Multi-scale analysis and optimization of building energy performance – Lessons learned from case studies
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Abstract
The sustainability of the built environment largely depends on its energy and environmental performances. The overall objective, across the different phases of the building life cycle such as design phase, construction phase, commissioning phase, operation phase and eventually refurbishment phase, is to improve building and system performances in terms of economics, comfort, environmental impact and durability.
Numerical simulation tools and optimization methods are needed to properly evaluate all the key performance indicators simultaneously, unveiling the existing gaps and identifying possible synergies and strategies in the performance estimation and decision-making processes for the building life cycle.
Further, several modelling methodologies have been developed in order to evaluate the energy performance of buildings. Generally, every modelling methodology responds effectively to some specific tasks, but there exists a lack of integration in the overall optimization process.
Given the multi-scale and multi-objective nature of the problem of optimization of the energy and environmental performances of the built environment, subject to economic and comfort constraints, an appropriate synthesis and integration process in modelling methodologies has to be identified, addressing realistically the uncertainties inherently present in every modelling strategy.
Data analysis and optimization techniques are successfully used in a wide variety of applications. Although these techniques have proven to be successful in both theoretical and applied domains, questions remains about their applicability for the problems introduced before. These questions involve primarily the robustness and efficiency of solutions procedures and the ability to identify relevant properties and to deal with large quantities of data.
The paper aims to analyse critically these topics by means of case studies, showing a possible path to create an integrated methodology able to synthesize all the relevant aspects previously mentioned.
Keywords: Multi-scale analysis; optimization; building performance; integrated design process.

1. Introduction

The interaction between factors such as building geometry, building physics, building components and system solutions creates a space for possibilities in the design process. The selection of the right materials and construction layers, the right dimensioning of spaces and volumes and the optimized organization of building functions can help minimizing the need for technical systems (cooling, heating, ventilation, lighting, etc.) that constitute, in many cases, complex design issue and a potential problem from the point of view of energy performance and cost. These tasks imply a profound reflection on the relevant elements to be designed in a building such as facades, roof, basement, transparent surfaces (e.g. glazing systems) and shading systems. The fundamental topics are, generally, insulation, thermal capacity, control of environmental conditions, solar geometry, internal air quality, etc.

More in general sustainability is necessarily a multi-disciplinary topic and cannot be reduced to the some simple separate issues. Sustainability, according to a widely adopted definition, has three sides: society, economy and environment. They clearly represent parts of a large and variously interconnected mechanism. A variation of one aspect on one side determines a wide range of derived effects. The causal relationships in many cases are not completely clear, but the most relevant ones can be nonetheless unveiled and the search for possible sustainable solutions can be represented by the best compromise among several possible objectives, partially conflicting each other.

1.1. Sustainability issues for the built environment

As introduce before, many factors related to the general definition of sustainability come into play when dealing with building design, for example the societal (implications of end-uses, comfort, etc.), economic (construction cost, O&M cost, etc.) and environmental (use of non-renewable resources, emissions, etc.) ones. While today many environmental labeling schemes are available as a specialized application of the knowledge developed in the several different sub-fields of sustainability [1], a deeper understanding of the holistic approach of design should be reached, because the specialization of the different field professionals may not guarantee, by itself, a sustainable design [2, 3]. In fact, the creation of a perception of sustainability often outweighs the interest in verifying the real sustainability of a building.

Energy use in buildings clearly connects directly to the societal, economic and environmental factors previously mentioned and thus considering it correctly, in the concept and early design phases, establishes the preconditions for sustainability. However, this requires an integrated design process from the very beginning, able to deal with the large variability of the design choices at the early stages. Focusing on the economic side of the problem, that determines ultimately the feasibility of a project (beyond technical feasibility), often buildings and facilities are developed by one or more subjects (e.g. general contractor, subcontractors, etc.) and the operation and maintenance costs are handed off to other subjects (e.g. building owners, ESCO, etc.).

This situation, in most of the cases, determines a condition in which the only objective is the minimization of the initial investment (capital cost) at the expense of whole life-cycle economic performance. Cost-optimal analysis [4-6], if set within a proper regulatory framework, can create a more correct perception of the relation between energy performance and cost in the building life cycle, although the robustness of technical and economic evaluations remains an issue to be carefully considered. In any case, social and economic pressure have to be present to improve sustainability.

1.2. Integrated design process and beyond

From the technical standpoint, the acknowledgment of the relation between design and performance evaluation according to social, economic and environmental indicators, should help avoiding costly and complicated technical systems that have to be generally introduced in the late stages of design in order compensate (often only partially) the inadequate or incorrect choices made in the concept and early design stages.
Starting from the necessity to consider simultaneously multiple criteria (occupants comfort, investment cost, energy efficiency, environmental impact, etc.), building design problem is difficult to formulate and to solve; nonetheless, a general integrated design process can be roughly summarized in the following steps:

1. identify the criteria, gather and validate data, diagnose and formulate the problem to solve;
2. define the goals with respect to the different criteria and generate different alternative solutions;
3. select one of the alternatives that will be an hypothetical solution;
4. validate the hypothetical solution or restart the decision making process.

The first step is represented by the selection of the criteria, goals and problem formulation. The design or the design team should evaluate the degree to which each design alternative satisfies the goals, then select, and validate (architects, engineers, clients) a solution that will be the final choice. Since no alternative optimizes all goals generally, a multi-criteria decision making method may be used to find the solution in a rational way.

A correct methodological approach to performance evaluation and quality control, not merely in the design process but during the whole life cycle of the building, could significantly contribute to the improvement of the real performance of buildings. Surveys and studies recently conducted, respectively in the US and EU [7, 8], showed how energy related issues determines a waste of energy between 10 and 15% on average and that generally no continuous evaluation of building performance is done. Therefore, in order to ensure long-term sustainability to the building sector, it is important to deal with the problem of energy efficiency correctly in the preliminary design phases and then to perform a continuous monitoring and performance evaluation process in the operation phase (periodic re-commissioning or continuous commissioning).

Further, it is necessary to establish a methodological continuity between simulation techniques [9], optimal control [10] and operation management of buildings [11], to ensure robustness of long-term performance and cost-optimality of solution subject to variable and uncertain economic and technical conditions.

From the research standpoint, a first step can be represented by the use of methodologies suitable for both the design and the operation phases, thus establishing a continuity between direct and inverse modeling techniques for building simulation [12]. The paper aims to show a preliminary application of these principles to a selection of case studies, namely 16 building (8 residential and 8 tertiary) constructed of refurbished in recent years.

2. Motivation of the research

Building energy performance simulation requires models, which describe physical phenomena with different levels of detail and accuracy. The models used in building performance simulation can be roughly subdivided into three main categories:

1. statistical models, built on data with different techniques [13];
2. simplified steady-state models, with limited input data but not particularly accurate [14];
3. detailed dynamic models, accurate but with detailed input data and long simulation time [14].

Statistical models and simplified steady-state models consider only the most important parameters that contribute to the determination of energy performance but are substantially different from the conceptual point of view. In fact, while statistical methods follow a top-down modeling approach [15] aimed at identifying the relation among parameters, simplified steady-state methods follow a bottom-up, starting by the component level up to the system level. Dynamic simulation models use a detailed bottom-up modeling approach, which requires the definition of a large number of parameters. In order to be able to standardize simulation and analysis procedures for benchmarking purpose, independently on the top-down or bottom-up approach of the tool employed, the relevant input and output data have to be identified.

For example, statistical methods can be used to simply estimate the heating consumption as a function of lumped thermo-physical properties and climate conditions. Heating consumption can be estimated also with a detailed simulation model, but it requires the definition of a much larger set of parameters at the system, subsystem and component level, which however turn out to necessary, for example, for verifying code compliance and developing detailed design.
As a matter of fact, all the models in the different categories listed before share at least part of the input and output data, with the possibility of using lumped (aggregated) parameters to avoid a detailed description of a component or a subsystem with the building.

In other words, the attention should be put not merely on the tools but more and more on the strategic role of data, depending on the specific type of evaluation. The different professionals involved in building performance simulation processes, not only in the design phase but also in the operation phase must set priorities (i.e. criteria and goals to be achieved) with respect to the specific task and, subsequently, select the more appropriate model.

2.1. Building industry

In the concept and early design phases the possible configurations to be studied in a building energy performance simulation process are particularly large and uncertain, while in the operation phase the elements to be studied are more specifically dependent on the building typology, end-use, technical systems, etc. [16]. What we see today in the building industry is that there exists a general lack of:
1. integrated design process;
2. third-party design and construction phase commissioning;
3. fully open protocols for building controls systems with accurate and strategically placed sensor and data acquisition systems;
4. building data management systems connected to Building Information Modeling (BIM) technology.

All these elements, in order to be successfully integrated within the building industry have to be necessarily improved and data have to accessible at different levels of detail (scales of analysis), using both bottom-up and top-down approaches, depending on the specific task. As a matter of fact, the processes and tools must be strategically connected to enable the cooperation among different field specialists during building life cycle and they have to employ common:
1. terminology and definitions;
2. performance metrics (across different levels);
3. building design and operation management approaches (integrated, data intensive, model based).

2.2. Building Information Modeling

On the one hand, it has been shown that decision made early in the design process can have a very large impact on the energy consumption of buildings and today, on the other hand, BIM technology is demanding more and more an effort in the initial design process. However, this effort can be problematic if the fundamental task is simply reducing upfront capital cost and there is not enough space left for the research of optimal configurations according cost-optimal analysis.

Therefore, in order to fulfill progressively the gaps currently present in the building industry, we must enhance the capabilities of the tools conceived to evaluate analytically design configurations and to help in the definition of knowledgeable decisions at the early stages of design process, ensuring a connection with BIM standards (software interoperability, data exchange formats).

2.3. Building simulation and optimization

In the “conventional” modeling approach a digital model is constructed and then simulations are run. The designer changes the models, creates another set of runs and compare the results against a baseline configuration, determined by building code requirements. The feedback from the analysis informs the design process through the interpretation of the modeler/analyst. Many modelers think that it is possible to determine the best solution by creating several options and testing them; those who have more knowledge and skills, built upon years of practice, understand what could be the best compromise solution. However, this is not really an optimization process, as the search space of possible variables is not extensively explored. The first step into a more correct understanding of the
The problem of optimization is parametric analysis. This technique is not an optimization technique on itself, since it does not find automatically optima (minima or maxima). However, if simulations are run according to Design Of Experiment (DOE) methodologies [17] the space of variability of the input data can be efficiently explored. These methodologies require visualization tools and statistical analysis to build “response surfaces”, i.e. surrogate models (meta-models) fitted to simulation data.

Another option is that of using direct search algorithms (genetic algorithms, particle swarm, etc.) in a sequential simulation running process. This strategy is computationally intensive and, unfortunately, cannot guarantee the identification of a global optima, but can stick in local optima during the iterative search. Finally, a more interesting approach emerged, based on a combination of surrogate models trained on simulation data and efficient optimization techniques, able to exploit the structure of the surrogate model formulation to find efficiently solution in the search space [18].

3. Methodology development

Starting from the general topics reported in the introduction and from the more specific tasks described in the motivation of research, we developed a methodological approach to enable a multi-scale analysis of the building case studies that will be presented in the following section. The approach starts from the definition of standard datasets for:

1. building materials;
2. building construction components;
3. lumped thermo-physical characteristics;
4. building thermal performance (heating and cooling demand);
5. climate data.

The visualization techniques selected are scatterplot matrices and parallel plot graphs, commonly used in multivariate data analysis. The data plotted are organized according to three different levels of detail:

1. component;
2. subsystem;
3. system.

Given the multivariate nature of the data considered, the analysis should be aimed at identifying, from a general standpoint, relations in data by means of analytical models (clustering, regression, etc.) to identify similarities, trends and, therefore, contribute to an easier performance benchmarking at different scales of the building system and, more in general, in the different phases of building life cycle. As outlined before, the methodological approach can be extended to encompass more dimensions related to building technical system and therefore enabling the comparison with metered performance data.

The visualization techniques are themselves weather-adjusting methods and can be used to normalize the building performance with respect to climate data. Further, it has to be stressed the fact that regression coefficients can have a physical meaning [19] if models are properly constructed and can be used to calibrate detailed dynamic simulation models [20].

These models are very detailed and require the user to carefully define the physical characteristics of the building construction components, the operating characteristics of the appliances and technical systems, occupancy and detailed hourly weather data. Statistical tools can contribute to the simplification of the process of simulation calibration (potentially up to automatic calibration).

The evidence of the research in building model calibration and optimization push forward to a more integrated and general approach with respect to the analysis of building data. In synthesis, the potential advantage of a multi-scale analysis approach are the following ones:

1. highly scalable approach to target and assess energy efficiency opportunities in one or many buildings;
2. low-cost inverse modeling approach, based on benchmarking data, that can be calibrated automatically with metered data;
3. advanced benchmarking capabilities for performance verification, simulation validation and identification of opportunities for energy efficiency improvement;
4. data-driven analytics to provide essential data for techno-economic assessment under uncertainty (e.g. cost-optimal).

The steps in the application of this methodological approach are the following ones. First of all, multivariate data have to be generated by simulation according to design of experiment methodologies (DOE), after that relevant statistics have to be calculated and confidence intervals have to be set. Finally, building simulation and real data can be compared, highlighting the discrepancies with respect to the regression coefficients and, consequently, to their physical counterpart. This approach combines the use of tools for automated sequential building simulation [18] and general purpose data analysis and visualization tools in a new synthetic way, aimed at filling the gaps described in the research motivation section.

4. Discussion on case studies

The case studies analyzed and discusses are 16 building newly constructed or retrofitted in recent years. The buildings have different end uses; 8 of them are residential buildings while the other 8 are tertiary ones. The analysis has been conducted on the following scales (levels of detail):

1. envelope components (component level);
2. lumped thermo-physical parameters (subsystem level);
3. thermal energy demand for heating and cooling and climate data (system level).

First of all, envelope analysis is performed according to the relevant international standards [21, 22]. One opaque component for each building has been selected as representative of external wall, rooftop and basement. Transparent components characteristic have been considered for simulation purpose, but are not reported in this example.

The data plotted in Figure 1 are:

- superficial mass, \( m_s \);
- thermal transmittance, \( U \);
- periodic thermal transmittance, \( |Y_{el}| \);
- decrement factor, \( f \);
- time lag, \( \Delta t_f \);
- internal areal heat capacity, \( k_l \).

As we can see from Figure 1, the data represented are highly dispersed, because the building where realized in different periods (with different requirements of building codes) and in different climatic zones within the Italian territory. Despite this variability, what appears to be evident is the correlation among some of the dynamic thermal properties such as periodic thermal transmittance, decrement factor, time lag and the superficial mass of the components. This is intuitive from a general point of view since thermal capacity is proportional to mass, but it tells us also that these dynamic thermal properties of opaque components can be further optimized (by selecting materials and layers appropriately) to avoid an overweight in components that can be negative, for example, from the structural point of view.
After that, the lumped thermo-physical properties have been calculated also according to relevant international standards [14, 23]. The selected quantities are:

- heat transfer coefficient for envelope transmission, $H_T$;
- heat transfer coefficient for ventilation, $H_V$;
- global heat transfer coefficient (transmission + ventilation), $H_{tot}$;
- effective thermal capacity, $C_m$.

The heat transfer coefficients have then been divided by the gross volume of the building while the effective thermal capacity has been divided by net floor area. This modification of the original data is done to enable the comparison of properties across the different sizes of the buildings. The results obtained are plotted in Figure 2.

In this case, the graphical representation is aimed at identifying similarities in data. For these reasons, two colors have been used, red for the residential buildings and blue for the tertiary ones. The variation of the performance with respect to the heat transfer of envelope is large and depends on the thermal properties of components, but also on the geometric features (e.g. surface/volume ratio) of the building fabric.

The heat transfer for ventilation is largely variable in tertiary buildings, as it depends directly on the internal air quality requirements that are dependent on the type of end-use.

On the other hand, the effective thermal capacity varies largely based on the dynamic thermal properties of the construction components (in particular the internal areal heat capacity) and on the geometry of the building.

Finally, we consider the thermal energy demand for heating and cooling of average operating days, one for each month and we divide it for 24 hours and for the gross volume to enable the comparison across the different building sizes. The other parameters considered are monthly average outdoor air temperature, total daily solar radiation on horizontal surface (one value for each month) and the building average free-running temperature, calculated as specified literature [24].

The parameters selected are therefore the following ones:

- average outdoor air temperature, $T_o$;
- average thermal power for heating and cooling (heating positive, cooling negative), $P$;
- daily solar radiation, $I_r$;
- average free-running temperature, $T_{fr}$.
The results are plotted in Figure 3, showing the correlation between the thermal performance for heating and cooling and the outdoor air temperature, and the correlation between outdoor air temperature and solar radiation, that enables the application of regression analysis to derive physical parameters as in energy signature methodology [19].

The correlation between outdoor air temperature and free-running temperature is also particularly interesting, in particular with respect to the evaluation of the potential of free-cooling and variability in set-points of internal air temperature with respect to different comfort models [24].
Fig. 3. Scatterplot of average power for heating and cooling, outdoor air temperature, solar radiation on horizontal surface and free-running temperature

5. Conclusions

Long-term sustainability of the built environment requires an integrated design process from the concept phase onward and continuous evaluation of performance during the whole life cycle of buildings and facilities.

In this paper, an initial reflection on a multi-scale analysis approach has been presented with respect to some selected case studies, represented by newly constructed and refurbished buildings.

The methodology focuses on three levels of analysis, construction components, lumped thermo-physical properties and thermal energy demand for heating and cooling with respect to climate. The visual and analytical tools presented enable the comparison of the performance in terms of heating and cooling with respect to the variations in the design parameters as well as in climate data patterns. In fact, simulation data obtained with a meteorological reference year can be plotted against metered data with actual climate conditions.

In other words, by extending the methodology for benchmarking purpose, we can be establish a comparison of the performance of different solutions in the same climate, or of a certain solution with respect to variable climate data patterns. The methodology can be also extended to encompass air-handling processes and hygro-thermal behaviour of buildings with adequate parametrization.

The multi-scale analysis may be used in connection first with clustering techniques that could enable the identification of similarities in data, also in a graphical way. After that, regression and model identification techniques may be used to derive physical parameter from data. As stated earlier, data can be collected and analyzed first in the concept phase but can then be compared to the ones obtained in the operation phase, for model calibration and validation purpose.

By completing the methodology with uncertainty analysis, a more proper assessment of the potential outcomes in terms of energy performance and economic impact becomes possible. A mixture of visual tools and numeric techniques, giving a more direct feedback to the design team in the initial phase and to energy management professionals in the operation phase, can constitute the evaluation itself. By transforming the multi-scale analysis methodology into one or more optimization problems under uncertainty, techniques such as convex and nonconvex programming can be used to explore efficiently the search space of variables, with respect to different objectives such as minimum thermal energy demand, maximum free-cooling potential, minimum energy for air handling processes, etc.

In the methodology presented, the optimization models have to deal first with the lumped thermo-physical and geometric variables (system level view), setting the conditions for the subsystem level variables (i.e. opaque components, transparent components, etc.). The problem of detailed design can then be solved at the subsystem level, validating the solutions or rejecting them.

Finally, the fundamental results of the research in this direction would be that of creating a “short circuit” between the methods, models and tools used in the different phases of the building life cycle, in order to enable multiple feedback processes and to establish dialogue among different disciplines and specialists. The comparison of simulated and real performance of buildings, within a transparent benchmarking framework, creates the possibility for a correct assessment of the uncertainties in building energy simulation in the early stages of design and more robust techno-economic analysis procedures that could ensure the feasibility of a fast, market enabled evolution of the building sector towards long-term sustainability goals.

References


