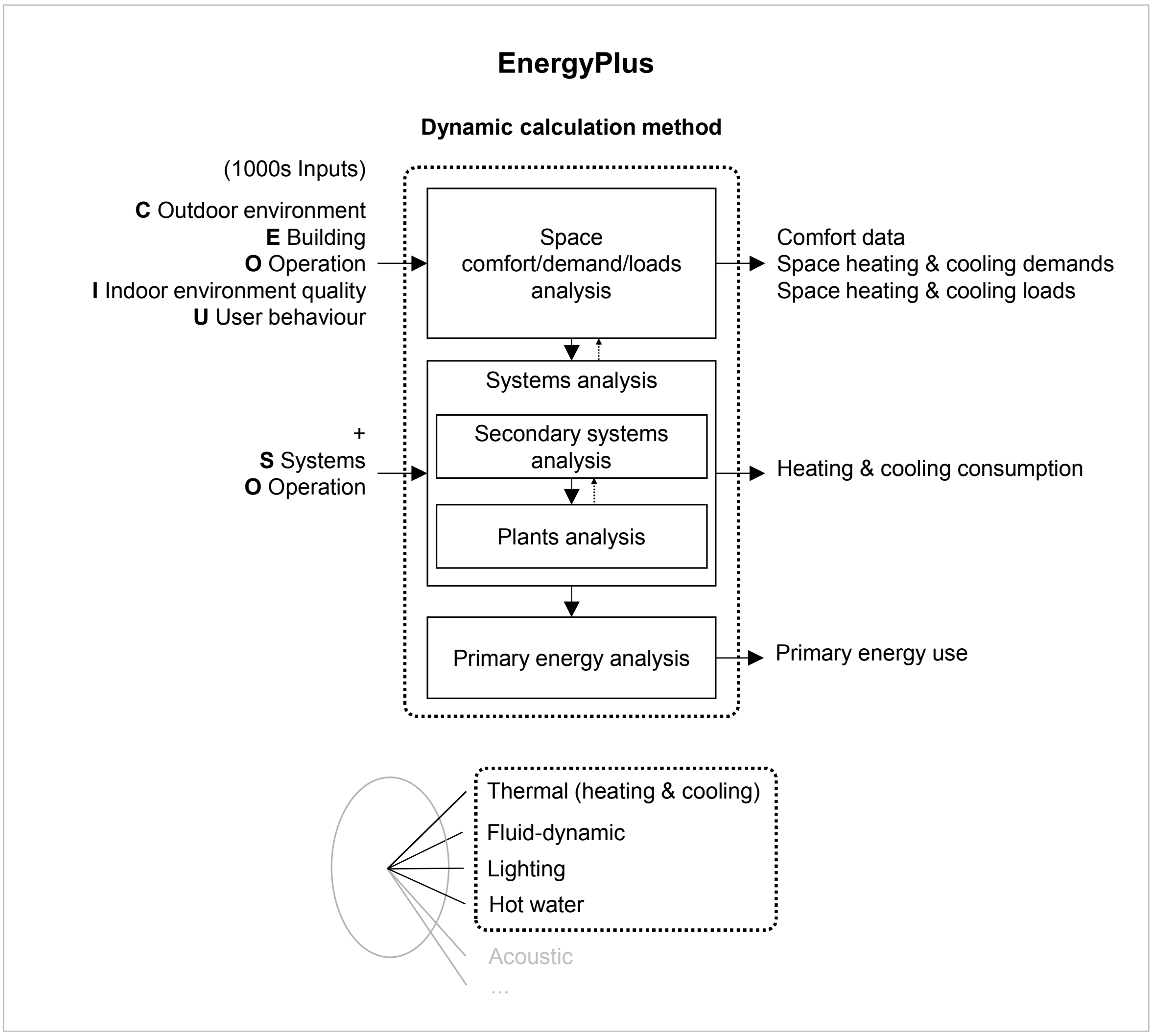


Figure 2.31. Summary of DesignBuilder features, including the flow chart of EnergyPlus calculation method at the core of the energy analysis.

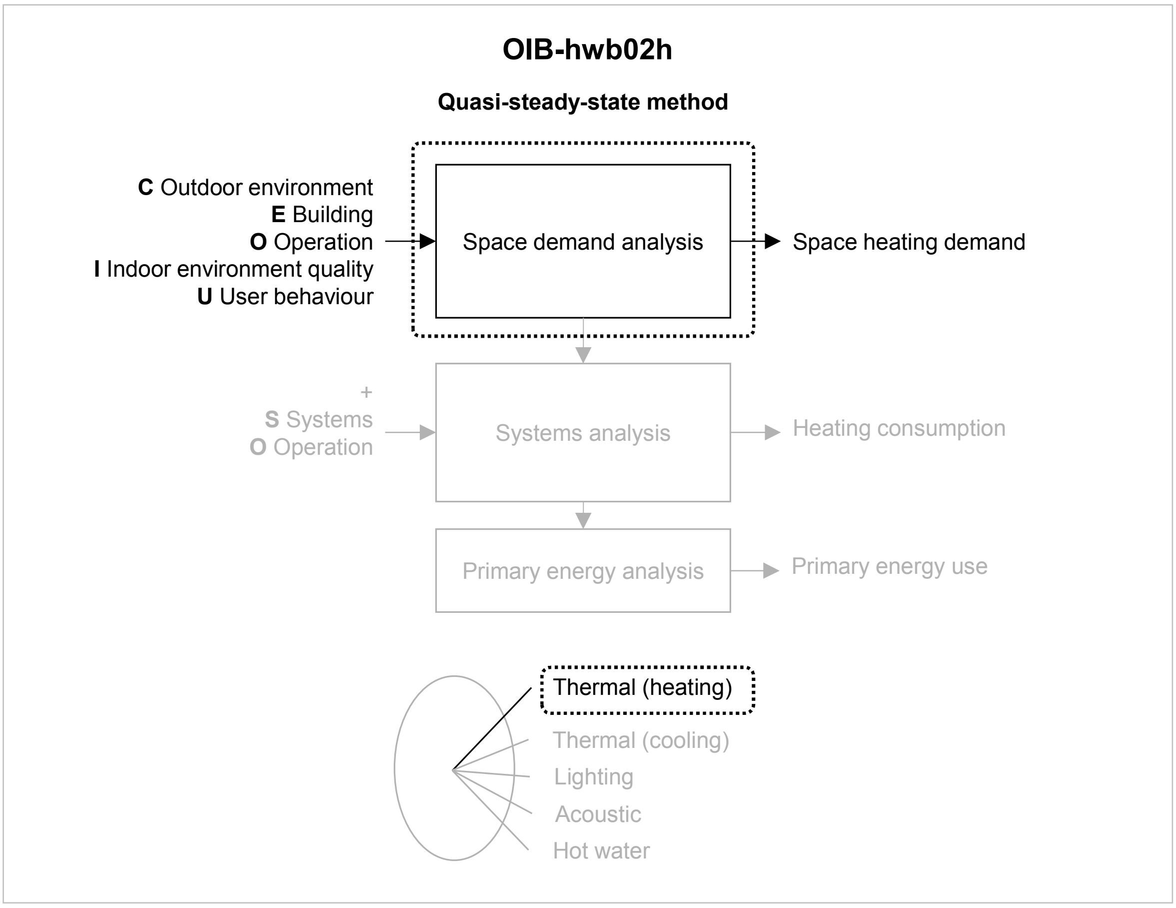


Figure 2.32. Summary of OIB-hwb02h features.

The boundaries of analyses encompassed by each tool are substantially different. In Archisun and DesignBuilder, besides heating and cooling thermal analysis other domains of analysis are included (such as lighting). Instead, the OIB-hwb02h tool is limited to thermal analysis, and in particular to heating. In addition, the tool provides no comfort analysis. Moreover, the extension of the thermal calculation flow charts differs among the three tools. The OIB-hwb02h tool is limited to the first step of space demand analysis. Instead, Archisun and DesignBuilder also include the mechanical systems analysis. Archisun systems analysis is very simple, limited to the application of a constant efficiency for each energy use. In DesignBuilder systems analysis may be performed according to different options: from simple analysis based on constant efficiencies, to detailed analysis based on the detailed definition of secondary systems and plants. Besides consumptions, the analyses enabled by DesignBuilder may be extended further to the estimation of Primary energy use and CO2 emissions.

In each tool the complexity of the calculation process differs substantially, in the detail used to reproduce the dynamic behaviour of the building. The OIB-hwb02h calculation method, introduce radical simplification compared with the other two tools. The quasi-steady-state method consists of a steady-state heat balance equation modified by the introduction of a gain utilization factor. Archisun calculation algorithm is more complex compared with the OIB-hwb02h method. Archisun is based on a simple dynamic method that reproduces dynamic effects in much more detail. The simplifications consist of the use of periodic functions and the reduction of the analysis to one typical period (of two weeks) for season. This allows users to reproduce the variability of parameters during daily cycles. The calculation algorithm implemented in DesignBuilder is certainly the most complex, as it reproduces the interaction of multiple phenomena and parts of the models at hourly (or sub-hourly) time steps.

2.6 REFERENCES

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Annex 3

Models

ANNEX 3: TABLE OF CONTENTS

3.1 INTRODUCTION

In the two case studies presented in this thesis the energy models of different design solutions are considered:

- Archisun 3.0 model of solution C1 and the variant C2 (in Chapter 5)
- DesignBuilder V 2.4.2.026 model of solution D1 (in Chapter 5)
- OIB-hwb02h model of the final design solution (in Chapter 6.)

These models of each design solution are described in this Annex.

3.2 CASE A – ARCHISUN MODEL

In Case A the alternative solutions C1 and C2 are produced and modelled with Archisun[1]. The model that we have created for the reconstruction of the design process is described in this section.

3.2.1 User inputs

The number of inputs that should be directly specified by the energy assessor to create this model is estimated in about 100.

Basic data are provided by the designers in the main screen including total volume of the building, building use and number of occupants (Figure 3.1).

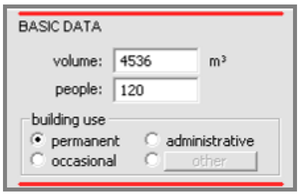


Figure 3.1. Basic data in the main screen.

[1] Serra (2000) illustrates how the user has to proceed to create a model with the Archisun interface.

In the definition of the location, the designers introduce the position on the map, the height above sea level and the urban density.

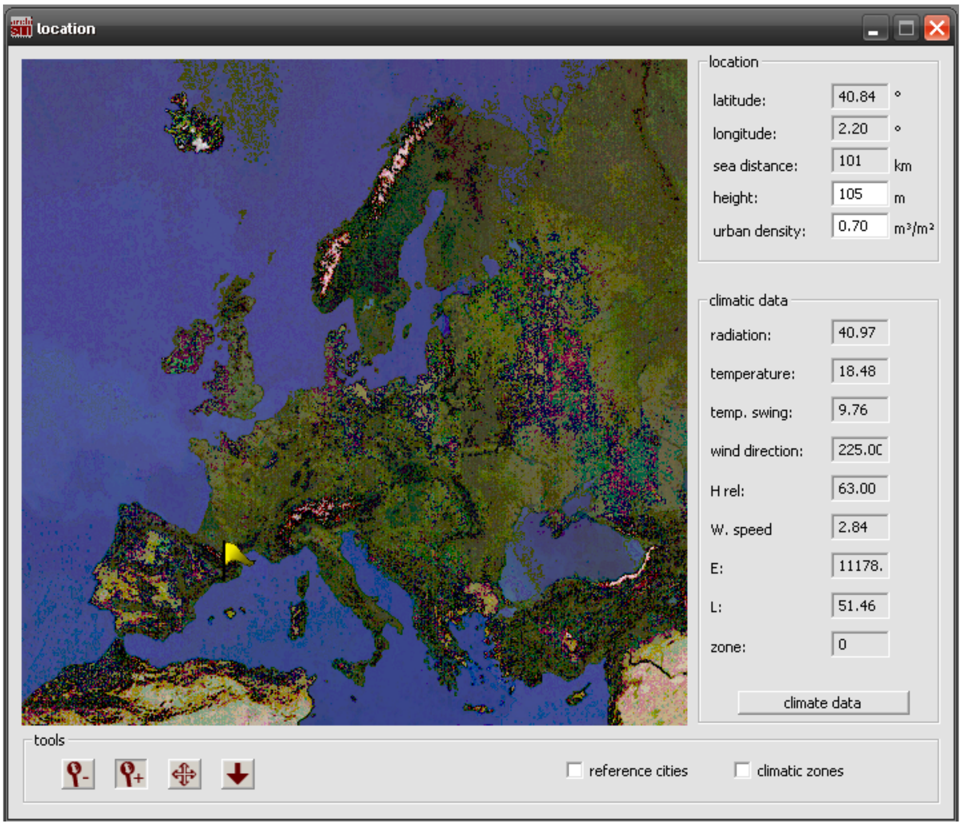


Figure 3.2. *"Location"* screen.

In the definition of environment, data of the building surroundings are introduced, including deciduous trees in the public street on the south side, on the west and east sides.

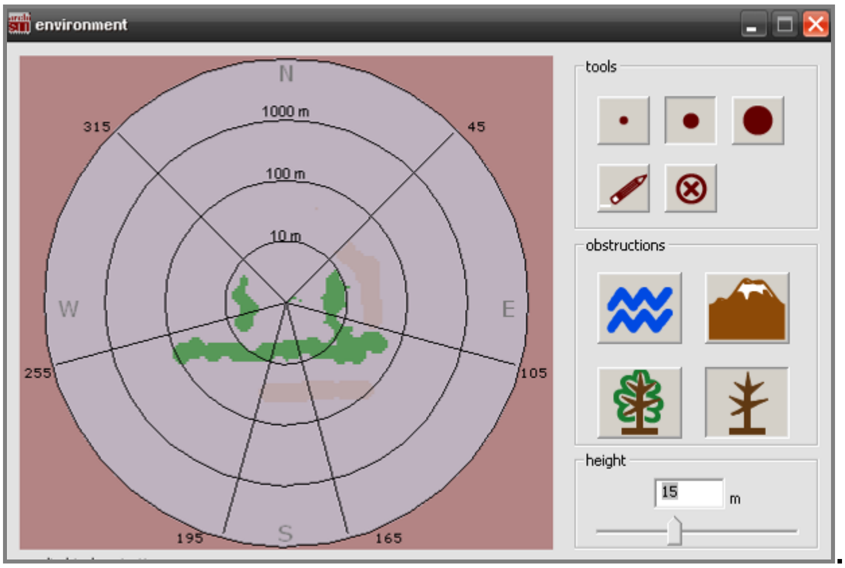
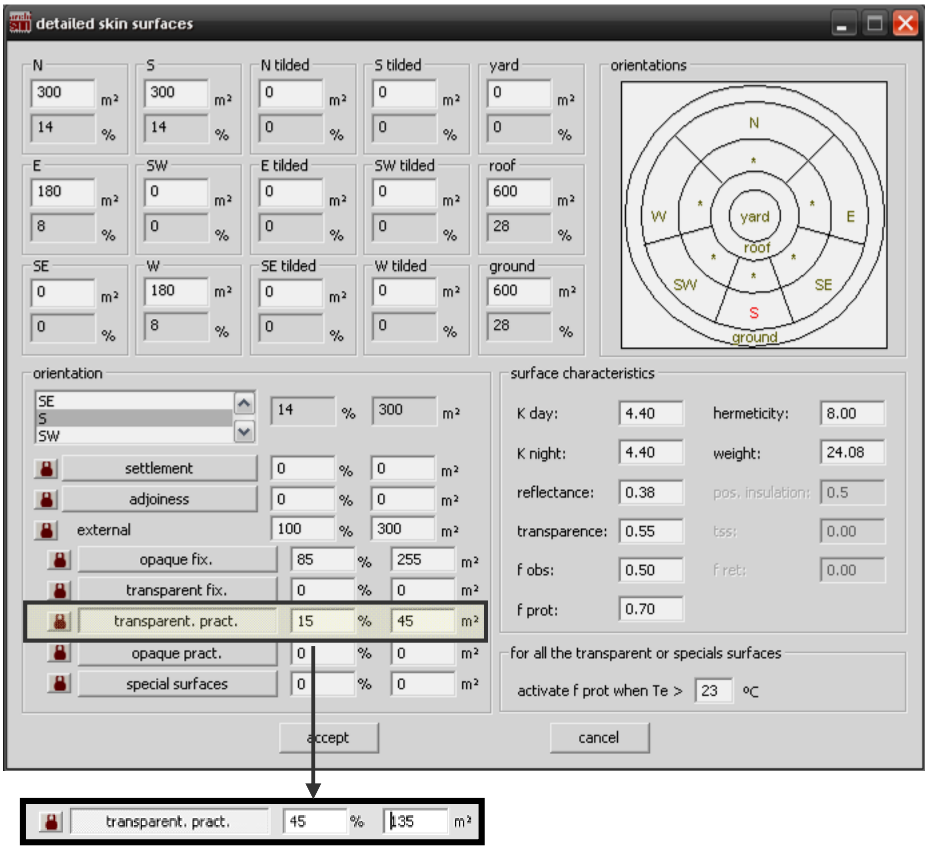


Figure 3.3. *“Environment”* screen.

For the definition of building envelope, the designers introduce the values of characteristics of each surface (Figure 3.4). The characteristics of opaque and transparent surfaces are assigned separately by orientation and condition of adjacency (to the exterior, the interior or the ground). The inputs are summarized in Table 3.1.

C1



C2

Figure 3.4. *“Detailed skin surfaces”* screen. Above, the inputs provided for the design solution C1, and below, the modification of the opening ratio in the design solution C2.

Table 3.1. Summary of skin surfaces’ characteristics.

Skin opaque surfaces	U-value W/m²K	Weight Kg/m²	Insulation position (0.1-0.9)				
N/S/E/W exterior opaque surface	0.95	300	0.9				
Roof exterior opaque surface	0.53	1000	0.9				
Floor to adjoined spaces	1.30	800	0.9				
Skin transparent surfaces	**U-value W/m²K**	**Weight Kg/m²**	**Exterior reflectance (0-1)**	**Transparence (0-1)**	**Obstruction factor (0-1)**	**Protection factor (0-1)**	**Hermeticity ⁰/₀₀**
N exterior transparent surface	4.40	24.08	0.38	0.55	0.00	0.00	8.00
S/E/W exterior transparent surface	4.40	24.08	0.38	0.55	0.50	0.70	8.00

In the model of the solution C1 the opening ratio (the input *“transparent pract.”* in Figure 3.4) of the south facade is 15%. In the solution C2, that value is increased up to 45%.

In order to obtain the energy demand for heating and cooling from the calculation results, the efficiency of mechanical systems is set as 1 by the energy assessor.

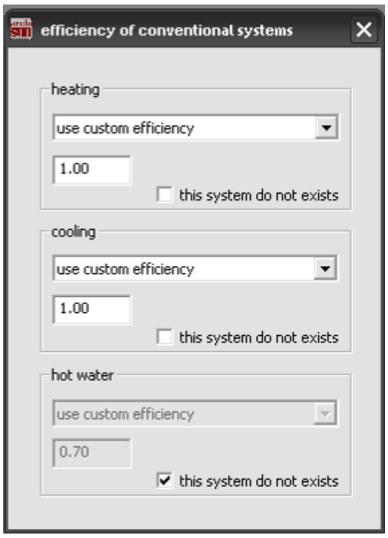


Figure 3.5. The screen *"Efficiency of conventional systems"*.

3.2.2 Results

The results for the solution C1 and C2 are shown in Figure 3.6 and Figure 3.7. Energy performance is expressed for each energy use in relation with the conditioned volume by kWh/m^{3}y. For the purpose of their analysis, the designers consider only space demands for heating and cooling (at the bottom of each figure). For each season, outdoor environment conditions are indicated. Over the winter, the average external temperature (T) is 9.2ºC, with a daily swing (dT) of 8.9ºC in average. Over the summer, the average external temperature is 27.7ºC, with 8.8ºC swing. For each season, the terms of the heat balance equations are also indicated.

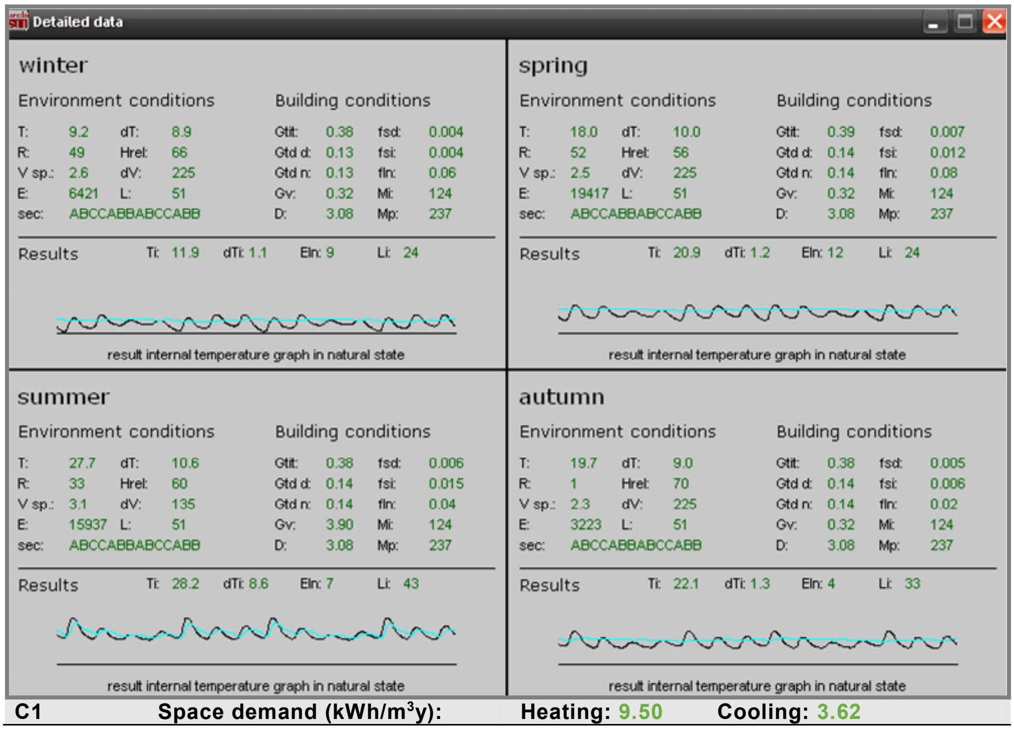


Figure 3.6. Results of the design solution C1 in the *"Detailed data screen"*.

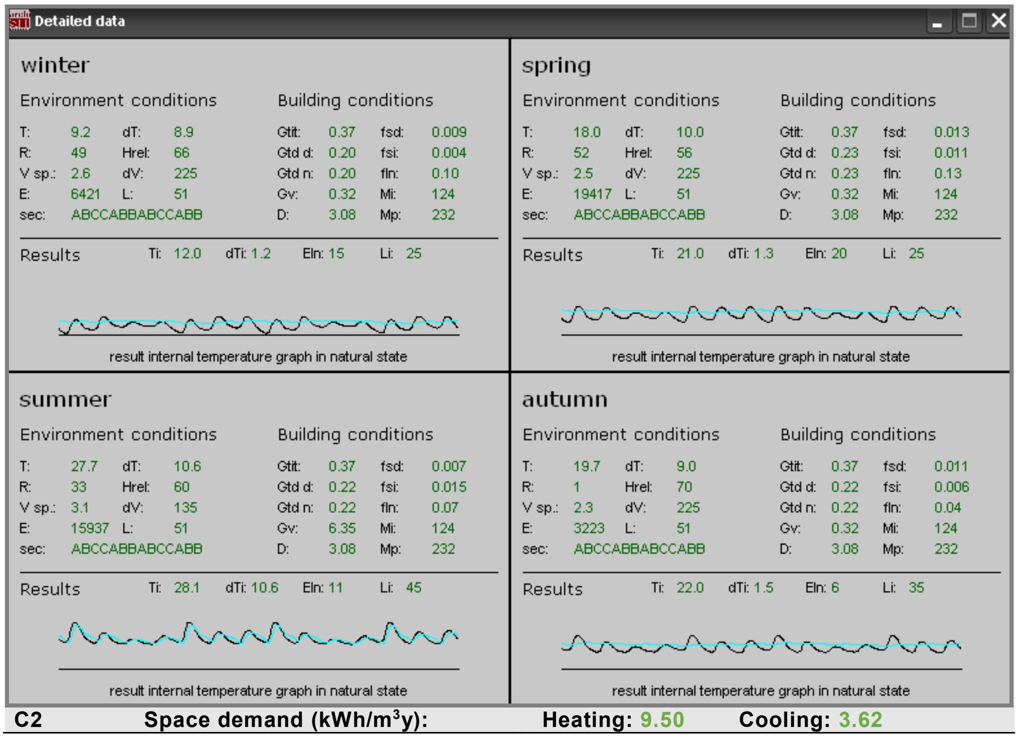


Figure 3.7. Results of the design solution C2 in the *"Detailed data screen"*.

Increasing the opening ratio (from C1 to C2), the increments of solar gains (indicated by the direct solar capitation factor, f_{sd}) is contrasted by thermal losses. Losses increment occurs both in the winter, with the increment of transmission losses (G_{dt}), and in the summer, with the increment of ventilation losses (G_v).

3.3 CASE A – DESIGNBUILDER MODEL

In Case A the solution D1 is developed and it is modelled with DesignBuilder. The model that we have created with DesignBuilder for the reconstruction of the design process is described in this section[2].

3.3.1 User inputs

To generate and calibrate the model with DesignBuilder, the energy assessor handles considerably more information compared with Archisun. In this case the number of inputs directly specified by the energy assessor to create this model are estimated at more than 150, plus spatial coordinates and dimensions of about 50 3D-objects created within the 3D editor (facades, partitions, windows, doors, and balconies), plus 1000s of defaults that are in small part directly verified by the energy assessor during the creation of the model.

Nº inputs specified	**+ Nº graphical objects**	**+ Nº defaults**
>150	~50	1000s

Table 3.2. Estimate of the amount of information required to create the model

The energy assessor selects the location of Barcelona Airport available in the tool, which is the closest one to the project site. The tool identifies associated climate data from its library for the calculation.

[2] The help guide provided by DesignBuilder illustrates how the user has to proceed to create a model with the tool interface (DesignBuilder, 2013).

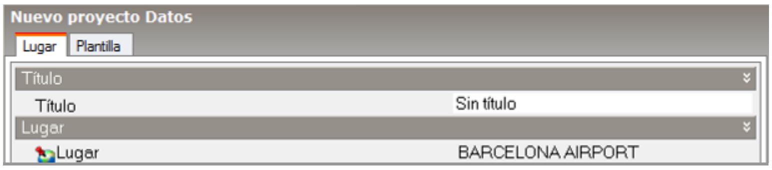


Figure 3.8. *"New project data"* screen.

The energy assessor creates a new building and selects *"Residential space"* template (a set of default values for of the building use is defined in this template including inputs of the Activity panel and other panels)

The designers create the geometrical model including the flat Le, which is the object of the thermal analysis, and the adjacent zones of the building with the 3D editor. The flat Le is separated from the outdoor environment by the surfaces of the south east and north facades and the roof. The surfaces of internal partitions separate the flat Le from other spaces of the building. The geometry of each window and of permanent solar protections provided by balconies is also defined.

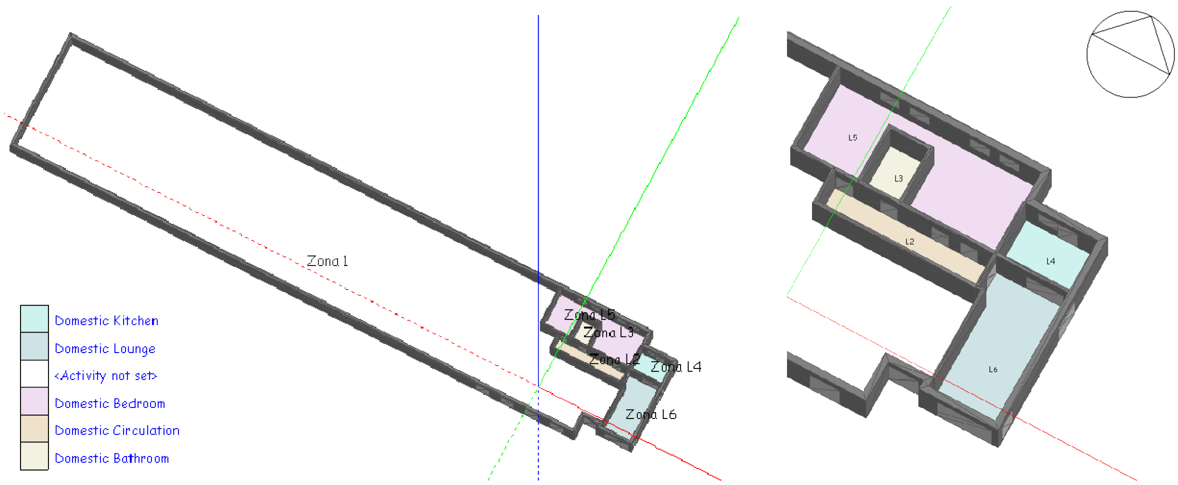


Figure 3.9. Geometric definition of model zones. Zone L2 to L6 correspond to the flat Le. The flat zones include the circulation (L2), the bathroom (L3), the kitchen (L4), the three bedrooms, modelled as a single zone (L5), and the living room (L6).

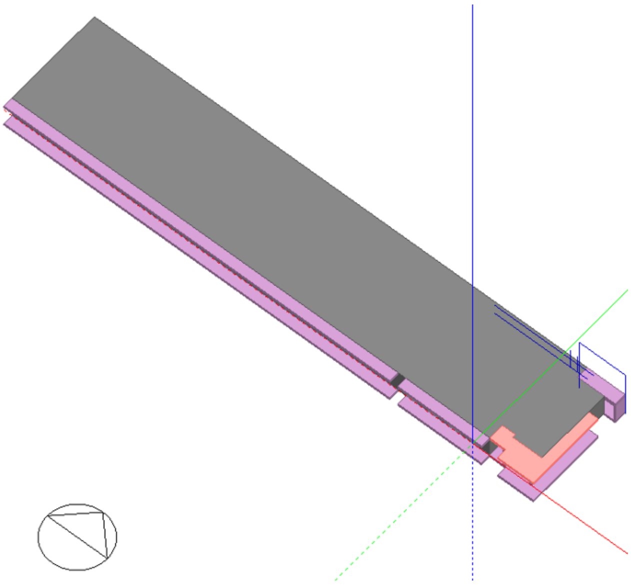


Figure 3.10. Geometric definition of the permanent solar protection provided by the balconies into the model.

The constructive solutions of facades, roof and partitions between the flat zones are defined into the model specifying thickness and thermal properties of each layer. Layers are mostly selected by the designers from the tool library.

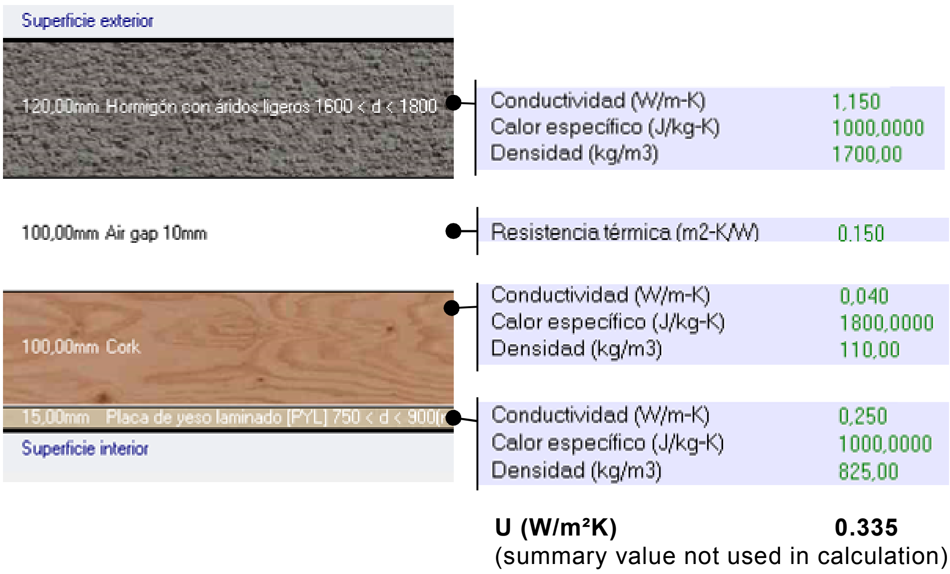


Figure 3.11. Main inputs for the **facade** component: composition form exterior to the interior (concrete panels, air gap, cork and plasterboard), layers thicknesses, thermal properties of the solid layers (conductivity, specific heat and density) and thermal resistance of the air gap.

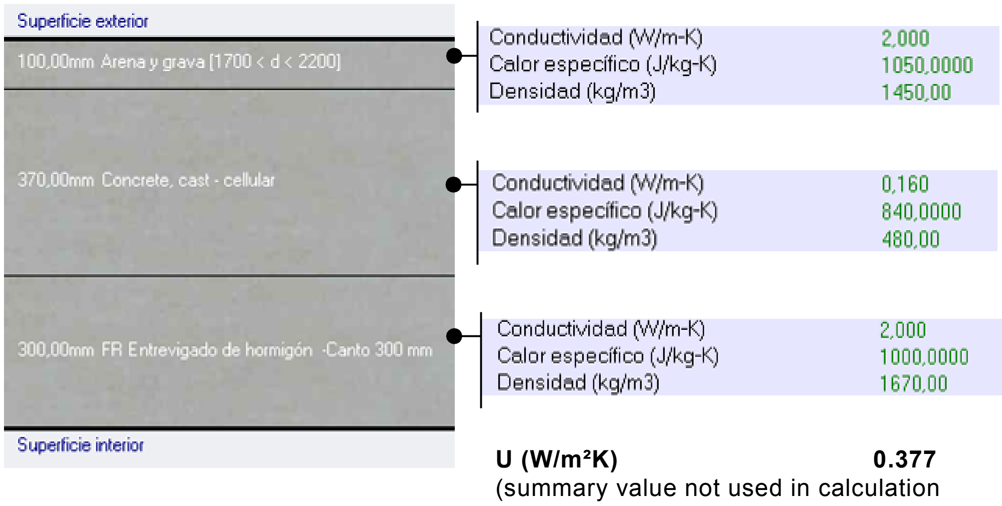


Figure 3.12. Main inputs for the **roof** component: composition form exterior to the interior (sand and gravel, cellular concrete and concrete slab), layers thicknesses and thermal properties (conductivity, specific heat and density).

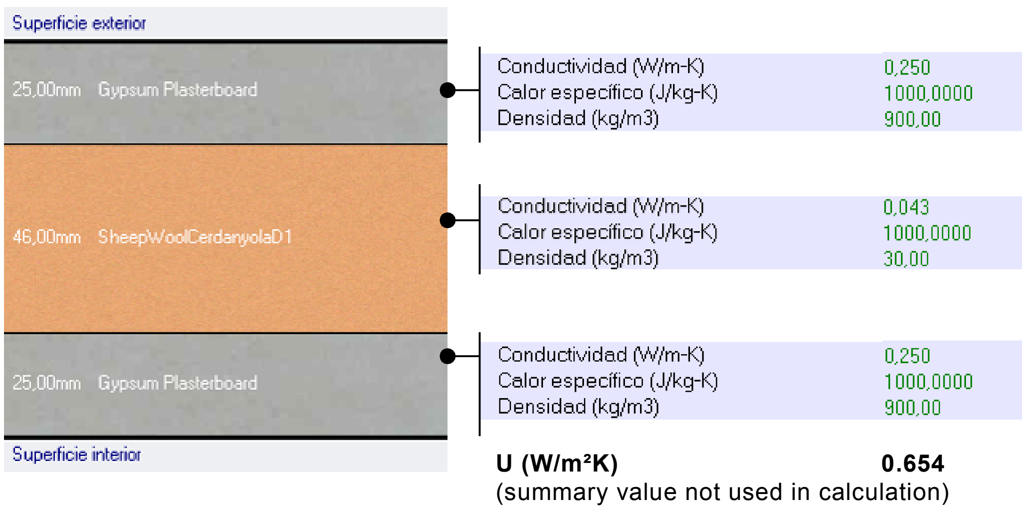


Figure 3.13. Main inputs for the **partitions**' components: composition (plasterboard, insulation and plasterboard), layers thicknesses and thermal properties (conductivity, specific heat and density).

All the internal partitions and the floor that separate the zones of the flat Le from other building zones are set as adiabatic.

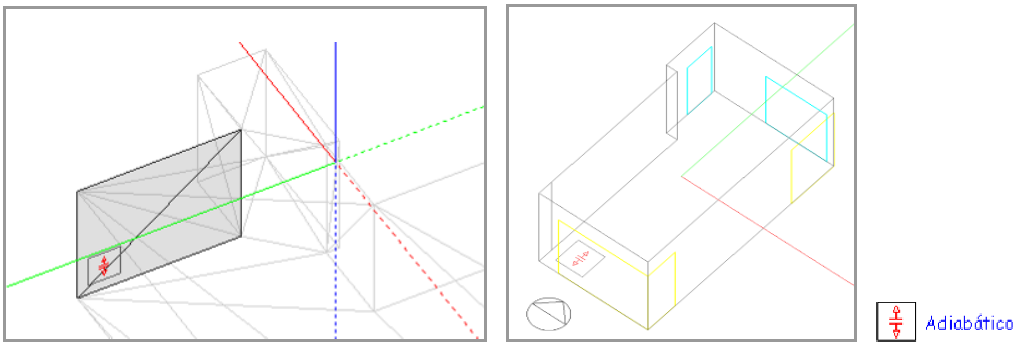


Figure 3.14. Adiabatic surfaces defining a partition and a floor into the model.

To simplify the model, only one type of window is created into the model defining the window frame ignoring vertical divisions. The type and position (to the exterior) of solar protections are specified. The option of time schedules is selected to input the control settings for the solar protection devices.

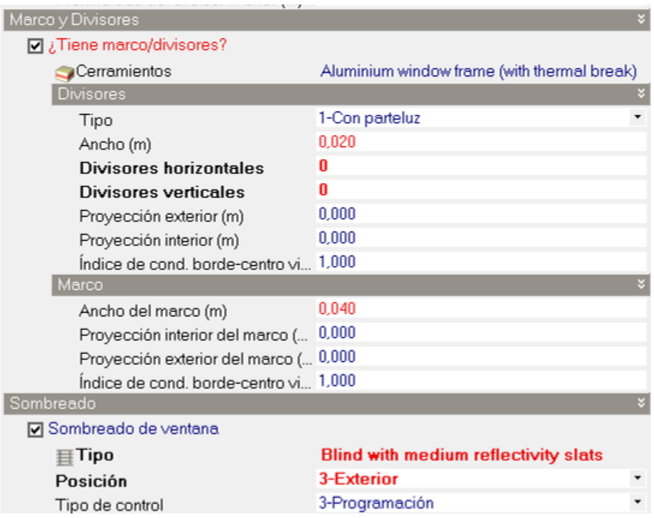


Figure 3.15. Type and geometry of the window frame, and type and position the movable solar protection device.

A simple option to model glazing is selected introducing the thermal solar and light transmission characteristics for the complete double glazing.

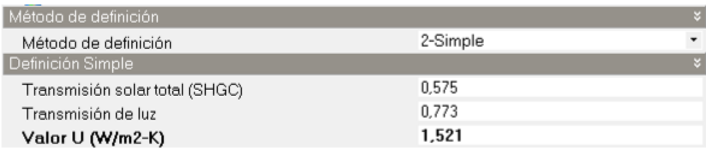
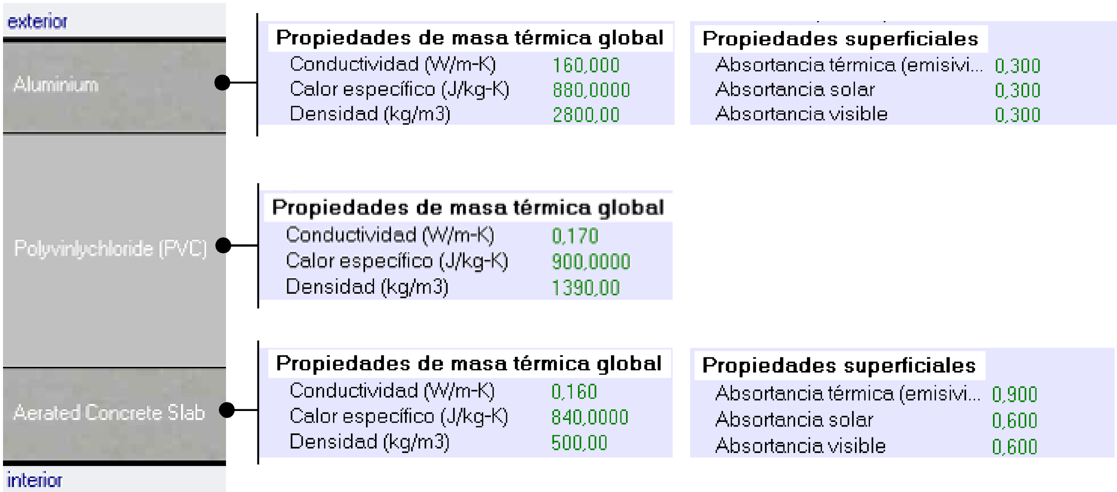


Figure 3.16. Option for the definition of glazing. Total solar transmission, light transmission and U of glazing.

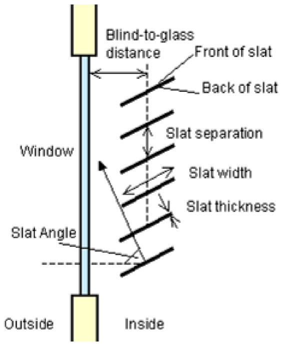
Aluminium frame with thermal brake is selected from the tool library.



U (W/m²K) **4.719**

Figure 3.17. Input provided for the window frame: thermal properties of materials and properties of exterior and interior surfaces.

Among movable protections types blinds are selected. A predefined blind type from the tool library is adapted to the project solution. The slats width and separation are changed, the slats angle and the gaps between the blind and the borders of the opening are reduced to 0.



Propiedades Solares de las Tablillas	
Transmitancia solar de las tablillas	0.000
Reflectividad solar de las tablillas, parte frontal	0.500
Reflectividad solar de las tablillas, parte trasera	0.500
Propiedades Solares Difusas de las Tablillas	
Transmitancia solar difusa de las tablillas	0.000
Reflectividad solar difusa de las tablillas, parte frontal	0.500
Reflectividad solar difusa de las tablillas, parte trasera	0.500
Propiedades Visibles de las tablillas	
Propiedades Visibles Difusas de las Tablillas	
Propiedades IR (Térmicas) de las Tablillas	
Aberturas	
Multiplicador de abertura superior de persiana	0.000
Multiplicador de abertura inferior de persiana	0.000
Multiplicador de abertura izquierda de persiana	0.000
Multiplicador de abertura derecha de persiana	0.000

Propiedades de Tablillas	
Distancia pantalla de sombreado - vidrio (m)	0.0500
Orientación de las tablillas	Horizontal
Ancho de las tablillas (m)	0.0500
Separación de las tablillas (m)	0.0520
Grosor de las tablillas (m)	0.0100
Ángulo de las tablillas (°)	0.0
Conductividad de las tablillas (W/m-K)	0.900
Ángulo mínimo de las tablillas (°)	0
Ángulo máximo de las tablillas (°)	0

Figure 3.18. Detailed inputs for windows blinds.

Two different time schedules for movable solar protections control are created for summer comfort calculation and for space heating demand calculation. For summer comfort calculation, the energy assessor assumes that in the hours when solar radiation is stronger and occupancy is lower, as most tenants are not at home, blinds remain closed. For space heating demand calculation, he assumes that no solar protection is provided.

Summer comfort calculation

```
For: Weekdays,
Until: 09:00, 0,
Until: 12:00, 1,
Until: 14:00, 0,
Until: 18:00, 1,
Until: 24:00, 0,
For: Holidays,
Until: 24:00, 1,
```

Heating demand calculation

```
For: AllDays,
Until: 24:00, 0 ;
```

Figure 3.19. Schedules for solar protections control for summer comfort calculation at the left and for space heating demand calculation at the right (0: protection is off; 1: protection is on).

For each zone, different conditions of use are specified, including: occupancy, set point temperatures for heating calculations, heat gains form appliances and natural ventilation. Default values provided for each type of zone are used except for natural ventilation. For heating demand calculation the minimum air change rate for air renovation is applied, using default values. For the calculation of overheating in the summer period, additional natural ventilation is activated. The energy assessor defines ventilation air change rates according to the occupancy schedules. The schedules are modified to introduce night ventilation in all zones. In that way, the air change rate increases up to 4 from 18.00 to 7.00[3].

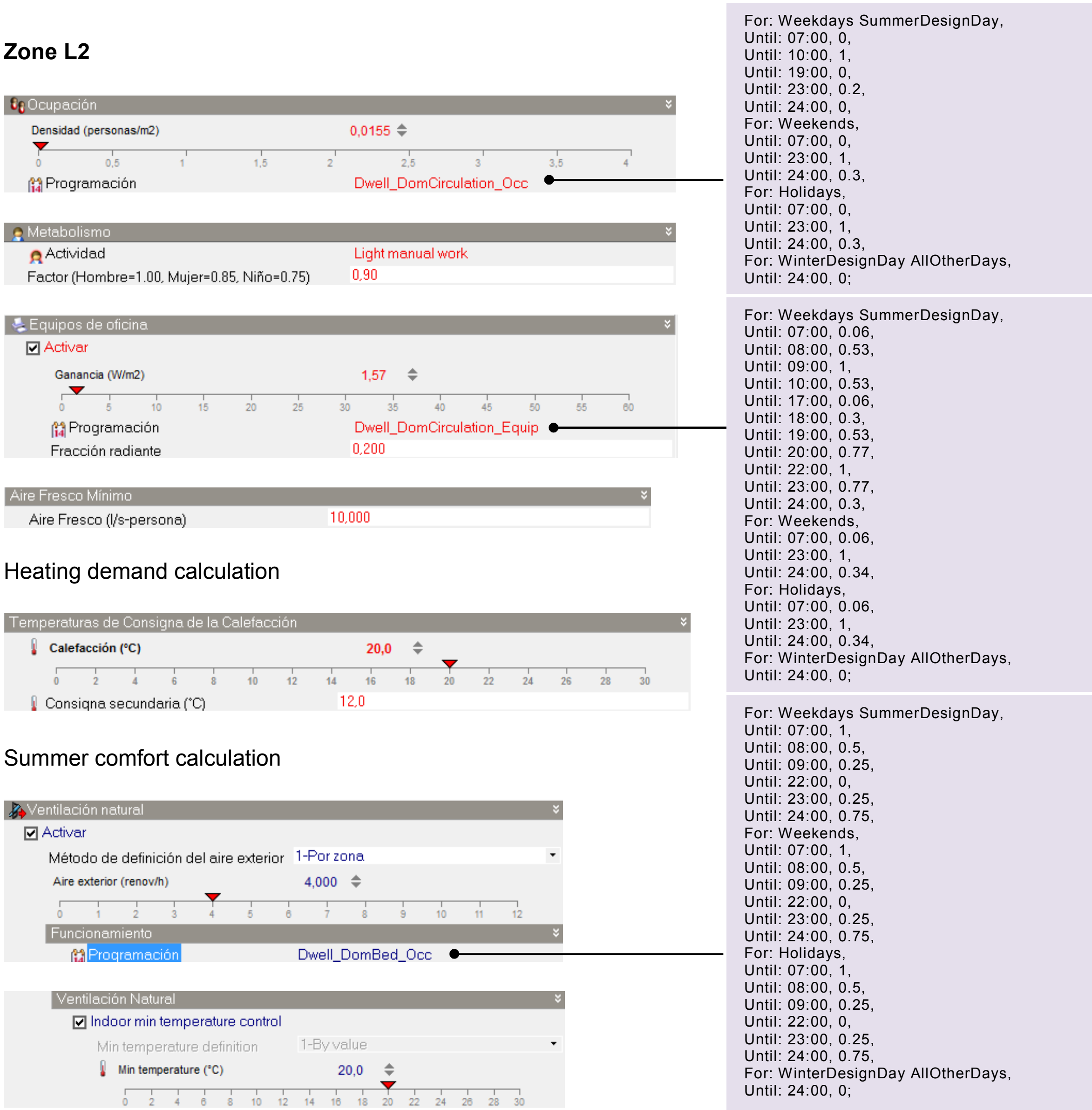
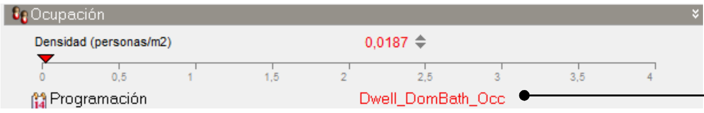


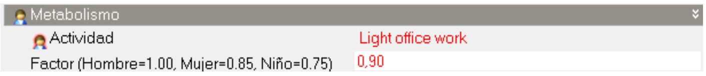
Figure 3.20. On the left, the conditions of use of the **corridor** (zone L2); on the right, the corresponding time schedules. The energy assessor specifies the conditions of use with constant values (of occupancy density, heat gains from appliances, temperature set point for heating, air change rate for natural ventilation, and minimum indoor temperature for natural ventilation) and corresponding schedule names. In the schedules each line indicates a time interval and a fraction of 1. Variable conditions of use result from the constant values multiplied by the variable fractions indicated in the schedules.

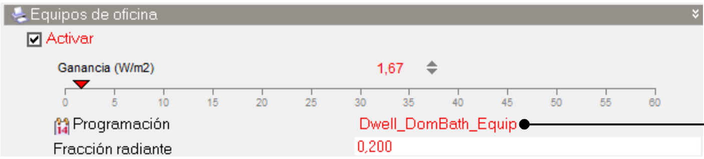
[3] The energy assessor considers as a reference for night ventilation official documents for energy certification in Spain, which indicate an air change rate of 4 during night hours in summer (Ministerio de Industria, 2007).

Zone L3



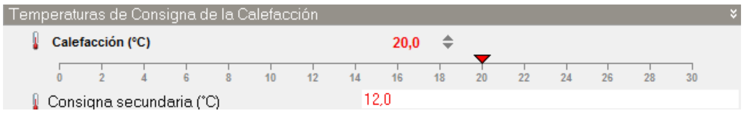
For: Weekdays SummerDesignDay,
Until: 07:00, 0,
Until: 10:00, 1,
Until: 19:00, 0,
Until: 23:00, 0.2,
Until: 24:00, 0,
For: Weekends,
Until: 07:00, 0,
Until: 10:00, 1,
Until: 19:00, 0,
Until: 23:00, 0.2,
Until: 24:00, 0,
For: Holidays,
Until: 07:00, 0,
Until: 10:00, 1,
Until: 19:00, 0,
Until: 23:00, 0.2,
Until: 24:00, 0,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0;





For: Weekdays SummerDesignDay,
Until: 06:00, 0.06,
Until: 07:00, 0.29,
Until: 09:00, 1,
Until: 10:00, 0.29,
Until: 18:00, 0.06,
Until: 19:00, 0.53,
Until: 21:00, 1,
Until: 22:00, 0.34,
Until: 24:00, 0.06,
For: Weekends,
Until: 24:00, 0.06,
For: Holidays,
Until: 24:00, 0.06,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0;

Heating demand calculation



Summer comfort calculation

For: Weekdays SummerDesignDay,
Until: 07:00, 1,
Until: 08:00, 0.5,
Until: 09:00, 0.25,
Until: 22:00, 0,
Until: 23:00, 0.25,
Until: 24:00, 0.75,
For: Weekends,
Until: 07:00, 1,
Until: 08:00, 0.5,
Until: 09:00, 0.25,
Until: 22:00, 0,
Until: 23:00, 0.25,
Until: 24:00, 0.75,
For: Holidays,
Until: 07:00, 1,
Until: 08:00, 0.5,
Until: 09:00, 0.25,
Until: 22:00, 0,
Until: 23:00, 0.25,
Until: 24:00, 0.75,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0;

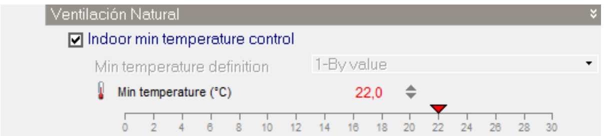
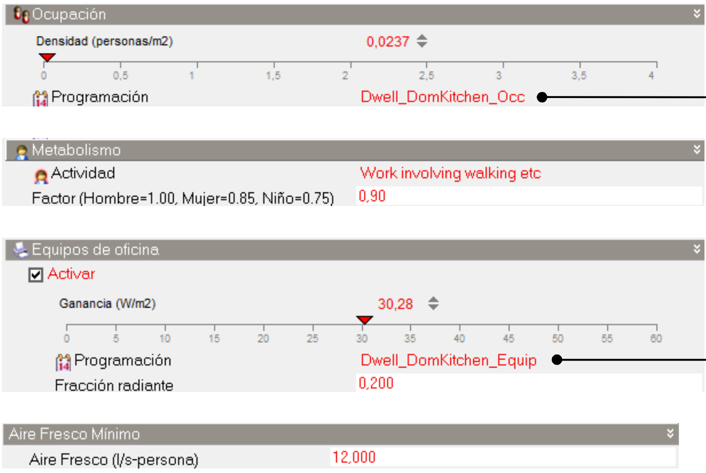


Figure 3.21. Conditions of use of the **bathroom** (zone L3).

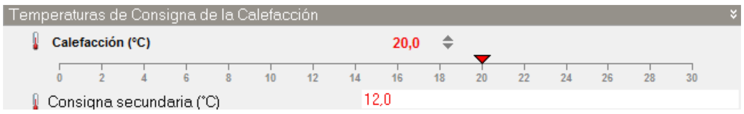
Zone L4



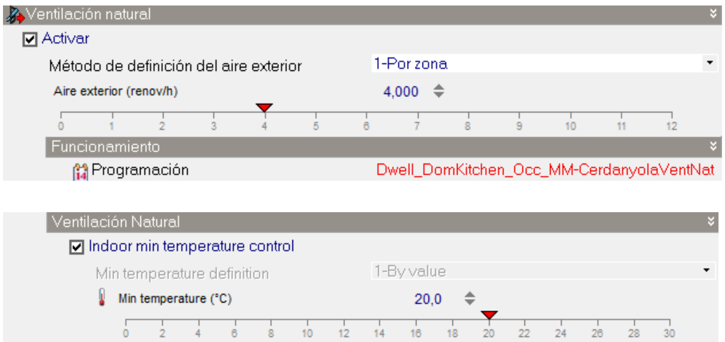
For: Weekdays SummerDesignDay,
Until: 07:00, 0,
Until: 10:00, 1,
Until: 19:00, 0,
Until: 23:00, 0.2,
Until: 24:00, 0,
For: Weekends,
Until: 07:00, 0,
Until: 10:00, 1,
Until: 19:00, 0,
Until: 23:00, 0.2,
Until: 24:00, 0,
For: Holidays,
Until: 07:00, 0,
Until: 10:00, 1,
Until: 19:00, 0,
Until: 23:00, 0.2,
Until: 24:00, 0,
For: WinterDesignDay AllOtherDays,

For: Weekdays SummerDesignDay,
Until: 07:00, 0.07,
Until: 10:00, 1,
Until: 19:00, 0.07,
Until: 23:00, 0.25,
Until: 24:00, 0.07,
For: Weekends,
Until: 07:00, 0.07,
Until: 10:00, 1,
Until: 19:00, 0.07,
Until: 23:00, 0.25,
Until: 24:00, 0.07,
For: Holidays,
Until: 07:00, 0.07,
Until: 10:00, 1,
Until: 19:00, 0.07,
Until: 23:00, 0.25,
Until: 24:00, 0.07,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0;

Heating demand calculation



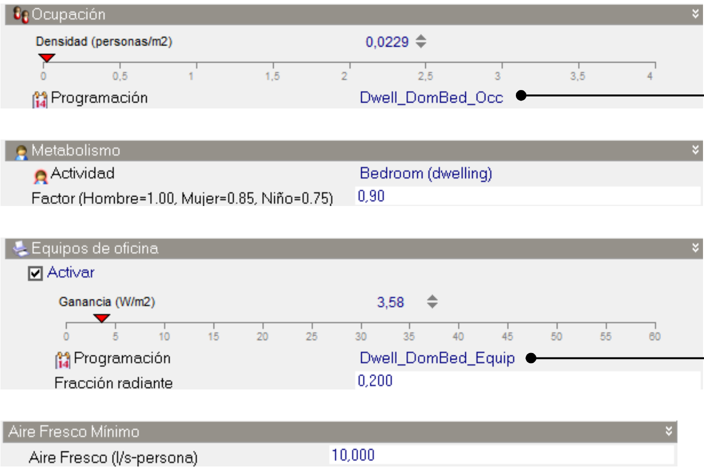
Summer comfort calculation



For: Weekdays SummerDesignDay,
Until: 07:00, 1,
Until: 10:00, 1,
Until: 19:00, 0,
Until: 23:00, 0.2,
Until: 24:00, 0,
For: Weekends,
Until: 07:00, 1,
Until: 10:00, 1,
Until: 19:00, 0,
Until: 23:00, 0.2,
Until: 24:00, 0,
For: Holidays,
Until: 07:00, 1,
Until: 10:00, 1,
Until: 19:00, 0,
Until: 23:00, 0.2,
Until: 24:00, 0,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0;

Figure 3.22. Conditions of use of the **kitchen** (zone L4).

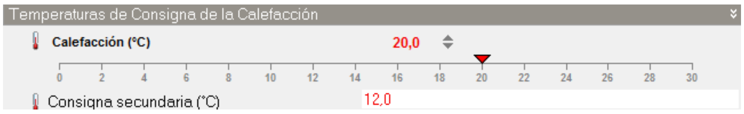
Zone L5



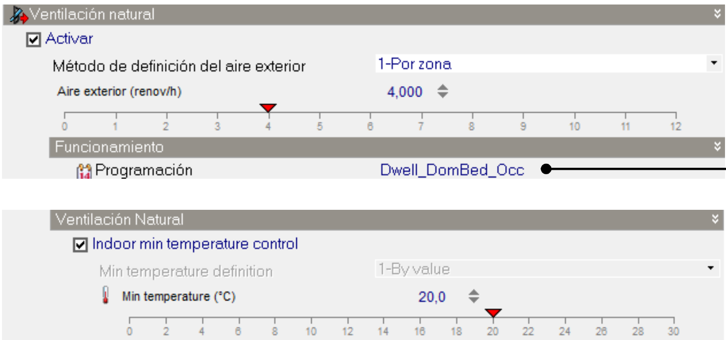
For: Weekdays SummerDesignDay,
Until: 07:00, 1,
Until: 08:00, 0.5,
Until: 09:00, 0.25,
Until: 22:00, 0,
Until: 23:00, 0.25,
Until: 24:00, 0.75,
For: Weekends,
Until: 07:00, 1,
Until: 08:00, 0.5,
Until: 09:00, 0.25,
Until: 22:00, 0,
Until: 23:00, 0.25,
Until: 24:00, 0.75,
For: Holidays,
Until: 07:00, 1,
Until: 08:00, 0.5,
Until: 09:00, 0.25,
Until: 22:00, 0,
Until: 23:00, 0.25,
Until: 24:00, 0.75,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0;

For: Weekdays SummerDesignDay,
Until: 07:00, 0.07,
Until: 08:00, 0.53,
Until: 09:00, 1,
Until: 10:00, 0.53,
Until: 17:00, 0.07,
Until: 18:00, 0.3,
Until: 19:00, 0.53,
Until: 20:00, 0.77,
Until: 22:00, 1,
Until: 23:00, 0.77,
Until: 24:00, 0.3,
For: Weekends,
Until: 07:00, 0.07,
Until: 08:00, 0.53,
Until: 09:00, 1,
Until: 10:00, 0.53,
Until: 17:00, 0.07,
Until: 18:00, 0.3,
Until: 19:00, 0.53,
Until: 20:00, 0.77,
Until: 22:00, 1,
Until: 23:00, 0.77,
Until: 24:00, 0.3,
For: Holidays,
Until: 07:00, 0.07,
Until: 08:00, 0.53,
Until: 09:00, 1,
Until: 10:00, 0.53,
Until: 17:00, 0.07,
Until: 18:00, 0.3,
Until: 19:00, 0.53,
Until: 20:00, 0.77,
Until: 22:00, 1,
Until: 23:00, 0.77,
Until: 24:00, 0.3,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0;

Heating demand calculation



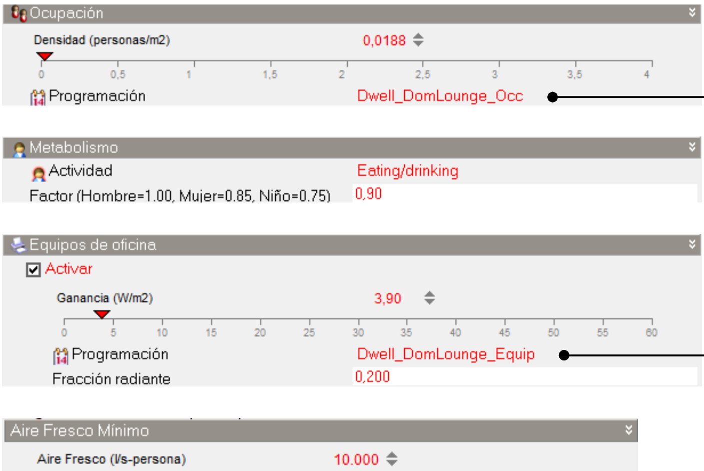
Summer comfort calculation



For: Weekdays SummerDesignDay,
Until: 07:00, 1,
Until: 08:00, 0.5,
Until: 09:00, 0.25,
Until: 22:00, 0,
Until: 23:00, 0.25,
Until: 24:00, 0.75,
For: Weekends,
Until: 07:00, 1,
Until: 08:00, 0.5,
Until: 09:00, 0.25,
Until: 22:00, 0,
Until: 23:00, 0.25,
Until: 24:00, 0.75,
For: Holidays,
Until: 07:00, 1,
Until: 08:00, 0.5,
Until: 09:00, 0.25,
Until: 22:00, 0,
Until: 23:00, 0.25,
Until: 24:00, 0.75,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0;

Figure 3.23. Conditions of use of the **bedrooms** (zone L5).

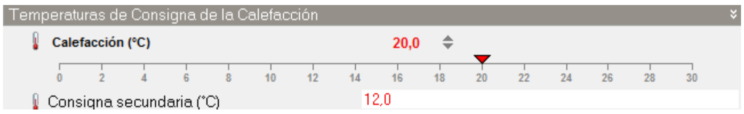
Zone L6



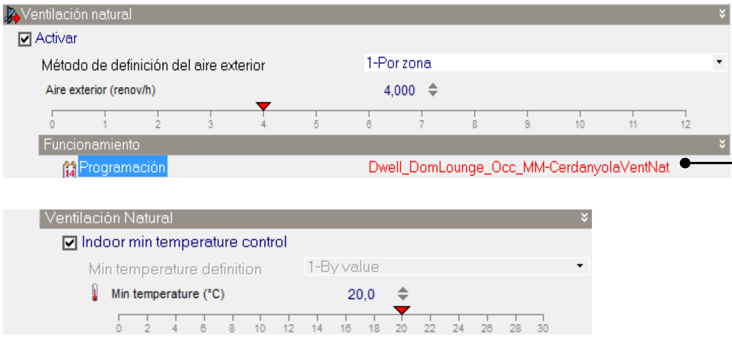
For: Weekdays SummerDesignDay,
Until: 16:00, 0,
Until: 18:00, 0.5,
Until: 22:00, 1,
Until: 23:00, 0.67,
Until: 24:00, 0,
For: Weekends,
Until: 16:00, 0,
Until: 18:00, 0.5,
Until: 22:00, 1,
Until: 23:00, 0.67,
Until: 24:00, 0,
For: Holidays,
Until: 16:00, 0,
Until: 18:00, 0.5,
Until: 22:00, 1,
Until: 23:00, 0.67,
Until: 24:00, 0,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0;

For: Weekdays SummerDesignDay,
Until: 16:00, 0.06,
Until: 18:00, 0.53,
Until: 22:00, 1,
Until: 23:00, 0.69,
Until: 24:00, 0.06,
For: Weekends,
Until: 07:00, 0.06,
Until: 23:00, 1,
Until: 24:00, 0.34,
For: Holidays,
Until: 07:00, 0.06,
Until: 23:00, 1,
Until: 24:00, 0.34,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0;

Heating demand calculation



Summer comfort calculation



For: Weekdays,
Until: 7:00, 1,
Until: 16:00, 0,
Until: 18:00, 0.5,
Until: 22:00, 1,
Until: 23:00, 1,
Until: 24:00, 1,
For: Weekends,
Until: 7:00, 1,
Until: 16:00, 0,
Until: 18:00, 0.5,
Until: 22:00, 1,
Until: 23:00, 1,
Until: 24:00, 1,
For: Holidays,
Until: 7:00, 1,
Until: 16:00, 0,
Until: 18:00, 0.5,
Until: 22:00, 1,
Until: 23:00, 1,
Until: 24:00, 1,
For: AllOtherDays,
Until: 24:00, 1;

Figure 3.24. Conditions of use of the **living room** (zone L6).

3.3.2 Results

The outputs calculated by the energy assessor include the indoor comfort conditions in summer and demand for space heating.

Based on the hourly simulation results the frequency distribution of temperatures falling above a given value is calculated by the tool. That means that for each temperature value in the diagram the number of hours when temperature overcomes the observed value is provided. The analysis is conducted for the summer period from July to September. The results are provided for each zone. Only occupied hours are taken into account in the frequency distribution.

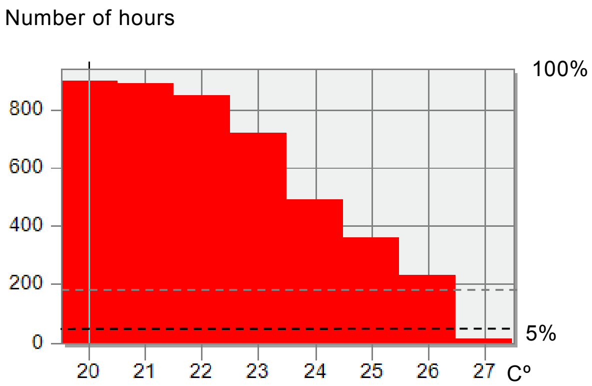


Figure 3.25. Number of occupied hours above specified temperatures in the **corridor** (zone L2) in the period from July to September.

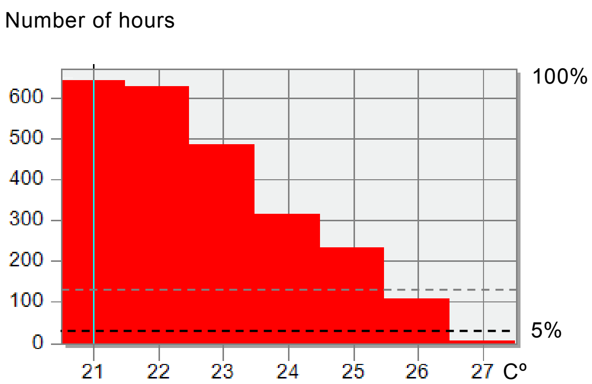


Figure 3.26. Number of occupied hours above specified temperatures in the **bathroom** (zone L3) in the period from July to September.

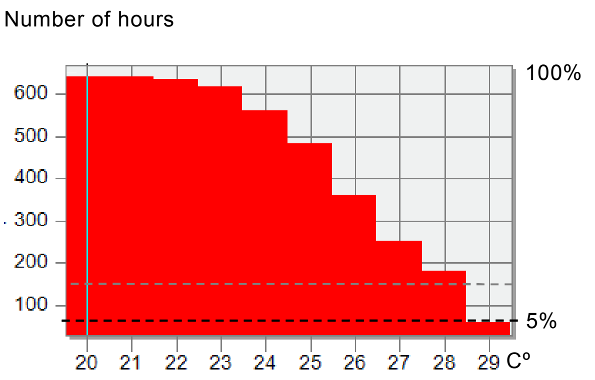


Figure 3.27. Number of occupied hours above specified temperatures in the **kitchen** (zone L4) in the period from July to September.

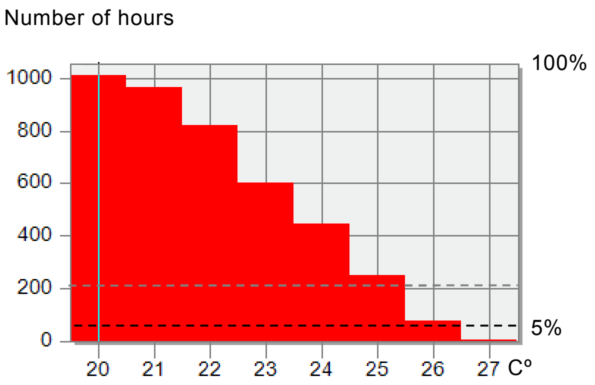


Figure 3.28. Number of occupied hours above specified temperatures in the **bedrooms** (zone L5) in the period from July to September.

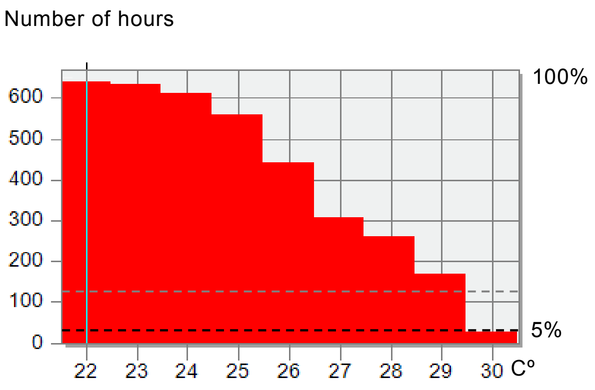


Figure 3.29. Number of occupied hours above specified temperatures in the **living room** (zone L6) in the period from July to September.

Also the space heat loads are calculated for each zone and aggregated on monthly and annual bases to obtain the demand for space heating.

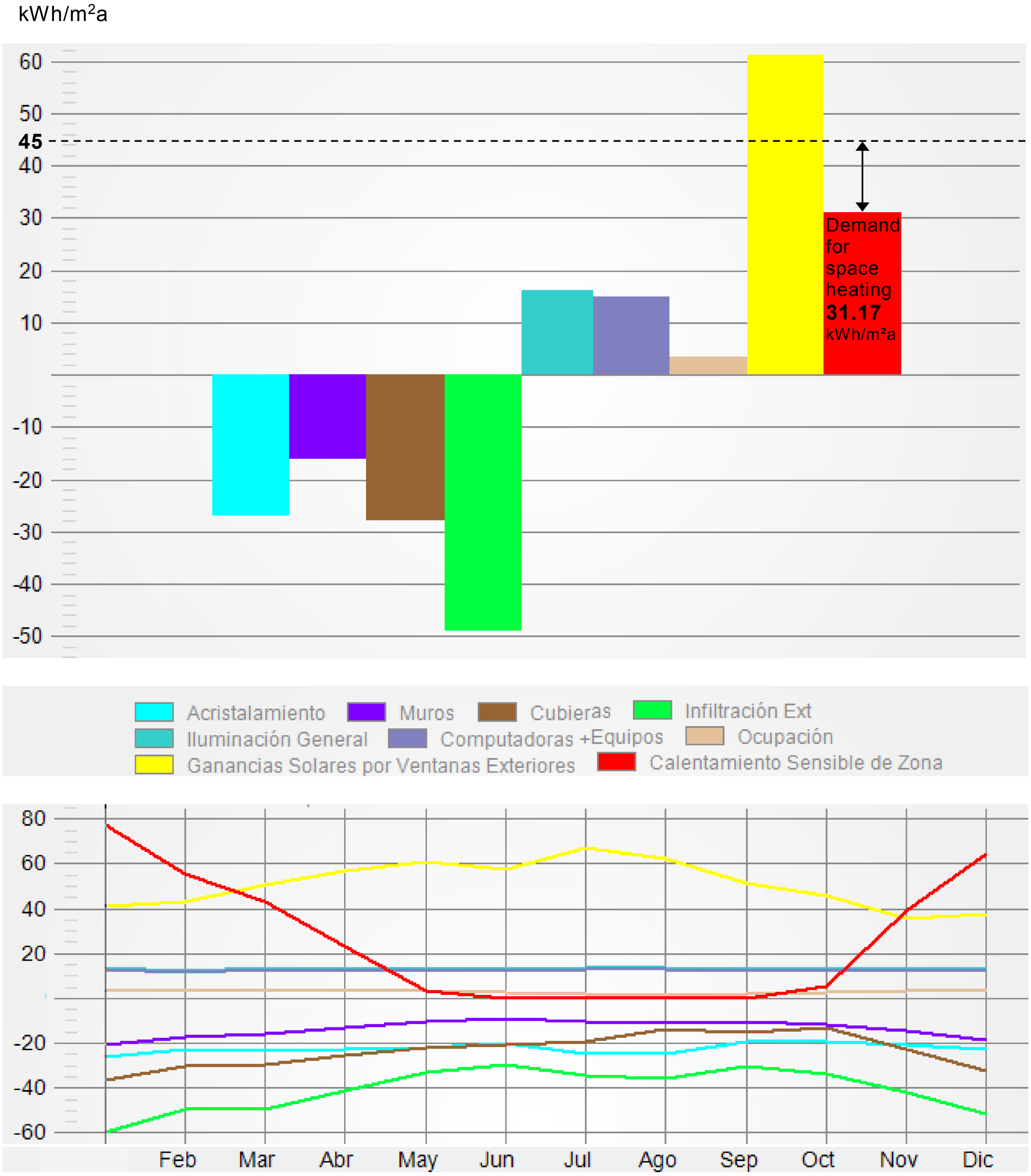


Figure 3.30. Different space heat loads integrated over a whole year and per month expressed in kWh/m²a. They include in the following order: losses through windows, walls and roof, infiltration losses, internal gains from lighting, appliances and occupancy, solar heat gains and finally the demand for space heating (sensible heat only).

3.4 CASE B – OIB-HWB02H MODEL

In Case B a design solution is produced by the design team and modelled with the OIB-hwb02h tool. The model created by the energy assessor is described in this section.

3.4.1 User inputs

Location of Vienna is selected. Based on it, the tool identifies the corresponding climate data of Vienna region from the tool library (Figure 3.31).

Standardisierte Klimadaten										
Wohnbau-förderung (WBF)	Seehöhe m	$HGT_{12/20}$ Kd/a	HT_{12} d	θ_e °C	θ_{ne} °C	I_S kWh/m²a	$I_{O/W}$ kWh/m²a	I_N kWh/m²a	$I_{horizontal}$ kWh/m²a	Land
Wien	-	3235	208	4,45	-12	356	210	150	368	W

Figure 3.31. Standard climate data (*"Klima Standard"*) of Vienna, in the tool library.

In the Technical information (Figure 3.32), data of the whole building are introduced such as multifamily residential use, gross conditioned floor area of 5295 m^2, mechanical ventilation mode. Simple calculation options for thermal bridges and windows are selected. The value of ventilation heat recovery efficiency is set here to reproduce the effect of the heat pump used to increase the heat transfer between exhaust and supply air.

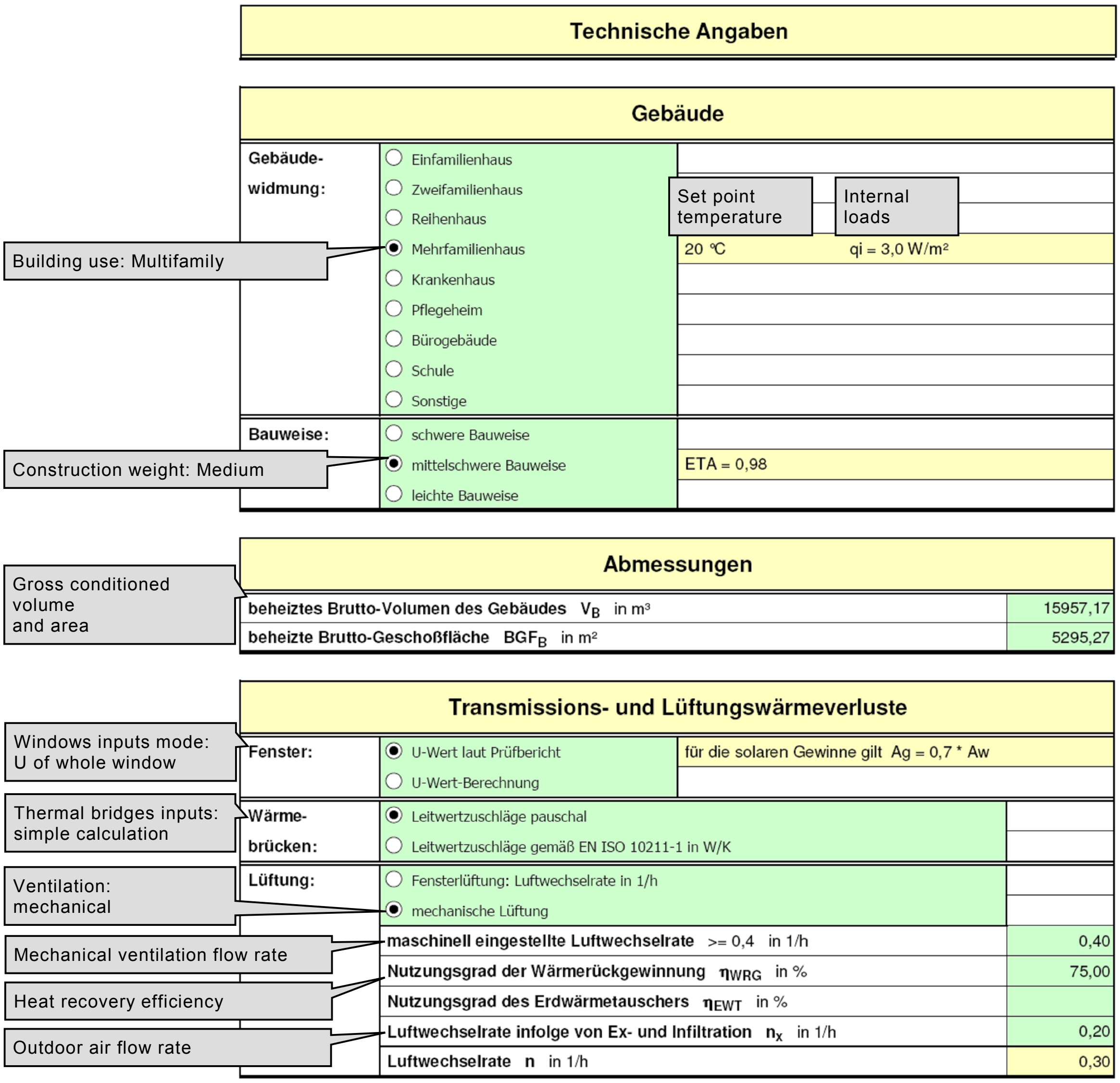


Figure 3.32. Technical information (*"Technische Angaben"*).

In Components (Figure 3.33), opaque envelope is described by specifying for each component the construction type (facade, roof, basement, etc.). The building physics assessor chooses the option of introducing the U-values of the construction components, instead of detailing the properties of each layer.

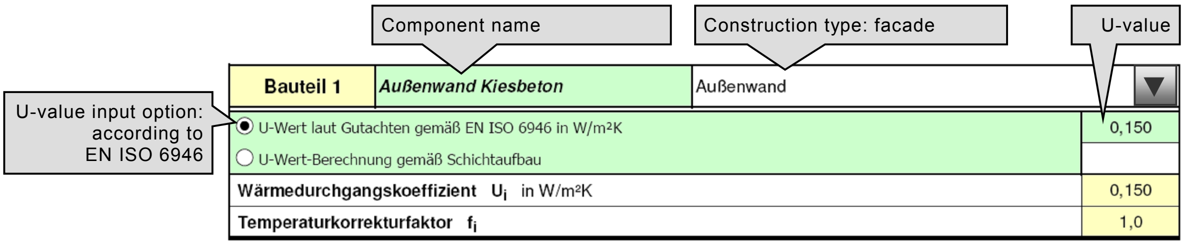


Figure 3.33. Component 1, in Components (*“Bauteile”*).

In Window type (Figure 3.34), the building physics assessor creates a single window type (*“Fenster F1”*), introducing the U of the window and g-value of glazing.

Fenster F1	*FENSTER von Wohnung*
U-Wert des Fensters U_w laut Prüfbericht in W/m²K	1,300
U-Wert der Verglasung U_g in W/m²K	
U-Wert des Rahmens U_f in W/m²K	
Wärmebrückenzuschlag ψ_g in W/mK	
Gesamtenergiedurchlaßgrad g	0,550

Figure 3.34. Fenster F1, in Window types (*“Fenstertypen”*).

In Window surfaces (Figure 3.35), different inputs are specified for each window type including, number of windows, individual windows’ dimensions and exposition, type of solar protection, and identification of the opaque component where windows are positioned.

Fensterflächen												
Anzahl	Fenster F1 - F10	in Bauteil 1 - 24	j	S	b m	h m	A_w m²	f_g	A_g m²	A_f m²	l_g m	U_w W/m²K
1	F1	1	N	U	1,06	1,34	1,42	0,70	0,99	0,43	4,26	1,300
1	F1	1	N	U	2,25	0,84	1,89	0,70	1,32	0,57	5,67	1,300
1	F1	1	N	U	1,06	2,21	2,34	0,70	1,64	0,70	7,03	1,300
1	F1	1	N	U	0,90	2,21	1,99	0,70	1,39	0,60	5,97	1,300
4	F1	1	O	V	1,06	2,21	9,37	0,70	6,56	2,81	28,11	1,300
8	F1	1	O	U	1,06	1,34	11,36	0,70	7,95	3,41	34,09	1,300
2	F1	1	O	U	0,53	1,34	1,42	0,70	0,99	0,43	4,26	1,300
1	F1	1	O	U	1,20	2,00	2,40	0,70	1,68	0,72	7,20	1,300
1	F1	1	S	U	2,25	0,84	1,89	0,70	1,32	0,57	5,67	1,300
15	F1	1	W	U	1,06	2,21	35,14	0,70	24,60	10,54	105,42	1,300
5	F1	1	W	V	1,06	2,21	11,71	0,70	8,20	3,51	35,14	1,300
2	F1	1	W	U	1,06	2,21	4,69	0,70	3,28	1,41	14,06	1,300
1	F1	1	W	U	1,06	1,34	1,42	0,70	0,99	0,43	4,26	1,300
2	F1	1	W	V	1,40	2,21	6,19	0,70	4,33	1,86	18,56	1,300

Figure 3.35. Extract of the table, in Window surfaces (*"Fensterflächen"*).

As shown in the figure, the number, dimensions and location of individual windows, is quite detailed in the modelled solution.

In Transmission heat transfer coefficients (Figure 3.36), building physics assessor specifies gross areas (including windows) and net areas for each wall, floor and roof. The resume of the total area and U-value of windows are also reported here.

	Bauteile			
	Bezeichnung	A_{brutto} m²	A_i m²	U_i W/m²K
Facade Kiesbeton	*Außenwand - Außenwand Kiesbeton*	3030,19	2366,79	0,150
Extensive green roof	*Außendecke - Gründach extensiv*	579,89	579,89	0,150
Terrace roof	*Außendecke - Terrassen*	210,58	210,58	0,200
Apartment floor over exterior space	*Außendecke - WHG über Außenluft*	2,63	2,63	0,190
Partition toward garbage/pram room	*Wand zu unbeheiztem Stiegenhaus - Trennwand gegen Müll/Kiwa*	73,85	73,85	0,420
Apartment floor over cellar/garage	*Decke zu Tiefgarage - WHG über Keller / Garage*	749,54	749,54	0,160
Apartment floor over garbage room	*Außendecke - WHG über Müllraum*	45,07	45,07	0,160
Apartment floor over pram room	*Decke zu sonstigem Pufferraum - WHG über Kiwa*	70,47	70,47	0,160
Green roof with Vacuum insulation panel	*Außendecke - Gründach VIP*	110,59	110,59	0,200

Fenster					
	Bezeichnung	A_i m²	U_i W/m²K	f_i	$A_i * U_i * f_i$ W/K
F1	*FENSTER von Wohnung*	641,80	1,300	var.	**834,34**

Figure 3.36. Transmission heat transfer coefficients (*"Leitwerte"*)

3.4.2 Results

In the results, the Space Heating Demand expressed for one year and for one unit of gross floor area is:

"Flächenbezogener Heizwärmebedarf" (HWB_{BGF}) 19,79 kWh/(m²·a)

Also the terms of the energy balance are reported from the calculation (Figure 3.37).

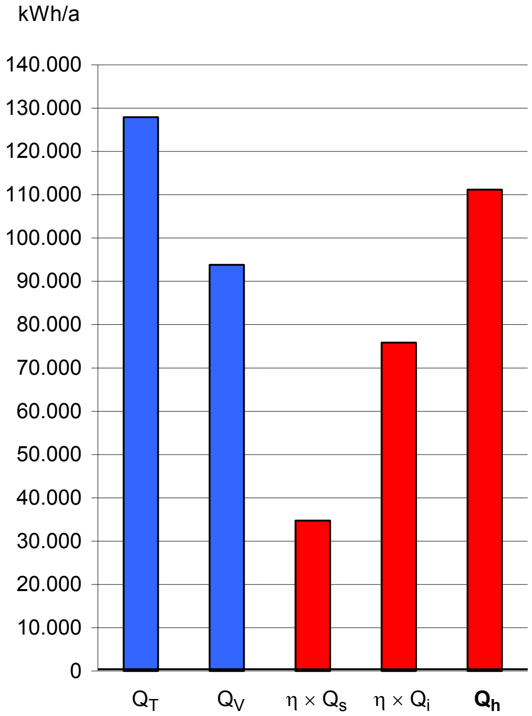


Figure 3.37. Terms of the energy balance – heat transfers by transmission (Q_T) and ventilation (Q_V), solar heat gains (Q_s) and internal heat gains (Q_i) multiplied the gain utilization factor (η) – in the output sheet EA2.

3.5 REFERENCES

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Ministerio de Industria, Turismo y Comercio & Ministerio de la Vivienda, 2007. *Documento de condiciones de aceptación de Programas Informáticos Alternativos*, Madrid: Gobierno de España, Ministerio de Industria Turismo y Comercio; Ministerio de la Vivienda.

Serra, R. & Roset, J., 2000. Energy Conscious Design Programme. In A. A. M. Sayigh, ed. *World Renewable Energy Congress VI*. Oxford, UK: Pergamon, pp. 494–499. Available at: http://www.sciencedirect.com/science/article/pii/B9780080438658500933 [2014-06-17].

Annex
4

Publications of the author

ARTICLES IN INTERNATIONAL JOURNALS

Madrazo, L., Massetti, M., Sicilia, A. & Wadel, G., 2015. SEÍS: a semantic-based system for integrating buildings' energy data. *Informes de la Construcción*, (in press).

CONTRIBUTIONS TO CONFERENCES

Massetti, M., Naomi, M. & Bednar, T., 2013. Energy calculation supporting the building design process. Retrospective analysis of a residential project in Vienna. In *2nd Central European Symposium on Building Physics – CESBP*. Vienna, Austria.

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Esta Tesis Doctoral ha sido defendida el día ____ de________________ de _______

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delante del Tribunal formado por los Doctores abajo firmantes, habiendo obtenido la calificación:

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