# THERMAL PERFORMANCE SIMULATION FROM AN ARCHITECTURAL DESIGN VIEWPOINT

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## ABSTRACT

The present paper is an attempt to bridge the gap between building designers and simulationists by proposing a common framework for discussion.

It is a positional paper written from a building designer's viewpoint that basically agrees with the proposition that design is no longer dominated by physical structure thinking but by performance and system based concerns. However, the authors still recognise the need to find appropriate criteria, which are directly related to design actions, to evaluate performance and therefore effectively relate design decisions to simulation results.

The proposed framework operates within an integrated dynamic system methodology in which outputs, performance goals, optimisation and controls are dealt with at the level of the building envelope response instead of the overall building response.

It is believed that the best way to set up a conversation between designers and simulationists is not to swing between the two points of view but to establish a unified framework for discussion disconnected from any specific tool or performance target.

## KEYWORDS

Integration, dynamic systems, methodology, holistic design, simulation output data.

## INTRODUCTION

The state of the art presented by SERI in 1985 acknowledged the fact that a comprehensive "design process" for energy efficient buildings was non-existent due to complex and case-by-case interactions between the weather and the building surroundings, usage, client preferences, etc. and this view is still valid today. The challenge of reducing energy consumption as a new design issue is still there in terms of architecture.

The difference between 1985 and today is that "environmentally friendly" components and simulation tools to evaluate building performance are now quite well developed, but much is still to be done with regards to the overall building context.

What SERI (1985) would call "re-invention"of the design process at that time, Bachman (2003) would call integration nowadays. In either case the identified need is to deal with the building as a whole not by assemblage of components.

We are now in an age where building performance targets will not only be set but will be explicitly measured as well, so architects who do not integrate creativity and rational technology risk becoming purely professional specifiers of "environmentally friendly" components that might even jeopardize the overall performance of a building depending on the overall context they are put into.

It seems to be a contradiction to think that Architecture, the last profession of integration (Bachman 2003) is not making it happen, and it is the aim of this study to understand why and to start a discussion about a possible way to overcome this problem.

The starting point is a literature review of the methods currently used to analyse simulation tool results, as well as the methods used to integrate simulation tool results into the design process. This review is not exhaustive, it is purely used to illustrate the main trends and to identify the overall reasons for this integration/re-invention not being happening.

The review is followed by a discussion which intends to propose a way forward in terms of methodology for architects and simulationists to deal with the problem.

## THE STATE OF THE ART

### Methods for results analysis and display

Output results of thermal simulation tools are mainly alpha-numeric charts difficult to use and interpret and generally composed of enormous quantities of data. From a building designer viewpoint these charts are difficult to be used and interpreted. These is a clearly understood problem and many attemps have been made by developers and researchers to set up methods for combining and processing these results in order for them to make sense for designers.

Some of these methods can be classified as:

- Decision support systems
- Database

- Datamining

*Decision support systems:*

The aim of decision support systems (DSS) are to transform simulation tools results into a knowledge base display that supports decision making activities. This method is one of the most common way of combining and processing results from simulation tools and has been developed since the late 90s.

Soebarto and Williamson (n.d) debated this idea stating that DSS had to be effectively design orientated and proposed the addition of a multicriteria evaluation (MCE) strategy to explore changes and introduce incremental design improvements, properly standardized once compared to a reference building. Each improvement is measured according to a single criteria such as energy consumption or thermal comfort for example and costs and benefits of the final decision result from a weight linear combination of each individual cost/benefit solution proposed. This weight linear combination depends on the decisions previously taken by the designer and is a function of specific design targets.

Papamichael (1997, 1999) stated that as the designer is responsible for decision-making a decision support environment should provide an efficient display system in which designers could easily compare and evaluate alternatives. He also believed in MCE and developed the BDA tool (Building Design Advisor), not existing anymore, with an MCE oriented display output interface to allow a fast evaluation of design alternatives.

Prazeres and Clarke (2003, 2005) also discuss how to communicate building simulation outputs to users and propose the IPV interface as a starting point to this. Cognition rules are used to make sure the information is displayed in the appropriate manner for possible users. The I2PV, a further development of IPV have graphical, geometry, alpha-numeric, image and sound data displayed together. A rating system that states the overall benefit of the options calculated based on a weighting system is also offered as an MCE tool.

*Database*

The aim of database output displays are to allow designers to formulate performance queries on the results, based on organised multiple simulation runs. The use of database methods to combine and process results from simulation tools is quite recent.

Mahdavi et al (2005) propose a framework to develop an information matrix of performance indicators considering magnitude, spatial and temporal extensions of these indicators.

Stravoravdis and Marsh (2005) propose the use of scripts to generate and store large amounts of output data in an online database that can be easily accessed. They present a case study with 280 models in which all the data analysis can be undertaken within a MySQL database and results of the analysis can be exported to an Excel spreadsheet to generate reports.

Knight et al (2007) also illustrate the use of a database, the Customer Advising Tool, to generate information for potential reduction in the cooling demand of buildings. Users can perform interative queries to understand the nature of the cooling demands to be met in a database of more than 11000 simulations.

*Datamining and statistical interpretation of results*

Datamining is a combination of visual investigation, regression techniques and uncertainty analysis which basically consists of combining data sources, selecting the task relevant data and extracting patterns from this data through a user defined technique.It can be seen in a way as a mixture of performance query and decision support system, but it is a constant refining process of including and removing variables combining with filtering. Morbitzer et al (2003) believe that because design questions are more complex than simple displays of simulation outputs, the analysis of results will involve the analysis of more than one parameter and therefore propose the output results to be analysed through the use of datamining.

Ghiaus and Allard (2003) also propose the use of statistics to investigate output results. The relationship between the free-run temperature and the outside temperature to evaluate building adaptability is assessed through regression.

Methods for analysing results discuss techniques to display data without a strong emphasis in the discussion of which variables and metrics are relevant to be displayed. The questions that are trying to be answered by using the proposed display techniques tend to be discussed sometimes when methods for integrating simulation tools in the design process are explored.

**Methods for integrating simulation tools into the design process**

The fact that tools tend to be used mainly in later design stages either to check compliance with regulations (Wilde et al 1999, 2002) meet marketing targets in which the objective is to get an "environmentally friendly" label (Soebarto and Williamson n.d) or to optimize a few parameters and to support some small decisions still to be considered, has led many researchers to focus on the development of methodologies to integrate simulation tools earlier into the design process.

Some of these methods can be classified as the following:

- Incremental levels of complexity
- "playing around with an idea"
- Simple generative forms
- Genetic algorithms

Incremental levels of complexity

Since the early 2000s, the need for a comprehensive methodology involving all design stages: feasibility study, conceptual design, preliminary design, final design, construction drawings and buildindg specifications seemed to be the main concern of researchers (Wilde et al 2001). It was believed that each design phase would increase in terms of levels of complexities and therefore tools should follow this same logic.

Believing that design is basically a sequence of decisive actions, and that by being so, early phases dictate the final behaviour of the building, Mourshed et al (n.d) proposed the ArDot methodology which, transformed into a tool, was a CAD input interface linked to a DSS optimization system used to investigate complex relationships between design variables and conflicting objectives.

Under a similar view, Wilde et al (1999, 2002) developed the DAI – Initiative (Design Analysis Interface), integrating design methods and decision support theories. Performance matrices of mulitple scenarios were elaborated and results were assessed according to predetermined requirements previously specified in these matrices, allowing designers to use simulation tools from the beginning of the process.

Apart from that, some of the existing tools were incremented in order to be as comprehensive as posssible and therefore used since the early design stages. One example were further developments in ESP-r (Hand 1998, and Hand and Clarke n.d) by adding new tools and extending its capabilities to be used from the initial design phases. Another one was the transformation of the EnerWin methodology (Soebarto and Degelman 1995) into a software with the already mentioned MCE tool output data interface.

"Playing around with an idea"

Believing that one of the most important parts of the design process is the initial phase when, through brainstorming, the most basic ideas appear and need to be evaluated quickly, Marsh (1996) developed Ecotect. In Ecotect designers are allowed to freely play around with ideas and at the same time evaluate their performance using an interactive interface which provide results to be used as feedback and encourage new experiments until a mature solution can be found. Performance criteria dictate important aspects of the form, surface area and overall builidng shape therefore it is essential to inform the designer as to how the building will perform related to its geometry and components so that architects can understand all ramifications of each of their decisions.

Simple generative forms

A derivation of Marsh's research about integrating simulation tools into the early design stages is the simple generative form concept. Simple generative forms methods consist of scripts that generate rough shapes, contained in grids, that respond to a certain perfomance criteria (Marsh and Haghparast 2004). The generated shapes are actually optimised forms and provide insights to the designers about possible ideas to be developed.

The idea of the simple generative forms is to bring optimisation used in the later stages of the design process to the beginning. It is believed that this is useful to help designers start with an optimum set of compromises from a predetermined range of possible options to develop design ideas further. The method consists of a translation of results analysis into geometric decisions and the computational generation of a building form that meets the performance criteria specified. A script is used to generate the geometry (inside a predefined grid), calculate its performance and iteratively modify it until the criteria are met. Simple investigations are already incorporated into Ecotect as a software feature in the otpimum orientation and tilt angle for solar collection and further investigations applied to meet compliance criteria such as right-to-light and to maximise solar radiation falling on a stadium pitch have also been tested (Marsh and Haghparast 2004).

Genetic algorithms

Genetic algorithms (GA) are also generative search procedures to look for optimized design solutions. However, GAs are more sophisticated then generative forms because they do not use scripts but algorithms. The algorithms start searching by randomly sampling within a solution space. Genetic operators control the evolution of the generations of a problem solution and the probabilities of a solution to be chosen will be proportional to the fitness of that solution in terms of the performance target. The amounts of possibilities in terms of solutions tend to be much wider and a higher level of complexity in terms of solutions can be achieved.

Caldas and Norford (2002) and Caldas et al (2003) show examples of applications of genetic algorithms to sustainable design. In the first case, they show the use of GA to optimize window sizes for lighting and heating and in the second case they show the use of GA to optimize facades taking into account architecture compositional rules by minimizing the overall building energy consumption. The method is recommended to be used in intermediate to late design stages so that the number of possible solutions is not that extensive.

The generative form methods might be considered more advanced than the other methods because of the amounts of technology involved and also because of the fact that a single "best"/optimized solution can be achieved. However, these methods are heavily restricted by the criteria used to define the scope of action of the GA or scripts.

Methods that deal with incremental levels of complexity and tend to comprehensively address the design process are less restrictive in terms of design possibilities but leave the search for optimum solutions mainly up to the designer. This search will be strongly dependant on the methods for result analysis and display used to output the simulation data.

In both cases, the main concern is still to define the proper evaluation criteria for a given solution that will either be used to set up a framework to generate design possibilities, in the case of generative form methods, or will be used to analyze the performance of a group of design alternatives to advise future design actions to be undertaken.

## DISCUSSION

Setting up criteria to evaluate performance and relate these criteria directly to design actions is a methodological problem independent of the simulation tool being used. It requires simulationists to fully understand the way designers think, i.e. essentially exploring interactions of all parameters together and dealing with all the variables at the same time.

### An integrated dynamic system approach

Architectural design needs to be understood as no longer being dominated by physcal structure thinking but by performance and system based concerns. In the physical structure dominated thinking architecture was seen as something static, stable with a graphic representation coherent with the resultant forces acting on the structure members (Bachman 2003).

In this way of thinking it was easy to integrate virtual reality simulation tools – the CADs – within the design process as those tools would be consonant with the architect frame of mind; essentially developed to deal with static problems and highly intuitive because of everyone's lifelong experience with gravity.

However, architects are now expected to manipulate the building physics and quantify what before was purely qualitative such as lighting and comfort (Bachman 2003). Designers are expected to establish goals and get there by acknowledging the dynamically and interconnected elements of their design solution. Such an approach requires a performance orientated and dynamic system way of thinking which implies:

- Understanding buildings as systems in which the envelope represents the boundaries and the content encapsulates the interrelationships and internal flows of material, forces and information.
- Understanding these building systems as dynamic systems in which aspects of their content change over time and there is no status quo or lasting steady state.
- Manipulating these buildings as dynamic systems by controlling, optimizing and simulating their performances.

A dynamic systemic view is not new in architecture. Since 1985, when performance simulation tools were in their infancy, studies from the Solar Energy Research Institute would show that in order to be performance orientated architecture needed to be reinvented and that this reinvention should happen within an integrated dynamic system frame of mind (SERI 1985). This shift in terms of architecture thinking is believed to be necessary if designers still wish to control their design as a whole instead of purely becoming professional specifiers (Bachman 2003).

### Building envelope design in light of the dynamic system approach

It is the intention to create a common language between designers and simulationists within a dynamic system environment so that both can work together to understand the cause/effect relationships prior to proposing system alterations that improve these cause/effect relationships. In order to do so a classic dynamic system approach (Shearer et al 1971) applied to architecture is discussed. This approach intends to apply the following definitions of basic dynamic system concepts to building design:

- Inputs
- Boundaries of the overall systems
- Outputs
- Performance goals
- Optimization controls

*Inputs*

Inputs consist of all the stimuli acting on the building envelope.

Completely independent stimuli acting on the outside face of the building envelope are the weather and the building surroundings.

Stimuli encapsulated within the building envelope, acting on the inside face of this envelope are defined by what happens in the interior space of the building. Whenever the interior space is unknown by definition (for example in the case of speculative office buildings, when the occupancy is decided in a post-

design stage and it is likely to change regularly), designers have to consider different occupancy scenarios to be tested.
The building is expected to respond properly to the weather, surroundings and the internal occupancy.

*Boundaries of the overall system*
The boundaries of the overall system comprise the building envelope - the place in which architects mainly have their largest input.

The envelope is seen as something mainly static but in reality it has a dynamic response especially with regards to thermal behaviour. This response is expected to be quantified and improved in order to optimise and control the overall system conditions.

It is important for architects to understand that the envelope acts either as a barrier, a filter or both, moderating the weather, surroundings and internal occupancy effects.

*Outputs*
Outputs are the changes in the overall system response due to the influence of the weather, surrounding and internal occupancy.

Taking this concept literally does not help designers to analyse the performance of a group of design alternatives because overall system responses do not take into account only the envelope response. Internal occupancy as well as HVAC systems will also influence this overall system response making it impossible to isolate the envelope response from them.

The need to define metrics that account for the envelope response only are paramount if the main concern is to define the proper evaluation criteria to be used in setting up a framework to generate design possibilities, or to analyse the performance of a group of design alternatives to inform future design actions to be undertaken.

It is suggested that a possible metric would be a separation and presentation of the heat transfer processes happening at the building envelope level clearly related to the design parameters and design scope of actions. Heat transfer processes are shaped by design decisions and will be driven by surface temperature differences between the weather, surroundings and the interior space. Once related to design parameters and design scope of actions they can illustrate exclusively the envelope response allowing designers to relate cause/effect phenomena to design decisions.

*Performance goals*
Although performance goals are the targets to be met in terms of the overall performance, in this study they will address only the envelope performance, i.e. the kind of envelope behaviour designers are aiming for to best meet the overall system performance.

An ideal target would be to have a building envelope that offsets all the heat transfer mechanisms through it considering the different possibilities of usage of the internal space as well as all possible variations in terms of weather and surroundings (Bachman 2003). However, by considering the envelope as a perfect hypothetical passive heating/cooling system, then it could be argued that humidity control, air motion, air filtration and ventilation air were not being addressed properly as it is believed that passive systems are not reliable providers of such requirements. A purely passive solution is unlikely to meet comfort targets whereas a purely active solution is unlikely to meet energy targets.

A different approach to the problem, perhaps more realistic is suggested by SERI (1985). The study recommends designers to understand which of the 3 design philosophies they wish to apply:

- Climate-rejecting envelope behaviour
- Climate-adapted envelope behaviour
- Mixed-mode envelope behaviour

It is important to understand that all the 3 options can be “environmentally friendly” so long as the target is to minimise the use of energy without being detrimental to comfort conditions.

A climate-rejecting philosophy would deal with the envelope as a complete barrier to the weather and surroundings and the internal conditions would be mechanically controlled. This envelope can be environmentally friendly if designers work to reduce as much as possible the energy consumption needed by the systems to meet the required internal conditions.

A climate-adapted philosophy would deal with the envelope as a filter and distributor of locally available energy sources to the interior space (SERI 1985). In an extreme philosophical situation this would mean not using any kind of HVAC system at all to control the internal space which would mean a really “environmentally friendly” building.

A mixed-mode philosophy would mean a situation in between, in which the weather and surroundings and the unneeded heat generated inside are repelled when detrimental and the HVAC is used only as a complementary source of energy, acting as a back up to the less reliable climatic sources (SERI 1985).
Whilst targets can be debated, it is important for the building designer to be able to visualise what shape

and magnitude of profile would be aimed for in each design philosophy in terms of the performance metrics used to evaluate the envelope response. In other words, what would be the profile shape and magnitude aimed for in each heat transfer mechanism once a certain design philosophy is considered.

*Optimisation and control*

Although optimisation and control can be applied to the overall system response, in this case they will strictly refer to the design changes that should be made at the envelope level to reach the envelope performance targets.

An interesting approach is again provided by SERI (1985) which refer to design changes to be made at the envelope level as either incremental or non-incremental.

Incremental changes refer to more specific improvements, little changes that do not affect the design as a whole.

They could be related to intermediate and later design stages in the literature reviewed methodologies and are generally approached in terms of “new building retrofits”, i.e. a specific envelope response is appraised, the benefits of improving this response in terms of design actions are evaluated and a comparison between the ‘before’ and ‘after’ stages is undertaken to check the benefits in terms of performance.

Incremental changes are specific to each design alternative and work well once major changes in terms of shape, surface areas, orientation, etc. are not desirable.

Non-incremental changes, on the other hand, are exactly the opposite. Alternatives are explored for the whole building and major changes in terms of shape, surface areas, orientation, etc. are tested.

These types of changes can be used either to evaluate the performance of a set of alternatives, a common situation in early design stages, or to analyse the importance and role of specific design parameters or components in the overall building context.

There is no direct path in this situation but a collection of design trade-offs with the correspondent performance.

It is important to understand what incremental and non-incremental changes mean in terms of design parameters so that designers can relate each type of change to the heat transfer mechanisms happening at the envelope level. Designers need to be aware of how the design decisions affect the metrics used to evaluate the envelope response in order to improve their design.

## CONCLUSIONS

It is believed that the main reasons that prevent simulation tools from being used more fully during the design process, and therefore prevent the design process from becoming more performance orientated are:

- Most of the tools were developed by specialists who provided methods of presenting results to designers centred on different ways of displaying information without considering the meaning of this information to the designer.
- There appears to be enough discussion going on about final targets for the overall building usage and HVAC system performance, and tools have been developed to provide the means to evaluate them quite well in terms of outputs and optimisation and controls. However, if designers are expected to derive meaning from performance simulation results it is important to discuss the appropriateness of methods and metrics used to describe and analyse building performance, not only the overall performance. It is also important to relate those methods and metrics to design parameters and design scope of actions.
- Integration between simulation tools and the design process tend to be proposed as a juggling between the 2 different points of view instead of trying to set up a unified framework to deal with it.
- Energy issues are related to performance and system based concerns, concepts not well understood by architects who are used to handling static, physical structure-dominated problems.

The paper intended to cover these topics by:

- Questioning the display of information without discussing its meaning and proposing that for simulation results to be better used by architects they have to address the performance of the building envelope, not only the overall system performance. Potential metrics to show this performance could be the heat transfer mechanisms happening at the envelope level, which are easily related back to design parameters and design scope of actions.

- Proposing to integrate simulation tools into the design process by setting up a common framework for discussion between designers and simulationists which uses an integrated dynamic system way of thinking believed to be a more suitable design philosophy when considering the challenges of a performance orientated age.

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