A critical and theoretical analysis of current proposals for integrating building thermal simulation tools into the building design process

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This paper critically examines the main trends in attempting the integration of building thermal simulation tools throughout the whole building design process, focusing on studies related to building design only, not addressing studies related to HVAC and servicing engineering design. It presents a review of the research literature on the issue showing that, so far, attempts have been concentrated in propositions to improve thermal simulation tools data interpretation as well as propositions to improve the role of tools in building design practice. Examples of the literature related to the two topics are critically examined by considering their effectiveness in addressing the interdisciplinary problem of integration. This critical examination leads to a thorough mapping of specific reasons about why integration is not happening, complementing the current information provided from empirical studies on the matter. Even though the author recognises integrated design should account for HVAC and servicing, it is necessary to first have a discussion that addresses assimilating simulation tools into the design process if proper integrated design is to happen.

Keywords: thermal simulation; data interpretation; role of simulation in design; integration of simulation in design; criticising integrated simulation

As part of control and regulation in energy use, building energy performance targets are being set and explicitly measured. Legislation, initially prescriptive with regards to energy efficient parameters, has evolved to what is called ‘performance-based’ in which compliance targets are clearly defined for new buildings. Targets are consonant with the industrial and technological development, they not only require professionals to be compliant with regulations but also direct designers to use ‘environmentally friendly’ building components as well as available technologies in order to meet them.

These currently ‘new’ requirements to predict energy uses and demands on a quantitative basis can be translated in practical terms into a widespread need to use computer simulation tools to predict and evaluate the energy performance of buildings being designed. However, much is still to be done with regards to how these tools can be better integrated throughout the whole building design process.

An overview of evidence from empirical studies (Morbitzer 2003, de Wilde and van der Voorden 2003, Soebarto 2005, Donn 2004, Donn 1999, Clarke 2001, Radford and Gero 1980, Hand 1998 and MacDonalds et al 2005) will show that as a whole there is a lack of knowledge from building designers about the fundamentals of thermal building physics as well as issues related to modelling. Additionally, there is a lack of knowledge from building physicists about the building designer’s way of working and thinking, which clearly illustrates a problem of communication between these two design professions.

The author proposes that further investigations based on theoretical reflections that critically evaluate the state of the art in integrating simulation tools throughout the whole building design process are necessary to thoroughly map specific reasons for why integration may not be happening fully.

The present paper critically examines the main trends in attempting to integrate building thermal simulation tools throughout the whole building design process. A review of the research literature on the issue is presented (following a similar approach to the one proposed in Bleil de Souza and Knight 2007) to illustrate the main trends and to identify reasons for the struggle to fully integrate simulation tools throughout the whole building design process, in addition to what has been noted by empirical studies. This review is divided in two parts, the first one discusses methods of improving simulation tools output data interpretation while the second part discusses the tools and their role in building design practice. A discussion and criticism is finally presented mapping specific reasons for why integration may not be happening fully.

1. Propositions to improve thermal simulation tools data interpretation

As the output results of thermal simulation tools are mainly alpha-numeric files generally composed of enormous quantities of data which are difficult to use and interpret, post-processing is crucial. Using this approach, developers as well as researchers have attempted to transform raw simulation results into something more useful for designers.

A review of the literature about thermal simulation tools shows that the two main approaches that have been used in order for raw results to make sense for designers are the following:

- Improving output interface data display systems and
- Setting up design advice systems in output interfaces.

A description of each of these two approaches is provided in the next two sub-sections together with examples from the literature that refer to them. These examples are far from being exhaustive and are used to illustrate the main ideas behind each of the two approaches.

1.1 Output interface data display systems

Improvements in output interface data display systems generally consist of transforming alpha-numeric results into tables and graphs that display either raw or post-processed data.

Tables are useful to provide summaries or detailed quantitative information about specific aspects of the simulation. For instance, information regarding what happens in a specific part of a day, year and so on. Graphs, on the other hand, are powerful visual display systems that present the substance of the data, showing many numbers in a small space, making large data sets coherent, comparing different pieces of data and revealing different levels of detail (Tufte 1991b).

Graphs reveal patterns and trends and for that reason they tend to be the preferred type of information display to be explored by software developers and researchers when attempting to improve output interface data display systems (examples can be found in Square One Research 2008, Design Builder Software 2008, Energy System Research Unit 2008 through IPV interface, Prazeres and Clarke 2003, Prazeres and Clarke 2005, Morbizer 2003, MacDonalds et al 2005, to cite a few).

When displaying raw data directly, graphs tend to be:

- Time-series of loads and temperatures (for the whole building, specific zones, specific building elements, etc);
- Frequency distribution of loads and temperatures and
- Grids that display loads in time or space (Figure 1) and grids that display temperatures in space.

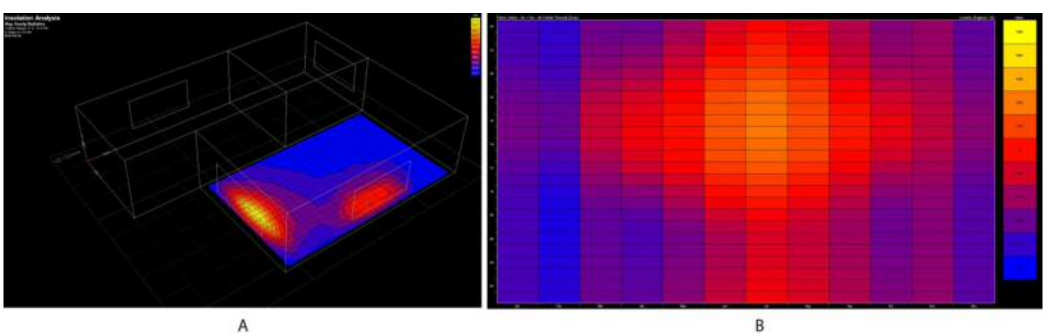


Figure 1 – Grids that display loads in space (a) and loads in time (b) (Square One Research 2008)

When displaying interpreted information, graphs tend to be:

- Bar charts of indexes that have some meaning for designers (discomfort degree days, monthly degree days, fuel type, CO2, costs, etc.);

- Linear graphs of comparative data as in Figure 2 (indoor vs. outdoor temperatures, gains and losses vs. outdoor temperatures, space loads vs. degree days, etc.);
- Grids that display indexes that have some meaning for designers in space as in Figure 3 (spatial comfort, percentages of insolation levels, etc).

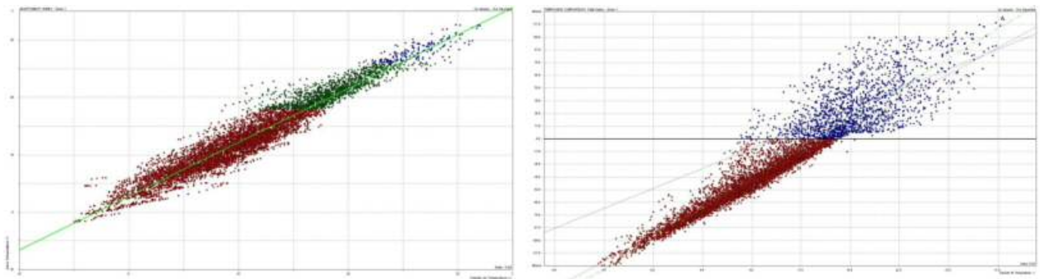
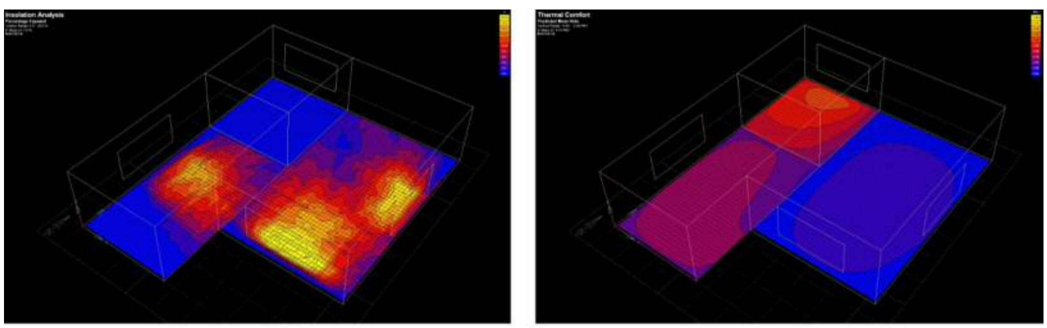


Figure 2 – Linear graphs of comparative data (Square One Research 2008)



A B

Figure 3 – Grids that display indexes that have some meaning to designers (Square One Research 2008)

Graphs that have time as one or two of the displayed variables provide shapes to quantities of phenomena that develop over time, but do not provide an explanation for the causal relationships that are happening (Tufte 1991b).

Frequency distributions are useful to display behavioural trends either of the building (through loads and temperatures) or of the impact of the building on its users. They provide quantities for qualitative analysis to be undertaken but without again providing an explanation for the causal relationships that are happening.

Graphs that have two resultant variables and/or two indices displayed are useful to show how one variable affects the other (Tufte 1991b). There is an account for causal relationships that are happening but these relationships are disconnected from time or space (Figure 2).

Graphs that have space as two of the display variables provide information about a specific behaviour, either of the building (through loads and temperatures) or of the impact of the building on its users (through comfort indexes, etc), at a specific instant in time. Quantities for a qualitative analysis to be undertaken are provided for a specific instant in time illustrating some causal relationships between spatial configuration and resultant behaviour, but only for this specific instant (Figure 3).

As a whole, even when made visual, the information displayed tends to be more useful for analytical purposes rather than for design advice because of the following reasons:

- It is difficult to provide a non-abstract illustration for causal relationships that are happening;
- When causal relationships are illustrated, they are represented in disconnection from their development over time.

It is usually difficult for designers to make sense out of the data that is presented. It is difficult for designers to understand the consequences of their design actions, as they mainly work with phenomena that develop in space, while simulation results are usually illustrated developing over time. As a result, in aiming to provide useful information for designers, most of the research in improving thermal simulation tool data interpretation concentrates on output interface design advice systems rather than on improving output interface data display systems.

1.2 Output interface design advice systems

Output interface design advice systems generally consist of environments in which designers can compare the results of different design alternatives. Comparisons either happen in absolute or relative terms, basically providing designers with feedback about the overall result of their design actions.

1.2.1 Performance indicators and notional building

The first step to make information useful for designers is to provide an artifice for numbers to somehow qualitatively express building behaviour or the impact of the building on its users. The most common strategy proposed in these cases is the creation of performance indicators – indices which quantify how far the simulated building performance is from a specific performance benchmark. Specific performance benchmarks can be either performance targets or notional buildings. Targets are generally provided by legislation (e.g. Approved Document L2 2002) whereas notional buildings can be found in different sources (e.g. SERI 1985, BRE 2008, ASHRAE 2004).

Different ways of communicating performance indicators are sometimes mentioned in the literature suggesting software output interfaces that mimic traffic lights (Prazeres and Clarke 2005) or more elaborate comparisons (ASHRAE 2004) rather than simple numeric displays and pass/fail systems (as in BRE 2008 for example).

1.2.2 Decision support systems

Comparing alternatives is seen as an important resource in performance assessment and more elaborate propositions that allow different design options to be displayed and compared comprise decision support systems – systems that transform simulation tools results into a knowledge base display that supports decision making activities. This method is one of the most common ways of combining and processing results from simulation tools and has been developed since the late 90s. It might provide a simple and efficient display system in which designers could easily compare and evaluate alternatives or it can be equipped with specific resources to explore the impacts of design changes in more detail.

Display systems in which designers could easily compare and evaluate alternatives are proposed in Papamichael, La Porta and Chauvet 1997, Papamichael 1999a and Papamichael 1999b. In this case, outcomes from different design alternatives are simply displayed side-by-side for designers to visually compare results (Figure 4b). More elaborate display systems, with the addition of multi-criteria evaluation strategies to explore changes, are proposed in Soebarto and Williamson 1999 as well as in Prazeres and Clarke 2005 (Figure 4b).

Multi-criteria evaluation strategies to explore design changes are proposed in Soebarto and Williamson 1999 by introducing incremental design improvements, properly standardized once compared to a reference building. Each improvement is measured according to one single criterion such as energy consumption or thermal comfort, and costs and benefits of the final decision result from a weighted 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.

A similar proposition is explored in Prazeres and Clarke 2005 who developed a weighting system to calculate the overall benefits of the different design options explored, ranking these options according to their performance outcomes. Radford and Gero 1980 also explore the idea of analysis multi-criteria. They set up a strategy to work with different objectives simultaneously, through the use of Pareto optimisation techniques, in order for decision makers to be able to make trade-offs with knowledge of their impacts.

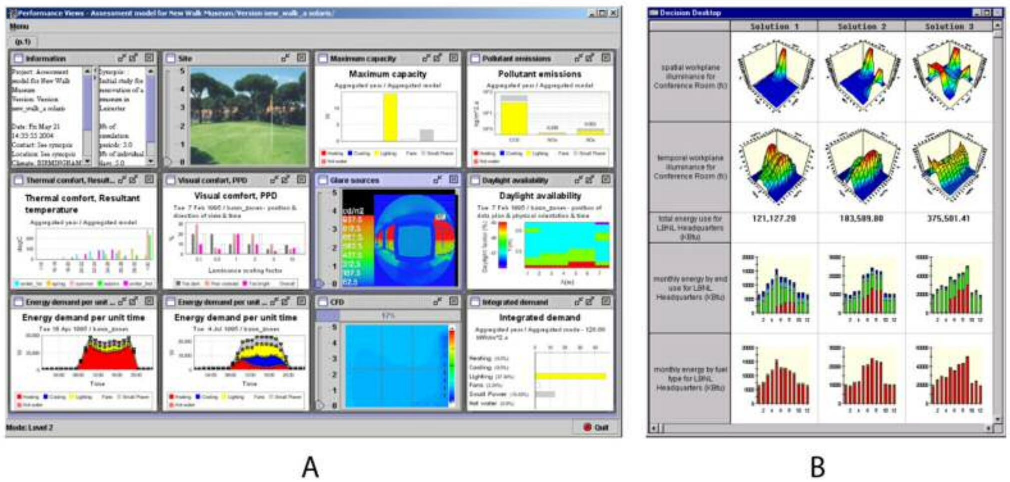
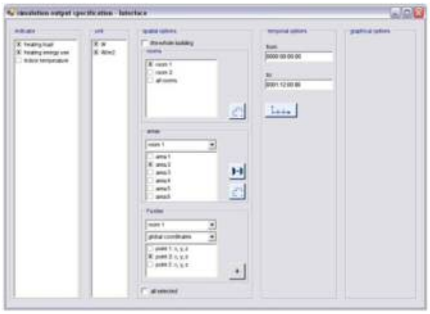


Figure 4 – Decision Support Systems: a – Different design alternatives (Papamicahel 1999a); b – More elaborated display systems (Prazeres and Clarke 2003)

1.2.3 Databases

In order to increase the number of design alternatives to be compared as well as to enhance capabilities to explore the impacts of design changes, database output display systems started being proposed in the 2000s. These systems enable designers to formulate performance queries on results, based on organized multiple-simulation runs.

A framework to develop an information matrix of performance indicators considering magnitude, spatial and temporal extensions of these indicators is proposed in Mahdavi et al 2005 (Figure 5). The use of scripts to generate and store large amounts of output data in an online database that can be easily accessed is proposed in Stravoravdis and Marsh 2005 (Figure 6). These authors presented 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. In Knight et al 2007, users can perform interactive queries to understand the nature of the cooling demands to be met, as well as to assess potential ways of reducing these demands, in a database of more than 11000 simulations, the Customer Advising Tool (Knight, Marsh and Bleil de Souza 2006).



Performance output dimension		Heating load	Temperature
Magnitude	Scalar component	10.1	25
	Vector component	-	-
	Unit	kW	°C
Spatial extension	Point	-	-
	Plane	-	-
	Bounded volume	Room 1	Room 1
	Resolution (grid)	-	-
	Aggregation mode	-	
Temporal exten.	Duration	Day 15	Hour 12, Day 195
	Resolution	1 h	1 h
	Aggregation mode	Arithmetic averaging	-

Performance output dimension		Heating load	Heating/ cooling/ electrical energy use	Tempera-ture
Magn.	Scalar component	✓	✓	✓
	Unit	W	kWh	°C
Spatial ext.	Point	✓	✓	✓
	Volume	✓	✓	✓
	Grid res.	1 m	1 m	1 m
	Aggregation	Arithm.	Arithm.	Arithm.
Temp. ext.	Duration	h	mo, a	h
	Resolution	1 h	1 h	1 h
	Aggregation	-	Sum	-

Figure 5 – Information matrix of performance indicators (Mahdavi et al 2005)

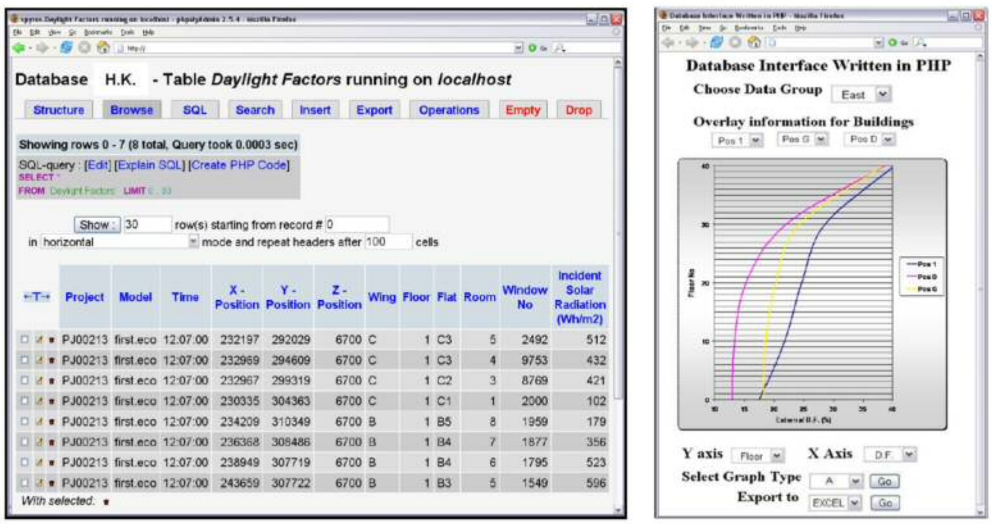


Figure 6 – The use of scripts to generate and store large amounts of output data in an online database (Stravoravdis and Marsh 2005).

1.2.4 Investigations using statistics

Although databases are a powerful artifice to manage large amounts of data, they are difficult systems in terms of retrieving useful pieces of information. A common approach to overcome this difficulty is to investigate cause/effect relationships using statistics which not only can be applied to database results but also directly in simulation result analysis.

A simple example of applying statistics to investigate output thermal simulation results is proposed by Ghiaus and Allard 2003, who assess building adaptability through regression considering the free-run internal building temperature and the outside air temperature (Figure 7). A more elaborate example of statistics application to analyse thermal simulation results is provided by Morbitzer et al 2003, who considered the analysis of more than one parameter affecting performance through the use of data mining.

Data mining 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 (Figure 8). 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 combined with filtering.

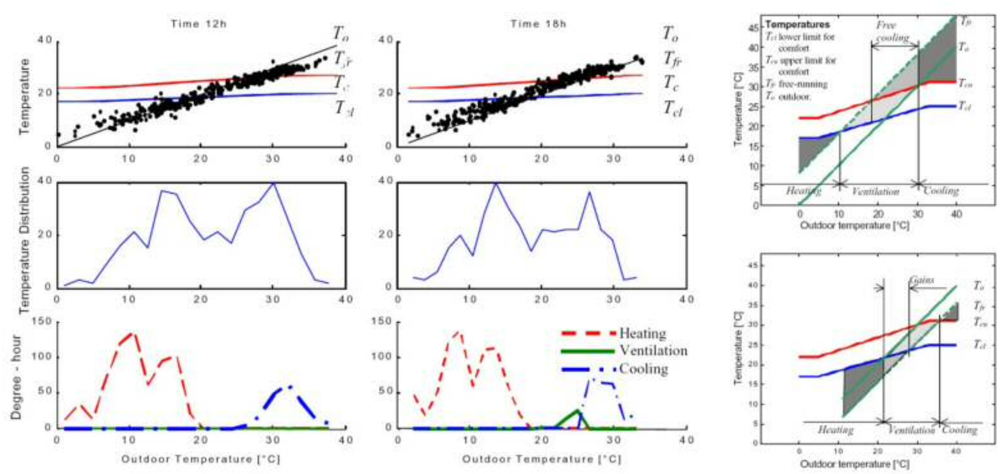


Figure 7 – Example applying statistics (Ghiaus and Allard 2003)

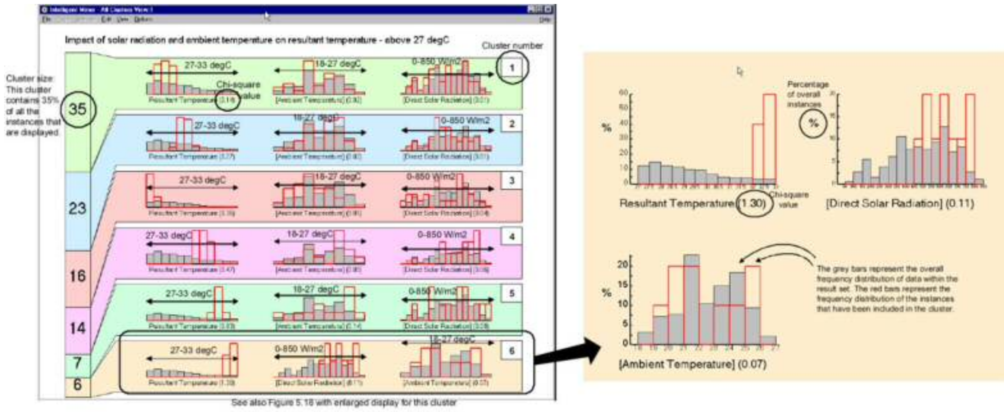


Figure 8 – Investigation using Datamining (Morbitzer et al. 2003)

1.2.5 Output interface design advice systems as a whole

Output interface design advice systems are useful for designers to compare the results of different design alternatives. Comparisons can be simple; they can depict results of different design alternatives side-by-side and/or be based on single comparisons between each alternative and a benchmark. Comparisons can be complex; they can involve a large amount of design alternatives and/or compare these alternatives with each other as well as with benchmarks.

In most cases, causal relationships that are happening within each design alternative are not addressed. Decision support systems provide methods to judge alternatives according to how acceptable their resultant behaviour is, whereas databases either follow this same proposition or simply indicate trends in behaviour based on an automatic generation of multiple design alternatives. Investigations using statistics are the only ones which explore comparisons between different design alternatives as well as causal relationships within each design alternative. However, as has already been noted in the previous section, it is difficult to illustrate such causal relationships let alone their development over time.

On the whole, propositions that address output design advice systems also tend to be more useful for analytical purposes rather than for design advice. This is the case because of the following reasons:

- They do not address directly the issues of output interface data display systems with regards to illustrating causal relationships;
- They provide designers with environments which enable them to compare the overall result of their design actions assuming causal relationships are going to be evaluated by trial-and-error.

As a result, aiming to provide useful information for designers, further research that proposes and prescribes how feedback from the tools can effectively inform the design process can also be found in the literature. This research is examined in detail in the next sub-section which deals with propositions to improve the role of thermal simulation tools in building design practice.

2. Propositions to improve the role of thermal simulation tools in building design practice

The fact that output interfaces are more suitable to be used for analysis rather than for informing the design process together with the fact that tools tend to be used mainly in later design stages, has led many researchers to focus on the development of methodologies to address how feedback from the tools can effectively inform the design process since its beginning. These methodologies are intended to widen the use of tools throughout the design process, a use which so far, according to de Wilde et al 1999, de Wilde et al 2002, Soebarto and Williamson 1999, to cite a few, have mainly addressed the following issues:

- Checking compliance with regulations;

- Meeting marketing targets in which the objective is to get an “environmentally friendly” label or
- Optimizing a few parameters and to support some small decisions still to be considered.

A review of the literature on the subject shows that two different approaches have been undertaken so far in order to integrate thermal simulation tools throughout the design process. These two approaches can be summarised as:

- Propositions that address the building design process as a whole;
- Propositions that explore the use of tools as design advisors in generating new design ideas;

A description of each of these two approaches is provided in the next two sub-sections together with examples from the literature that refer to them. Again, the examples are far from being exhaustive and are used simply to illustrate the main ideas behind each of the two approaches.

2.1 Propositions that address the building design process as a whole

There is a trend in propositions that address the building design process as a whole to assume that building design consists of a procedural sequence of stages with incremental levels of complexity (Morbitzer 2003, de Wilde et al 2001, de Wilde et al 1999, de Wilde et al 2002, Hand 1998, Hand, Clarke et al 1995, Soebarto and Degelman 1995, to cite a few).

Under this frame of mind, researchers believe building design is basically a sequence of decisive actions which might be specified according to different levels of detail depending on which design plan of work source was considered. Although some examples (de Wilde et al 2001) provide quite detailed sequences of actions (including: feasibility study, conceptual design, preliminary design, final design, construction drawings and building specifications), others (Morbitzer 2003) will use simplified versions of it (outline stage, scheme stage, detailed stage). A commonality among the different propositions seems to be that independently of the design work plan used, the sequence of decisive actions would increase in terms of levels of complexity and therefore “simulation tools should adapt to the design process and not vice-versa” (Morbitzer 2003).

Another commonality among researchers is the belief that architects should be running tools in the early design stages and engineers/building physicists should be running the tools in later design stages. That means architects should be running the tools while conceiving, creating and developing a design idea whereas engineers/building physicists should be running tools while refining this design idea. This proposition seems to widely accepted in the simulation community which believes that changes in the early design stages are non-incremental and as a consequence they have a large design impact and a large performance impact, whereas changes in the late design stages are incremental and as a consequence they have a limited design impact and a limited performance impact (SERI 1985). With this being the case, propositions that address the building design process as a whole will tend to concentrate on:

- Developing simplified tools, to be used by architects in the early design stages, that connect with more advanced simulation tools, to be used later on by engineers/building physicists;
- Developing different interfaces (input and output) to address the particularities of each design stage on its own but guarantee that all simulations are undertaken in the same tool;
- Coordinating different designers as well as the different applications they use.

2.1.1 Simplified tools for architects

Examples of simplified tools to be used by architects in the early design stages, that connect with more advanced simulation tools to be used later on by engineers/building physicists, can be found in Square One Research 2008.

The intention behind Ecotect (Square One Research 2008 and Marsh 1996a and Marsh 1996b) is that designers are allowed to freely 'play around' with ideas and, at the same time, to evaluate their performance using an interactive interface which provides results to be used as feedback and encourages new experiments until a mature solution can be found. The most important quality of Ecotect is its user friendly input interface that intends to encourage basic ideas to be quickly modelled and evaluated by building designers while designing.

However, issues with regards to output data display systems also appear in Ecotect. Although designers are allowed to freely 'play around' with the idea, they still have to use output interface data display systems that do not easily communicate causal relationships that are happening within the design alternatives being evaluated. Besides that, Ecotect is quite limited with regards to its calculation engine and the use of more advanced tools is necessary if deeper analysis is to be undertaken. Under this frame of mind, it is not uncommon to find propositions that simply include more user friendly interfaces to communicate directly with advanced simulation tools (Design Builderr Software 2008) or propositions that deal with different interfaces to address different design stages guaranteeing all simulations are undertaken in a single powerful and advanced tool.

2.1.2 Different interfaces for different design stages

Examples of propositions that deal with different interfaces (input and output) to address the particularities of each design stage on its own, guaranteeing that all simulations are undertaken in the same tool can be found in Morbitzer 2003, Hand 1998, and Clarke et al 1995, to cite a few. In the most recent example (Morbitzer 2003), constrained ESP-r (Energy System Research Unit 2008) user interfaces are proposed, in terms of inputs and outputs, and users are expected to conceive and manipulate the object being designed through the use of wizards together with support databases with default values, after importing geometry data from CAD software.

Although in these propositions the simulation engines are quite powerful, the idea of having different interfaces to different design stages ends up restricting not only design possibilities but also simulation possibilities due to the number of a priori assumptions that need to be undertaken in order for them to be conceived. As a result, single intelligent design environments to coordinate different professionals through software interoperability seem to be a logical step to overcome these problems.

2.1.3 Coordinating different designers as well as the different applications they use

Examples of propositions that focus on coordinating different designers as well as the different applications they use can be found in Clarke et al 1995, de Wilde and Van der Voorden 2003, Augenbroe et al 2003, de Wilde et al 1999, de Wilde et al 2002, to cite a few. All propositions in this approach consider that “integration of building simulation and building design process take place in the category of tools for design teams with experts” (de Wilde 2004).

Propositions that include experts and their tools directly in a design team have been explored by the Scottish Energy System Research Group (MacDonalds et al 2005) and basically consist of in-house performance-based assessments to provide design advice to generate better design solutions. These propositions tend to be quite successful as they are flexible enough to account for the idiosyncrasies of each different practice. Although consultants, when taking part in the design team since the conceptual design stages, can deal with many questions that arise in dealing with the problem at hand, the tools they use are still not appropriate to cope with the particularities of all design stages. This is mainly due to their lack of sophisticated input methods and limited interpretation of architecture drawings.

This probably explains why some studies concentrate on expanding tool capabilities with regards to information exchange (COMBINE project in de Wilde 2004 and Clarke et al 1995). These propositions generally contain a central product model connected to several building performance evaluation tools managed by tool-specific interfaces. Although these propositions are, to an extent, important to set up a practical basis for collaboration to happen, they make it difficult to handle major design changes. Interoperability separates models from analysis, making it even more difficult to assess cause/effect relationships.

Propositions that attempt to better handle the problem of separation between models and analysis can be found in Mahdavi (1999) in which, through a shared model linked to various simulation tools, building design and building performance are interconnected. The effect of changing a design variable on the resulting building performance as well as an indication of which design variable need to be changed in order to achieve a specified change in performance can be displayed (de Wilde 2004). However, the interfaces are not easy to manipulate and can become quite restrictive in order for bi-directional feedback to happen.

In order to simplify the manipulation of tools as well as the communication between participants, minimalist interfaces related to suitable simulation tools to be used in each specific analysis task are proposed in Augenbroe et al 2003, de Wilde and van der Voorden 2003 as well as de Wilde 2004 through the Design Analysis Interface initiative. In this initiative, a tool kit is provided for a design team enabling the team to customise its analysis scenarios from design questions by automating many of the steps to perform simulations and analyse results. In this type of environment, data transfer happens automatically and is minimised, consultants take care of integration, and tools are re-defined to cope with interoperability. Although many features can be customised in this proposition, components and options as well as relevant criteria for analysis and performance indicators need to be a priori specified. In order for that to happen de Wilde (2004) prescribes a clear and well-staged procedure for designers to adopt when designing so that consultants, with their simulation tools, can be 'plugged in' along the way and performance requirements can play a role in the decision-making process. It is a rigorous top-down approach which relies on a highly stratified team work composed of a 'collage' of specialists.

2.1.4 Summarising propositions that address the building design process as a whole

Overall, although many methodologies to integrate tools throughout the whole design process have been discussed, a need to better investigate the cause/effect relationships between performance and design changes, particularly in the conceptual design stages, still exists even when input interfaces are user friendly and when consultants are part of design teams.

When strategies move towards extreme specialisation, the problem of understanding the causal relationships that are happening seems to be even stronger as interoperability tends to separate model from analysis. Attempts to overcome that through shared models that enable bi-directional feedback make design possibilities quite restricted. Efforts to resolve this problem through a tool-kit with minimalist interfaces require the process to be clear and well-staged for consultants (and their tools) to be placed within it, and the acceptance of this approach from building designers as well as the quality of solutions that result from it are highly debatable.

As a result, propositions that address the design process as a whole either do not deal with the main problem of relating cause/effect between resultant building performance and design changes, or take it into consideration to the detriment of the designer's freedom to approach problem-solving. Attempts that are less prescriptive with regards to the building design process and at the same time intend to make the use of tools more effective in building design practice, concentrate on exploring the use of simulation tools as design advisors in generating new design ideas. These approaches are discussed in detail in the next section.

2.2 Propositions that explore the use of simulation tools as design advisors in generating new design ideas

A review of the literature shows that there is a trend for addressing cause/effect relationships between design changes and resultant performance in the early design stages mainly by using the tools as design advisors to generate new design ideas. This trend is quite recent as it uses techniques that require intensive computer processing and the two most common approaches that deal with it are:

- Simple generative forms and
- Genetic algorithms.

2.2.1 Simple generative forms

Simple generative forms consist of scripts that generate rough shapes contained in grids, which respond to certain performance criteria (Marsh and Haghparast 2004). The shapes generated are actually optimised forms and provide insights to the designers about possible ideas to be developed.

In simple generative forms, optimisation methods, generally used in late design stages are brought to the beginning of the process. It is the intention that through generative forms, designers start with an optimum set of compromises from a predetermined range of possible options to develop design ideas further. Result analysis is translated directly into geometric decisions through a computer generated rough building form that meets a set of specified performance criteria. 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 generative forms are already incorporated into Ecotect (Square One Research 2008) as software features in the 'Shading design calculation wizard' such as 'extrude objects from solar envelope', 'generate optimised shading devices' and 'project solar shading potential' for instance. Further examples of this strategy can be found in Marsh and Haghparast 2004 when investigating the right-to-light as well as maximization of solar radiation falling on a stadium pitch.

2.2.2 Genetic Algorithms

More elaborate generative procedures can be found in Caldas and Norford 2002 and Caldas et al 2003 who explored the use of genetic algorithms in search procedures to look for optimized design solutions in sustainable design. These procedures, based in algorithms rather than simple scripts, undertake searches 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. When genetic algorithms are used, the amount of possibilities in terms of solutions tends to be much wider and a higher level of complexity in terms of solutions can be achieved.

Caldas and Norford 2002 show the use of genetic algorithms to optimize window sizes for lighting and heating whereas Caldas et al 2003 show the use of genetic algorithms to optimize facades taking into account architecture compositional rules by minimizing the overall building energy consumption.

2.2.3 Summarising propositions that explore the use of simulation tools as design advisors in generating new design ideas

On the whole, propositions that explore the use of simulation tools as design advisors in generating new design ideas are actually automatic systems of comparing and evaluating design alternatives. Instead of asking the designer to undertake comparisons and equipping them with methods, as in design advice systems, these automatic systems require the designer to define the evaluation criteria for an automatic process of 'generating – evaluating – generating' to happen.

In both cases, there is no need to evaluate causal relationships as the computer can generate a myriad of design alternatives in a short period of time. The designer's task consists of defining design criteria together with one of the following activities:

- Defining the proper evaluation criteria for a given solution that will be used to set up a framework to generate design possibilities, in the case of generative forms or
- Defining the proper evaluation criteria for a given solution to be used to analyze the performance of a group of design alternatives to advise future design actions to be undertaken, in the case of genetic algorithms.

Genetic algorithms and generative forms clearly shift the whole problem of investigating cause/effect relationships between design changes and resultant performance to a problem of defining design and evaluation criteria for automatic design alternatives generation and evaluation.

3. Conclusions and criticism

The present paper illustrates that critical thinking and theoretical reflections can assist in integrating thermal simulation tools throughout the whole building design process. These approaches can assist in identifying specific reasons why current propositions to improve thermal simulation tool data interpretation and the role of thermal simulation tools in building design practice are not sufficient to solve the problem of integration.

This work derives from the author's background as an Architect, which includes practical experience as well as academic teaching in design studio, with an MSc in Civil Engineering and a PhD in using design problem-solving to discuss the integration of building thermal physics and architecture design (Bleil de Souza 2008).

From this knowledge, together with the foregoing review of the literature, it is possible to conclude that, in addition to what has been noted by empirical studies, the integration of building thermal simulation tools throughout the whole building design process seems to be failing due to the specific following reasons:

- Output interface data display systems are not succeeding in illustrating the causal relationships that are happening, especially when these relationships develop over time, making it difficult for designers to understand the consequences of their actions (Examples can be seen in Figure 1a and Figure 3).
- Results are always presented disconnected from the models, i.e. designers have to model in 'input interfaces' and assess the resultant building behaviour in 'output interfaces', rather than having instantaneous feedback about the consequences of their design decisions (Figure 1b, Figure 2 and Figure 4 to Figure 8).
- Design advice systems when equipping and enabling designers to compare different design alternatives, assume causal relationships are going to be evaluated

based on trial-and-error. Design advice systems having the capabilities to automatically generate and evaluate design alternatives, assume designers work with clearly defined criteria to propose and evaluate design alternatives (Figure 4 to Figure 8).

- Most propositions tend to be based on the generation of a large number of design alternatives which consequently slow down the whole design practice.
- Most propositions tend to be restrictive with regards to investigating multiple parameters, mainly parameters related to geometry and topology, either because strategies do not handle them well or because results are difficult to assess.
- Most studies that propose and prescribe how feedback from the tools can effectively inform the design process tend to be highly focused on reinforcing professional specialisation, for example as intelligent design advisors. They either prescribe which agent uses what type of interface, or prescribe clear and well-staged processes for consultants to be placed within.
- In all cases, assumptions about the building designers' process, from the way they make decisions up to the variables they manipulate, are viewed as procedural.

In addition to the above, the literature confirms that one of the main obstacles is a lack of understanding of the design process from the building simulation community side and that "tools are being developed following a false paradigm about how designers work" (Donn 2004). As a result, the following problems can be inferred:

- Different ways of presenting results to building designers are explored without considering the meaning the information presented has for these professionals (Figure 4 to Figure 8);

- Design advice systems, as well as their data manipulation capabilities provided, are based on a series of unverified assumptions about the building design process;
- Design methods that improve the use of tools in the process, as well as to determine clearly the role of specialists, are prescribed based on a small number of observations from designers in action and/or on design work plans from chartered professional institutions.

4. Discussion

The foregoing conclusions and criticism open a debate in which engineers and simulationists would suggest that causal relationships detection is a skill which can be learned and, although there is not much information about how causal relationships could be better investigated, it is important that practitioners and/or students need to be trained and have the time to practice these skills before they can learn how to drive the tools. In addition, engineers and simulationists believe that causal and temporal relations can be put together and that information displays are as useful for analysis as they are for design because students iteratively improve design by reviewing information displays, adjusting parameters and re-running a simulation.

Alternatively, building designers would suggest that design advice systems incorrectly assume designers work with clearly defined criteria, and as a consequence those who develop simulation tools have a false paradigm about the way designers work. Additionally, from a building designer's viewpoint, if collaboration between architects and engineers in the early design stages is undertaken through software interoperability then this makes it more difficult to assess cause/effect relationships and test new design alternatives as models and analysis are separated from each other. Concluding these two viewpoints, it appears that an effective form of communication between the design and simulation community is still to be established.

The author acknowledges that both professions have legitimate viewpoints and concludes that one of the main stumbling blocks towards better integration is that there is a general lack of knowledge from building designers and architects about the fundamentals of thermal building physics, and particularly about the issues related to building modelling. At the same time, there is also a lack of knowledge from building physicists about how building designers work and think.

This general lack of knowledge from one knowledge domain in relation to the other comes from the fact that although both professionals can be ultimately considered problem-solvers they subscribe to different paradigms when undertaking their everyday activities.[1]

The study of these paradigms, seen as pre-requisites for perception (Kuhn 1996), as well as how they impact in different worldviews, representation systems, the use of computers as well as professional practices is complex and beyond the scope of this paper, though the author intends to pursue these issues in subsequent papers.

However, from Bleil de Souza 2008 it is possible to see that building physicists tend to approach problem-solving by mapping existing problems into known structures constructed based on the laws of natural sciences. They tend to solve problems using a scientific approach to investigate cause/effect relationships generally ‘shaped’ as prediction/evaluation cycles which imply the need to have a well-defined object to be simulated and a well-defined set of criteria for acting upon simulation results.

As a result, users need to be trained to map a design proposition into an existing model, predict its behaviour and judge its value by comparing it with a predefined reference and act towards an aim that improves the design proposal. Tools

[1] Evidence of this can be found in design science literature referring to design problem-solving (Simon 1999, Cross 2001, Kuhn 1996, Zimring and Craig 2001, Eastman 2001, Craig 2001, Simon 1973, Akin 2001, Goel 2001, Goldschmiedt 2001, Harfield 2007, Rittel and Weber 1974 among others)

assume the whole design process is therefore procedural and actions taken to improve performance can easily become deterministic, bounded by the laws of natural science.

In this sense, simulation tools are strongly analytical in nature and design advice tools (optimisation algorithms, genetic algorithms, cellular automata, etc. i.e. search algorithms developed to operate together with these simulation tools) act like 'experiments' by establishing iterative prediction/evaluation cycles.

In building physics because phenomena develop over time it is very difficult, if not impossible, to develop intuition about quantitative results. It is very difficult to visually represent interactions between the whole and the parts, as well as interactions among the parts over time, which justifies a procedural approach to design problem-solving based on mapping problems into known structures together with the use of very clear search strategies.

The literature about design science (Schon 1991, Schon 1988, Cross 2001, Lawson 1997, Coyne and Snodgrass 1991, Zimring and Craig 2001, Coyne 2005, Buchanan 1995, etc.) shows that actually architects solve their design problems using a completely different approach. It is quite common for practitioners to recognise phenomena without providing an accurate or complete description of them; make judgements of quality without being able to adequately state criteria; display skills without stating rules and procedures (Schon 1991).

Although maps of the product of the design process used for management, control, budget and deliverable purposes do exist, the process itself is far from having achieved consensus. Different schools, different practices, different individuals will have different ways of acting upon a problem. Architecture practice tends to be constructed on a case-by-case basis. Practice ends up being summarised as a complex interrelation between product and process in which the main task is to solve the problem of solving the problem at hand rather than setting clear aims and finding the best way to achieve them.

Besides that, as the ultimate product of architecture design is form, phenomena related to form in space are central in all types of design problem-solving exercises. As phenomena develop in space it is much easier to develop intuition about quantitative results. There is a place for a general approach to design problem-solving in which rigid structures are broken for creative ideas to arise. It is easy to visually represent interactions between the whole and the parts, as well as among the parts, which makes procedural approaches to problem-solving unjustifiable in terms of time and resources.

As a result, the problem of putting causal and temporal relations together is far from being simple and can be better expressed as a problem of putting together phenomena that develop in space with phenomena that develop over time. Once causal relations with the space domain can be established in simulation tools output interfaces, it is more likely that they are going to be useful to building designers. Whether this can be properly established with interoperability or we should be aiming towards more integrated and 'unified' software alternatives is still open to debate.

In addition, it is important to say that the complexities of interactions that happen in space, manifested through a myriad of different visual representation systems, together with a lack of standard procedures to be followed through the process of developing a design idea also do not establish the role of computers in architecture design as a consensus. Basically how far the computer will be able to assist in the design process will depend on the type and nature of information computers allow designers to manipulate. And the type and nature of information designers manipulate are currently more comprehensive than is possible to be handled efficiently by computers, if at all.

In the end, the author believes there is no global solution currently available which is comprehensive enough to cope with the rich universe of possibilities involved in building design. Simulation tools need to be designed with configurable interfaces that can be tailored to address the idiosyncrasies of each practice together with the peculiarities involved in dealing with a specific problem at hand.

A decision about which parts should be rationalized and at which stage this should happen will have an impact on the design of the tool interfaces. If this decision is to be made every time a new problem arises or on the basis of the idiosyncrasies of each practice, interfaces would need to be somehow customizable to account for it. The level of customization could determine an important role for consultants.

The computer is a tool used for reasoning during the design process, therefore the distinction between 'input' and 'output' interfaces could well be replaced by interfaces in which a mixture of interactions between understanding the behaviour of the building *while* conceiving, creating, manipulating and developing it are the aim. The most important feature to enable this to happen is visual real time performance feedback relating behaviour over time with its causes in the space and form domain enabling heavily procedural prediction/evaluation cycles to be 'diluted' within 'softer' ways of exploring ideas.

In order for that to happen, empirical appreciations of the problem and practical attempts alone will not suffice. There is a need for theoretical understanding together with a great deal of critical reflection for building designers and building physicists to be able to properly communicate and effectively construct a joint practice; a need that should be addressed throughout both professional's education.

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