Energy Simulation Supporting the Building Design Process

A Case Study at the Early Design Stage

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***Abstract*—This paper shows a case study proposed in a doctoral thesis currently in progress. The thesis investigates the application of energy calculations to support the design process, ranging from simple energy calculation methods to detailed simulations. In the case study, the design process of an apartment building block in Spain is proposed. Different energy calculation tools are applied at each stage of the project. This paper focuses on the early stages of the design process, in which a simple modelling and calculation approach is adopted. The paper shows, by means of the discussion of the case study, the importance of key factors identified by the authors for the choice of a suitable energy calculation method during the design process.**

Keywords-building design process; energy calculation; energy simulation; key factors; multiple design problems.

I. INTRODUCTION

Research and professional experiences of architects and energy specialists [1] reveal that ordinary professional activity rarely involves deep energy analysis and calculations to support the building design process, despite the expected potentials of these tools [1][2][3]. In the field of building energy simulation, McElroy [1] and Clarke [2] proposed to integrate energy simulation with a specific design methodology, but from their experiences they recognized that several barriers still exist. In order to address this issue, it is fundamental to understand which factors must be considered to integrate effectively calculation tools at the different phases of the design process. Few indications are provided by previous investigations in this field [4][5][6]: to face this issue, a doctoral thesis is on going on this topic. The thesis analyses this issue considering energy calculation in the specific context of the building design process: attention is paid to the evolution of the process through different stages, the integration of different competences and the interaction of multiple design problems, not merely quantifiable. In fact, it is fundamental to understand the complexity of the design process: extensive studies exist on the architecture design process and the application of design methodologies [7].

To illustrate this complex problem and to support the investigations, a case study is proposed in this paper.

In particular, in Section II, the design process of an apartment building block in Spain is presented. Different phases are identified: Conceptual and Development Design phases, followed by the Operational phase. In each design phase a suitable calculation tool is adopted - from simple calculation to detailed simulation tools.

In Section III, the paper focuses on Concept design phase. The software Archisun 3.0 [10] is adopted to evaluate building energy and indoor environmental performances. In Section III.A, the project constrains are identified including the constraints imposed by the indoor environmental requirements, by the regulation, by the building program, etc.. In Section III.B, the main decisions at stake in this project at Concept design phase are also identified. In Section III.C, with reference to the defined constraints and decisions, specific hypotheses for energy modelling are established, fixing the boundary conditions and letting the other variable free in order to represent design possibilities to be explored. Section III.D describes how different design alternatives are developed and modelled by the design team, and the corresponding energy performances are obtained by the tool. The obtained performances are considered together with other design aspect, to assess the design solution and take more conscious decisions about the solution to be further developed.

In Section IV, several factors influencing the choice of the suitable tools to support the building design process are identified: these factors are specifically discussed with reference to the case study.

In Section V, conclusion and future perspectives are presented.

II. CASE STUDY OF A SOCIAL HOUSING DESIGN PROCESS

A social housing apartment building block recently completed in Spain is considered. In this paper, the authors wish to replicate retrospectively a possible design process that the design team could have followed using energy calculation to support the design decisions, see Madrazo et al. [8]. The case study intends to exemplify as far as possible an ordinary project, in terms of building use, size and budget. For this reason, at the concept design stage, a small design team working in close cooperation is considered.

A. *The existing building*

The building is a recently completed 24 apartment social housing block, in Cerdanyola del Vallès, Barcelona, Spain, which has been built by the public housing institute Incasol.

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The rectangular block is aligned to the street, with the main expositions facing South and North. 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. Lobbies and commercial areas are located in the ground floor. The first, second and third floors are addressed to residential use. The typical floor is organized around two cores serving four dwellings each one (Figure 1).

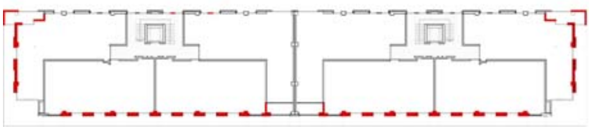

Figure 1. Cerdanyola residential building, typical floor. In red, solar wall in south/east/west façades.

The building design process has been recreated by means of a hypothetical scenario assuming that different energy calculation tools are used according to each specific design stage.

B. *Scope and strategy of the case study*

The case study, referring to one specific building design process, can support but not demonstrate the validity of theoretical hypotheses about the use of energy calculations in the design process. However, the case study can provide a useful example aimed at discussing the key factors influencing the choice of energy calculation method (see Section IV). Therefore, the research focuses on the application of energy calculation through the process more then analysing in depth energy performances of different solutions.

Moreover, the case study doesn't provide an exhaustive replication of the whole design process. In fact, (a) it focuses on the energy performance of the building, stressing only some (of the innumerable) relations with other design aspects. (b) At each design stage, only some representative solutions (among many ones) are taken into account from more extended design scenarios. (c) Only some specific moments through the different stages of the building life cycle are described.

In line with the arguments of different authors [7][9], it is here assumed that the design team methodology is flexible to the specificity of the project and to the evolution of the design circumstances. This methodology is not necessarily totally explicit and predefined, but it can be partially implicit and embedded in the design team experience, and at some extent improvised according to the project evolution. The main references used to reproduce a realistic design process based on different design stages are INTEND [9] and McElroy [1].

C. *Design process overview*

Different stages of building life are considered: the building Design – Conceptual Design and Design Development – and the building Operation stage. Energy calculation tools, which support the building Design, are considered for the investigation. Each Design stage is characterized by specific decisions associated with specific project constrains. Both influence the specific hypotheses for energy calculation at each design stage. For the analysed case study, at each design stage, different calculation tools are used to predict building energy performances:

- Archisun, based on a simple energy calculation method
- EnergyPlus (DesignBuilder interface), based on a detailed energy simulation.

At the conceptual design stage, two design alternatives (C1 and C2) are investigated among different solutions, where the second one is a variant of the first one. Archisun is used to predict energy performances.

At the next design stage, a solution from concept design is developed. Two design alternatives (D1 and D2) are considered, as in the previous stage, and EnergyPlus is used to predict energy performances.

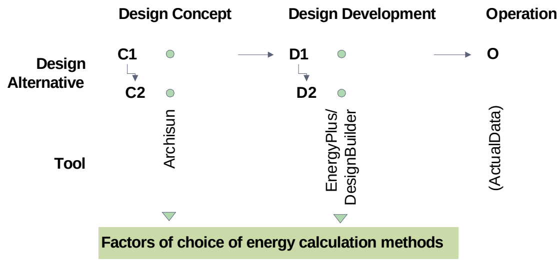

Figure 2. At each phases of design process a specific tool is used: two design solutions (C1-C2 and D1-D2, respectively) are generated through the process and modelled with the corresponding tool.

At the operational stage, the data obtained (by means of measurements, surveys and energy bills) from the real building are considered to verify the mach between predicted and actual energy performance [9].

III. Focus on the Concept Design Stage

This section describes the specific constraints of the project at the concept stage, the decisions to take, and then how they are translated in modelling hypotheses for energy calculation. Finally concept design solution(s) is described. The section structure doesn't correspond to a predefined sequence of steps as it is assumed that different design tasks within the design process are strictly interrelated: consequently, they may occur simultaneously or in aleatory order [7].

A. *Project constrains at concept design stage*

The following conditions are mostly identified by the design team since the beginning of the concept design phase including: building program (description of the general requirements for the building), budget and specific goals, which are defined by the design team and the client, site conditions and applicable regulation, which depend on the context.

The building program consists of the following points:

- 24 social housing apartments for rent (one of them must be adaptable).

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- 2 independent staircases and roofs
- 4 apartments at each floor for each staircase, with maximum useful floor area of $70m^2$
- 3 rooms for each apartment, with all rooms visitable
- 5 people for each apartment
- Commercial areas at the ground floor
- 1 underground floor for the garage.

The client budget is 3.170.000 euro.

The main applicable regulation constraints are identified from the technical regulations about construction [11] and systems [12] and the urban regulation [13].

Site conditions are also considered, such as: environmental conditions (thermal, acoustic, lighting, etc.), social conditions (social composition, population density, etc.) and perceptive conditions (as surroundings' views).

Finally, the design team agrees specific project goals with the client, referred to different design aspects, including among the others energy performance goals:

1. Indoor environmental comfort indicators
2. Energy Demand for Heating, Cooling and Domestic Hot Water
3. Primary Energy Consumption
4. Energy Cost
5. Embedded Energy

Energy calculation with Archisun is used at this stage to assess the points 1 and 2, in order to highlight the trend of the performance indicators with the variation of design solutions and to support design decisions (as exemplified in Section D). The aim of the analysis is to compare the effect of different solutions on energy indicators.

B. *Object of design decision at conceptual design stage*

At conceptual design stage, the main decisions regard Building and Systems, while the building Use related factors are not yet considered. In particular the design team explores different options about:

- Building orientation
- Building shape
- Building envelope opening ratios
- Building envelope components performances
- Systems types
- Systems - in situ renewable generation

Section D provides an example of the different Building envelope opening ratios explored during the design process.

C. *Hypotheses for energy calculation at conceptual design stage*

Building program, site conditions and applicable regulation (Section A) are translated to hypotheses for energy calculation. These hypotheses apply to the conceptual design stage and are initially common to any building design alternative (including C1, C2), as they do not initially depend on the design solution.

The parameters affecting energy performances (Figure 3) may be design variables (e.g., U value of the envelope) or they may be design given inputs imposed by the context of the project (e.g., outdoor temperature of the site or input imposed by the regulations, etc.).

The design team defines the same energy calculation boundary conditions for all the building design alternatives. Boundary conditions include all design given inputs imposed by the context and those design variables the team decides to fix as boundary conditions. In fact, some design variables are fixed by the design team as they do not influence the design decisions taken at this stage (see Section B). In Figure 3, the main Building (E) and System (S) characteristics are open to design decisions. Instead, the building Use related factors (User behaviour - U, Indoor environmental quality - I, Operation - O) which are not object of decisions are fixed. Exterior environment data (C) on climate and building surroundings are also fixed, being given inputs imposed by the context.

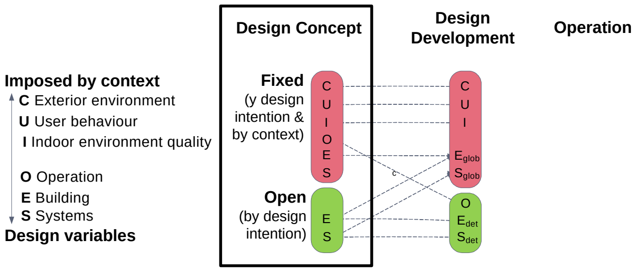

Figure 3. At the concept design stage, the design team fixes some to energy performances variables - red field. While they let main Building (E) and System (S) characteristics open to design decisions - green field.

The calculation tool as well imposes boundary conditions for some energy performance variables which can mach with the boundary conditions assigned by the designer. At this point, it is fundamental the choice of a suitable tool. The design team chooses Archisun (the choice is discussed in Section IV) in a way that the boundary conditions imposed by the tool are coherent, as far as possible, with the boundary conditions they want to define. This logic (outlined in Figure 3) applies to the specific modelling hypotheses of the design alternatives (C1, C2) simulated with Archisun, which are considered hereafter. Input data are summarized in Table I.

Archisun input deta	Value		Comments
Exterior environment (C)			limited options constrainted by the tool
Map position			imposed by project context
Height over sea level	105	m	imposed by project context
Urban density	0.9	-	imposed by project context
…climate data			imposed by context, taken from tool library
Bulding geometry and construction (E)			
Conditioned volume*	4536	m3	depending on program
…envelope data			
System (S)			
…system efficiency data			
User related factors (U, I, O)			limited options constrainted by the tool
Maximum occupancy	120	p	depending on program (=5people*24flets)
Building use	perm.nt		depending on program
temperature set point	f(t)	ºC	imposed by the tool Archisun
...ventilation settings data			imposed by the tool Archisun
...other building use data			imposed by the tool Archisun
*: it includes only appartments (1680 m2 useful floor, 2.7m useful internal height)			

TABLE I. SUMMARY OF ARCHISUN INPUT FOR CONCEPT DESIGN OF THE CASE STUDY. CONSTRAINED INPUT ARE IN RED, UN-CONSTRAINED INPUT ARE IN BLACK

Archisun allows to model one single zone, accordingly with design team intentions. The building is modelled as a single zone representing all apartments, excluding the building areas with different uses and common spaces. The tool imposes the indoor environmental conditions of the adjacent spaces. The values are between the conditioned space and outdoor conditions. The modeller assigns the useful volume value (4536 m3), deduced from the building program, to the “volume” input. The other building data are not fixed as they depend on the explored design possibilities.

Tool inputs data like map position, altitude and urban density are fixed by the context. Inputs, as urban density, not directly available from any source, must be assessed in advance by the modeller. After map position, altitude, sea distance and urban density are given by the modeller, the tool assigns default climate data for four seasonal sequences of typical reference days [10]. Mean external temperature is 9.6ºC in winter (7.5ºC daily variation) and 28.1ºC in summer (8.8ºC variation).

Input data related to building use, imposed by the building program (Section A), are translated to specific values by the modeller: building use is set as “permanent”. Then the tool, based on this single input value, assigns a set of default values for each day of a representative week. The tool constraints on detailed use parameters are coherent with the design team intention to constrain building control strategy. At this stage in fact, control strategy is not object of design decisions.

D. Generation and evaluation of concept design alternatives

After the definition of the input parameters (Section A), alternative conceptual solutions are outlined. A large number of alternatives of the design solution are admitted to be explored by the team during concept design. Among them, we describe here only one design solution, C1, and its further modification in another solution, C2, already identified in Figure 2.

The design solution (C1) is generated from multiple initial considerations about the urban regulation constraints, the access from the public space and the climatic aspects.

The design conditions and some initial concept solutions are progressively represented through an evolving sketch. The urban plan is the starting point for the concept formalization. Given the floor surface of the building, urban plan influences significantly Building Orientation (North/South) and Building Shape (4 floors compact block), and the design team has no much possibility to decide about these issues. Therefore, the form of the building rough volume in the project site can be defined very early in the process. Moreover, the building program requires two independents staircases to give access to the apartments. With the typical solution of this region with the stairs internal to the building fabric, some apartments would have only one external façade. This suggested the designer to adopt an external access system to assure two external façades for each apartment.

The solution (narrow layout / double exposition for each apartment) addresses multiple aspects of the design problem. The uniform linear configuration entails uniformity of solution for all apartments under different aspects, including environmental conditions (in relation with solar radiation and ventilation) as well as internal distribution, views, etc. It also fosters uniform constructive solutions, having implications on construction cost. Meanwhile, the external balcony proposed to solve the access to apartments raises privacy and security issues.

In this moment, the design team decides to deepen some of these aspects: energy demand and indoor environmental conditions. The generated concept solution requires special attention to the façades (with large south and north surfaces), to explore and evaluate appropriate relations between transparent and opaque surfaces of envelope. Energy calculation can inform the designer on the trend of variation of energy demand with the variation of opening ratio.

This is the moment when concept solution is modelled in order to calculate its performances with Archisun. First, the boundary-conditions specified in Table I are modelled. Later, the description of the design solution is completed with the other modelling data initially unconstrained (in Figure 3).

Building envelope is characterized by 15% windows opening ratio in the South façade (C1) and then the ratio is increased to 45% (C2) to explore the effect on the energy demand. The calculation informs the design team on the appreciable reduction of heating demand produced by the variation (Table II). The design team deduces that heat lost through the South façade is compensated by increasing the solar gains (see Section C).

	Opening ratio	**Demand kWh/m^3·y**	
		Heating	***Cooling***
C1	15%	9.43	3.42
C2	45%	8.63	3.65

TABLE II. OPENING RATIO EFFECT ON HEATING/COOLING DEMAND

Meanwhile, calculation informs the design team that C1 and C2 show no significant difference in terms of cooling demand, due to the permanent shading elements on the transparent envelope. Finally, the simple and rapid modelling process and performance visualization facilitate the evaluation of energy performances results together with other aspects of the design problem affected by the opening ratio, such as lighting, privacy and external views.

The simplicity of compared alternative in this scenario permits to focus on the integration of energy calculation through the design process, accordingly with the aim of the research.

IV. DISCUSSION - FACTORS OF CHOICE OF ENERGY CALCULATION METHODS

ASHRAE defined few key factors for the choice of the energy calculation methods and tools [4]. Although, specificity of the different design stages are not stressed. In this paper, different factors are discussed, carefully considering the complexity of the building design process: attention is paid to the transition through different process stages, the convergence of different competences and the interaction of multiple design problems, not merely quantifiable. The factors influencing the choice assume different importance and priority at each design stage.

In the presented case study, each design stage is characterized by specific conditions and decisions at stake, thus specific hypotheses apply for energy calculation, as Section III illustrates for the Concept design stage. Therefore, at each stage a suitable software tool for energy calculations is chosen. The Factors influencing the choice of the energy calculation method are here identified and they are discussed to evaluate Archisun suitability to this design scenario at concept design stage.

- **Level of discretization (detail)** of Archisun building model is quite low. The building is modelled as one single entity with a limited set of attributes. It corresponds to a single zone. Dynamic data are defined on daily basis for few typical days [10]. The limited detail required for modelling input responds to the general decisions considered in concept design stage. It helps to keep under control the design problem/solution and to understand the problem/solution which at this stage is not completely clear. It also limits the time and resources consuming demands of modelling. Modelling detail is limited to the essential for the fulfilment of an acceptable accuracy, cf., McElroy [1]. In the example (Section III-D), only a single input of transparent surface ratio is necessary for each façade to model solution C1-C2.
- **Level of complexity of calculation algorithm** of Archisun is relatively low for automated calculation, thus limiting Accuracy but enhancing Feedback immediacy – a priority at this stage. The limited Level of complexity of the calculation algorithm is expected to enhance the understanding of input variables effect on energy performances.
- **Responsiveness to design decisions** of Archisun is appropriate for the project. The tool inputs correspond to the few main overall variables of Building and Systems, that the designer needs to explore in order to face the typical decisions of this stage, e.g., transparent surface ratio of C1 and C2. In fact, Archisun shell not constraint any project variable explored at this stage (cf., Section III-C). Inputs respond to the specific decisions considered for this stage, made at global level of the building (e.g., global U of the envelope), and do not force to anticipate further decisions (e.g., on detailed components characteristics). Moreover, Archisun outputs provide the performance indicators for the whole building conditioned space, which are useful at this stage to take decisions.
- **Feedback immediacy** of Archisun is high, as its calculation method is relatively simple (cf., Level of discretization and Level of complexity of calculation algorithm). High Feedback immediacy is a priority at this design stage in order to explore rapidly a large number of alternative solutions that are highly uncertain and open (note that C1 and C1 are just a small sample of a more complex scenario). The small design team works in close cooperation and real-time calculations offered by the tool make much easier for the architect to obtain the specialist feedback before moving forward, having immediate communication with the energy specialist, cf., INTEND [9].
- **Flexibility to design modification** of Archisun is adequate to the project concept stage. Modeller can quickly explore modifications of the solution under analysis. A radical concept reformulation, e.g., of the building shape, can be represented with a moderate effort, manipulating a few parameters without a deep re-modelling. This characteristic is strictly related to the Level of discretization and with the Responsiveness to design decisions of the tool (as Flexibility is important specifically for the key parameters for design decisions). Archisun also allows, throughout the concept design, to adjust with a moderate effort the hypotheses for energy calculation boundary conditions initially set down (e.g., Conditioned volume), manipulating few parameters without a deep re-modelling. Flexibility is lost in case design modifications impose to skip from a higher to a lower level of input complexity: in this case several data must be re-introduced.
- **Flexibility to solution representation** indicates that Archisun model is able to suitably represent the conceived alternative solutions at this design stage. The model input, envelope opening ratio, represents directly the solution (C1/C2) conceived by the designer, without any stretching. The low Flexibility of this tool in the representation of building Use related factors does not limit the design solution exploration, as the design team decided that Use related factors are not object of design decisions at this stage.
- **Accuracy** of Archisun is expected to be acceptable for a residential building project (with simple HVAC system) at this design stage (cf., Level of discretization). At this stage, high Accuracy in energy performance prediction is not the first priority. But a minimum Accuracy is necessary to correctly point out and compare the different performance of design alternatives C1 and C2. The approach of Archisun versus the uncertainty of some parameters is of fixing to default values some quantities (in particular, building Use related factors), instead of entrusting them to the concept designer discretionality (see constrained variables in Section III-C) in order to avoid arbitrary modelling assumptions. Archisun sensitivity analyses are provided by Palme [14].
- **Integrability in multiple design problem** of Archisun is facilitated by its low Discretization, which limits the design team resources dedicated to energy analysis and subtracted to other design aspects. Archisun is characterized by a high Feedback immediacy, which allows a rapid shift

from one problem domain to another, and by a wide range of multiple performances that can be calculated (thermal, lighting, acoustic comfort and energy). Integrability facilitates a better understanding and control of the overall problem: this is crucial when energy and environmental performances are considered together with all the other aspects of the design problem.

- **Data coherence preservation capability** is facilitated by the double level of complexity of Archisun input model which intends initially to handle overall solutions and later to refine them. Thus, in the later refinement the initial data are preserved. Nevertheless, in this scenario different tools are used at each design stages, in order to fulfil with their different requirements. Therefore, Data coherence preservation does not depend only on Archisun. Data coherence passing from one stage/tool to the next is actually not easy to solve. In particular, the transition of energy calculation input from one tool to the other is demanding, but it cannot be simplified as a matter of tools limitation. In fact, driving the solution from some generic model to more specific one (e.g., from one single U for façade to specific components properties) is right the role of designers. A limitation of Archisun is its lack of transparency about the building use related data, that consequently can hardly be reproduced coherently with Energy Plus in the next design stage.

According to most of the considered factors, Archisun seems appropriate for concept design stage. Nevertheless, many of these factors are strictly interrelated, controversial and in some cases one is conflicting with another.

V. Conclusion and Future Work

The case study highlights the role of several factors identified in this paper as predominant for the choice of suitable energy calculation method to support the design process. The proposed key factors pretend to make a step forward in the line of precedent literature indications [4][5][6], as their discussion in the case study intends to explain. In fact, existing energy calculation tools and the underlying methods are many and very different, and a good choice, based on their specific characteristics, is fundamental to foster the exploitation of energy calculation potentials through the entire design process. In particular, the factors for the choice of suitable energy calculation methods are specific for each design stage, as shown in the case study. Finally, the priority and the evaluation (favourable or not to the choice) of these factors vary according to the specificity of the individual project and of the design process evolution – not totally predictable a priori.

Therefore, it is suggested that the factors of choice should provide solid applicable principles, which are flexible to the specificity of the project. In fact, their purpose is not to impose rigid and deterministic rules, universally applicable in advance to any project. With this regard, a remark is addressed to the fact that most of these factors are strictly interrelated, someone is controversial and in some cases one is conflicting with another, therefore this procedure does not provide an absolute judgment.

Within the future work, authors intend to

- extend the analysis to the whole design process, including the design development phase
- improve and provide more specific definitions and discussions about the key factors identified in this paper.
- corroborate the hypothetical scenario with the feedback from direct experiences of different practitioners in Europe.

VI. Acknowledgment

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