THERMAL SIMULATION SOFTWARE OUTPUTS: PATTERNS FOR DECISION MAKING

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ABSTRACT

This paper describes a structure that enables simulation software developers and building designers to produce thermal simulation results meaningful to design decision making. The structure is based on the development of 'patterns' in which analysis processes are applied to thermal simulation outputs to produce relevant information to inform design actions and decisions. A discussion is made on how the patterns can be developed and examples illustrate the suggested development process and generation of simulation outputs. The patterns are intended to bridge the gap between the needs of the designer for useful design oriented software, and the needs of the software developer for technical information on exactly what is required by this user.

INTRODUCTION

The aim of this paper is to discuss the development of *'Patterns for Decision Making'*, a structure for thermal simulation software developers to produce post-processed information that better responds to the needs of building designers.

There is currently a lack of knowledge about the relationship between simulation outputs, and design decisions. Bleil de Souza (2009, 2012) has examined the background as to why building designers as opposed to building services engineers are not well served by the types of output commonly available in thermal simulation programs, and found that the paradigms of thinking and *modus operandi* of these groups were essentially different. The designers tended toward a constructivist approach to problem solving and the engineers toward a scientifically based approach.[1] This difference is seen as a useful theoretical proposition in explaining why building designers have not taken up thermal simulation as part of usual design practice, and does not preclude other explanations such as thermal simulation taking up more time than is typically available.

Researchers have previously attempted to address the problem of understanding what simulation tools and processes would be useful to building designers by employing research methods including interviews with building designers, on-line surveys, reports on specific case studies and reports on interactions between specialists and building designers while working in collaboration to solve specific software design problems[2]. These methods were successful in listing design requirements but did not provide any hints about what would be useful solutions to these requirements.

In order to better address the problem of matching design requirements with appropriate solutions, one of the current authors (Bleil de Souza, 2013) reports findings from a study in which over 130 novice designers were invited to produce what they thought would be meaningful metrics and representation systems to inform design decision making. The data sample of this study was expanded and analyzed using Information Visualization and Qualitative research methods from Social Science as well as methods from Human-Computer Interaction and from the relatively new field of Interaction Design. From this analysis an open-ended framework to guide the development of simulation outputs meaningful to building design decision making was constructed and is described in detail in an accompanying paper.

The framework is an empirical construct derived from reverse engineering examples of design processes which used building thermal physics to aid design decision making. It provides a structure to collect and propose alternatives to meet requirements building designers have for using thermal simulation tools.

Important components of this framework are the 'Patterns for Decision Making', structures for software developers to produce post-processed information that responds to building designer's needs. Patterns[3] are abstract descriptions of connections between design actions and analysis processes established through recognition and acknowledgement of a building designer's goals

[1] See Bleil de Souza 2012 for a full discussion on different paradigms of design thinking behind these two types of professionals.

[2] See Bleil de Souza (2009, 2013) for a comprehensive list of examples

[3] The idea of design patterns was introduced by Christopher Alexander and colleagues (Alexander et al., 1977, 1979).

when using thermal simulation data to assess and inform design decisions.

Unlike other components of the framework, the patterns did not emerge directly from reverse engineering of design processes. They are seen as an appropriate construct to put all the components of the framework together and therefore deserve to be discussed in separation in this paper.

BACKGROUND AND METHODOLOGY

The hypothesis behind this research is that developers need a structured way to collect and address requirements of building designers for productive use of thermal simulation tools. 'Patterns for Decision Making' are seen by the authors as a suitable structure to achieve this.

The pattern approach originated in the work of Christopher Alexander and colleagues on architectural design (Alexander et al., 1977, 1979) and from subsequent work in the field of software engineering (e.g. Gamma et at., 1995). It has also been used in the field of Interaction Design (Borchers, 2001) and Human Computer Interaction (Tidwell, 1999, 2011). The pattern approach considers that there are common recurring problems that designers face, and corresponding solutions to these problems that can be reused when required. In Alexander's patterns problems and solutions are abstractly described so that designers can use them to create form.

For Alexander '*Each pattern describes a problem which occurs over and over again in our environment, and then describes the core of the solution to that problem, in such a way that you can use this solution a million times over, without ever doing it the same way twice'* (Alexander et al., 1977).

Therefore a pattern recognises that no two contexts of a problem are exactly the same but that the essential problem to be solved is the same. As patterns are abstractly described they provide a structure within which solutions can be made individual, according to the context and circumstances. In Alexander (1979) patterns are linked to other appropriate patterns, and describe 'timeless' aspects and features of towns, buildings and construction. Together the patterns form a network or a language that comprehend all the important social and physical features and uses of towns and buildings that create good places for people to live.

An example is a pattern that addresses the problem of 'how to provide for the nightlife of a city', and solves it by placing shops and services that are open at night together to form a well-lit lively area (pattern 33 in Alexander et al., 1977). This pattern is linked to patterns of 'magic of the city' (pattern 10), 'community of 7000' (12) and 'promenade' (31) which all describe social or physical features commonly found in successful human settlements at city scale. It is also linked to patterns such as 'carnival' (58), 'street café' (88), 'local town hall' (44) and others, all of which describe social or physical features of the built environment, and which could be used as elements in the pattern for 'provision of nightlife'.

The authors believe a similar approach to the one of Alexander can be used to produce thermal simulation outputs meaningful to design decision making. Examples of Alexander's propositions that could be drawn upon include:

- The replacement of 'recurring problems' by 'recurrent design actions and goals '.
- The replacement of 'solutions to the problem' by 'appropriate analysis processes to assess or inform design actions'.

The data used to generate the structure of the patterns come from reverse engineering examples of design processes which use building thermal physics to aid the design decision making. The development of initial example patterns has been carried out through communications with software developers and the results are illustrated using two examples.

PATTERN DEVELOPMENT

The patterns carry out two important functions:

1. Acting as a vehicle for communication between designers and developers for the formulation of useful design related simulation outputs.
2. Linking together design actions and analysis processes in light of the designer's goals, to display information using relevant metrics and representation systems for design decision making.

The structure of the patterns therefore reflects these two functions.

Elements of the pattern: Inferred or Assumed Goals

One of the key elements of the patterns are the goals of the designer in using thermal simulation to assess and/or inform design decisions. These goals determine how design actions are connected to analysis processes. Sometimes the goals are named by the user, even if vaguely (e.g. 'optimisation' of a certain parameter). As most of the time goals are not consciously known or formally stated by the designer they either have to be inferred, if a sample is available, or assumed by the researcher.

From reverse engineering design processes in which designers used building thermal physics data to inform and assess design decisions, a set of 5 recurring goals were identified;

- Understanding a specific performance result
- Exploring a specific design strategy
- Meeting a target

- Assessing a specific product
- Optimisation

These goals correspond to the uses of simulation commonly found in practice. This list is far from exhaustive and can be expanded to other professional communities by using techniques from Interaction Design (see Cooper et al., 2007) to identify new users and understand their goals (e.g. HVAC engineers, investors, etc.).

Elements of the pattern: Design Actions

Patterns are informed also by recognition of the plurality of potential design actions, which are related to changes in the form, materials and components of the building, and its operation. They can also be informed by different design strategies (e.g. to support actions intended to result in a passive design such as 'designing shading to prevent overheating by solar gains through transparent elements') and enable multiple design processes to be adopted or explored. All action relate to elements and parameters that building designers manipulate.

Elements of the pattern: Analysis Processes

The analysis processes specified in a pattern are the set of procedures and post-processing techniques that produce relevant information to designers to support their design actions. The processes can either inform further design action, or assess the action undertaken, or be a combination of both. An example of an analysis process might involve observation of the effects of a parameter change on an aspect of performance, leading the user towards the goal of understanding of how the building works through a process of experimentation. A different process might be to employ 'systematic trial and error' towards meeting a performance or compliance target (see Norman and Draper, 1986, for a list of search strategies).

The choice of analysis process is also influenced by the technical operation of the simulation engine. The information available to be presented as outputs may be limited by the calculation methods and algorithms used to run simulations. Knowledge necessary to simplify reality into building simulation models (e.g. modelling resolution, zoning etc.) also influence patterns in relation to analysis processes.

Elements of the pattern: Database of Metrics and Representation Systems

The patterns refer to the metrics and representation systems used to display dynamic thermal simulation outputs to support design decision making. These were developed by drawing from the main techniques of data and information visualisation described by Ward et al., (2010) and by Mazza (2009). The type of metric and representation system should depend on the way that the user interacts with the visual information. The following techniques of interaction with information proposed by Shneiderman (1996) were adopted in the patterns;

- Overview: Gives the user a broad picture of a phenomena
- Zoom/filter: Allows the user to focus on an area of specific interest.
- Details on demand: Requires the user to actively ask for a specific type of detailed information
- History: Allow the user to retrace steps.
- Relate: Enable the user to compare information.

Ideally, the choice of the metrics and visualisation technique should be informed by the needs of a particular user. A more technically minded designer for example might prefer a table of frequency bins of temperatures, and a non-technical designer might prefer a colour coded floor plan indicating the degree to which the different zones overheat. The pattern structure should be comprehensive enough to list all relevant outputs to the specific case addressed so that information can be filtered and tailored to specific users.

Structure of the patterns

The principles that guide the formulation of the patterns are as follows:

- Patterns *should not interfere with a designer's workflow* and therefore are not tied in to any model of design process as design processes are assumed to differ to some degree between designers. The patterns connect design actions with analysis techniques through assumed goals, and a key characteristic of patterns is that *design actions are left to the designer to decide.*
- The patterns focus on producing meaningful metrics and displays to aid the design of low energy buildings.
- Outputs resulting from the patterns must represent with integrity the physical phenomena modelled by the thermal simulation software.

Patterns follow a consistent format and include details of;

- How design actions are connected with analysis processes through goals, using relevant metrics and representation systems to building designers.
- The post processing techniques necessary to produce the outputs required, the quality assurance procedures involved in running and analysing simulation results and the level of modelling resolution involved in each particular case.
- Possible links to other patterns so as to contextualise the use of the current pattern

and to provide information about related aspects of the design and its performance.

The requirements of users and software developers are combined in a structure presented in Table 1 where the sections within the structure are to be initiated and completed by users, developers or both.

SECTION	**DESCRIPTION**
Pattern name	A descriptive name for the pattern with reference to design actions, analysis processes and goals.
Context	The relationship of the pattern to its context, describing a design situation that requires the use of this pattern.
Goals addressed	Clear description of the design aims in using dynamic thermal simulation.
Design actions	List of potential design actions involved in this pattern.
Analysis process afforded	List of types of analysis involved in this pattern (qualitative and quantitative) with their corresponding purpose including '*side effects'* in other performance metrics
Examples	Reference to projects, precedents and theory that addressed this pattern
Type of simulation post-processing required	Description of simulation outputs, post-processed variables and procedures to produce requested outputs
Information Display	Database of different metrics and representation systems used to display the required information to building designers considering; - Data overview - Data involved in zooming and filtering for areas of interest - Potential information details user might request - Types of comparisons afforded - Information recorded to enable user to retrace steps
Simulation Quality Assurance Procedures	Description of performance assessment methods (PAM) used to validate thermal models involved in this pattern
Usefulness to building designers	Description of test mechanisms to assess the usefulness to building designers of the pattern and information display OR Description of results to the above if known
Comments and further development	Any comments or further developments from building designers, and software developer's feedback.
Link to other patterns	Suggestions for other patterns that can potentially be linked to this pattern.

Table 1. Generic pattern structure

EXAMPLES AND DISCUSSION

The structure of Table 1 has been used to produce a number of patterns that have been worked up to various degrees of completion and examples are given in Tables 2 and 3. Data used to produce the upper, design-related sections of the tables come from research into the needs of the user. Data used to produce the lower sections related to outputs and post processing is obtained from a combination of suggestions from users and from project collaborators from ESRU (Environmental Systems Research Unit, University of Strathclyde).

Key aspects of the patterns that were found as a result of developing the examples are;

- The development of a pattern is a dynamic process that leads readily to ideas for new patterns, and modifications to existing ones.
- Output information produced by simulation tools for post processing depends on data inputs, levels of modelling resolution and a number of modelling assumptions. Therefore the patterns must specify the time periods for analysis, models of thermal comfort employed, the climate files used and so on.
- Parts of the patterns can refer to procedures than run automatically (e.g. parametric variations, or quality assurance tests).

There are many potential patterns that could be considered for development, responding to the large number of combinations of the type of users, their context and goals, design actions, analysis processes and data and information visualisation techniques.

Developing the examples involves communication between building designers and software developers. Table 3 shows the example of a pattern for understanding the causes of overheating in a free running building where a designer wants to be informed of the main causes of overheating in terms of the building variables that can be altered through design actions. Where some developers believe that this can be achieved only through sensitivity analysis it would be useful to have an indication in just one simulation to shortcut the number of parametric runs.

By comparing mean radiant temperature with inside air temperature it can be decided whether the analysis can be conducted in the first instance at the air heat balance (i.e. if the temperatures shape and magnitude do not differ significantly over a 24 hour period on typical days, it can be assumed that the building is lightweight and the analysis can focus first on the air heat balance node). If the convective heat transfer from surfaces is far lower than the other air heat balance components, design action can be undertaken before analysing the fabric in detail.

The example (which would need further development and testing) illustrates how there can often be a tension between what a user might want (or think they want) and what it is possible to provide.

In the case of using heat balance equations it was necessary to take account of which fluxes are recorded at the air nodes and at the surface nodes, and provide a link to a pattern for 'sensitivity analysis' which would be used under conditions where it was not possible to determine the relative contributions to overheating of fluxes at the two different nodes.

Network of patterns

A full consideration of where a particular pattern fits within a larger network or language is beyond the scope of this paper although this aspect has been alluded to in terms of links to other patterns. Patterns could either be completely 'stand-alone' (i.e. not part of a linked network or language) or could be developed within such a network. In either case, it seems useful to suggest links between patterns as this provides the user with hints or pointers toward possible further implications of the design actions currently being undertaken. Patterns could potentially be linked in formal ways, with outputs from one pattern providing appropriate choices for the user to select further patterns.

An example of why it may be useful to link patterns with other patterns is given in table 2. This pattern allows the designer to carry out an exploration of the degree of overheating and under heating until a satisfactory design is achieved. Aware of the performance results, the designer can proceed to investigate further aspects. The mitigation of overheating is however linked to many other aspects of performance, often in complex relationships, by the dynamics of the building and the climate and its users. Each of these aspects could have related patterns for the designer to choose from as the design proceeds.

Automatic post-processing in patterns

There are several automatic simulation post processes that occur or could occur as the result of requesting a specific output. An example is a study of the effect of varying a building parameter on a performance metric, where in order to obtain the required output a number of simulations can be automated by a script. Another example is the automatic auditing of simulation inputs and procedures to check for correct modelling practice (e.g. checking that the required resolution of the output is matched by the resolution of the model used for the simulation).

Patterns could automatically address quality assurance procedures (e.g. comparing data inputs with benchmarks to highlight modelling errors and contradictions) and performance assessment methods (Clarke, 2001). Patterns could be automated for testing performance under future climate change scenarios, ranges of operational conditions, and user behaviours.

CONCLUSIONS

The concept of 'Patterns for Decision Making' has been used to propose a communications process by which simulation outputs suitable for the design of low energy buildings can be produced. The patterns described in this paper have the following features:

- They represent a different approach to collaboration between building designers, software developers and other members of design teams.
- They form an open ended catalogue of analysis and design approaches to common design problems, with focussed simulation outputs meaningful to design decision making.
- They are non-procedural and therefore can support multiple design processes.
- The generic structure behind them enables new patterns to be developed in the light of multiple requirements from simulation users.
- They can be connected or related to each other and so support an unlimited number of sequences of analysis and design actions. Some sequences may prove to be more useful than others, but it is left to the users to determine which are most appropriate.

The examples given here tend to be oriented toward the non-technical simulation user, who in particular may benefit from some indications of why a specific behaviour is happening and how to respond to it. It is intended to continue the development of patterns and to further test them among building designers.

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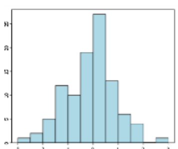
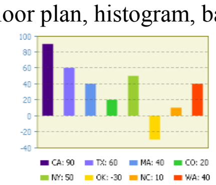
Exploration of design actions with a record of their impact on free run environmental temperatures	
Context	A building designer wants to freely explore different design possibilities. At the same time the designer wants to be able to keep a record of the consequences of his / her actions on environmental temperatures. The building has no HVAC.
Goals addressed	Exploring the effect of a set of specific design strategies on an aspect of performance.
Design actions	Any action desired by the user (see examples below).
Analysis process afforded	Quantitative description of overheating, with potential for comparisons between models to be made ('Side effects' are listed for each design action).
Examples	- Change of window size and analysis of the effect on the inside air temperature of the specific zone affected ('Side Effect'; change in daylight levels, lighting requirements, glare, and possibly ventilation and noise levels). - Change of floor to ceiling height and analysis on its effect on the inside air temperature of a typical floor plan, etc. (Warning flag required if a different approach to modelling is required due to thermal stratification).
Type of simulation post-processing required	**Simulation output:** Environmental temperatures resulting from free running simulations. **Post-processing** 1) Separate user controlled runs with results recorded for comparison.
Information Display	**Metrics**: A) Frequency distribution of environmental temperatures above, below and within the comfort zone. B) Degree hours above below and within the comfort zone. **Type of representation**: Coloured floor plan, histogram, bar chart.    **Overview:** *Metric*: Metric A for typical year, all zones in typical floor plan – highlighting zones with best and worst performance and grouping zones with very similar performances. *Type of representation*: Coloured floor plan + histogram for metric A and B. **Zooming, filtering and selecting**: 1) Zooming into user selected time frames (seasonal and monthly) and into floor plans.

	2) Filtering information by orientation – e.g. all zones adjacent to the north façade. 3) Filtering information by zone. **Details on demand**: To be decided. **Comparisons afforded**: Comparisons between different zones, different floor plans, different orientations, different time periods, results from different design actions.
Simulation Quality Assurance Procedures	- Auditing all simulation inputs (automatically as much as possible). - Audit all modelling and simulation assumptions and requirements (automatically as much as possible).
Usefulness to building designers	The pattern is presented to building designers in a workshop and designers are asked to comment on its perceived usefulness and every aspect involved in it – including proposals about new metrics and representation systems to be addressed in further development.
Comments and further development	To be completed after a workshop as development would depend on feedback from building designers.
Link to other patterns	- Link to a pattern that identifies the main causes for environmental temperatures to be outside the comfort zone, following each change to the model. - Link to a pattern related to thermal comfort models.

Table 2. Example pattern 1: Exploration of design actions with a record of their impact on free run environmental temperatures.

Understanding the main causes of overheating in a passive building	
Context	Building designer wants to understand why the designed building is overheating, i.e. where and when overheating is happening and what design parameters are mainly causing it. The building has no HVAC.
Goals addressed	Identifying where and when overheating is happening and understanding the main causes - highlighting main design parameters involved.
Design actions	Design parameters directly affecting overheating can be changed once identified.
Analysis process involved / afforded	Descriptive for overall performance results (where and when overheating occurs). Comparative for causes of overheating.
Examples	Overheating in an open plan office space caused by high equipment and occupant gains and large heavily insulated windows facing south. Potential change in window size, G-value, U-value and different open plan spatial arrangement might mitigate overheating. ('Side Effect': Under heating conditions, artificial lighting requirements).
Type of simulation post-processing required	**Simulation output:** Operative temperatures resulting from free running simulations. Mean radiant temperatures and inside air temperatures. Heat flows of all components of inside air heat balance nodes. **Post-processed variables:** 1) Frequency distribution of operative temperatures above the user specified comfort zone (occupied periods only) and Degree-Hours above the user specified comfort zone and number of days in each month when overheating occurs – to be used as a performance assessment metric. 2) Inside air temperature profiles for typical Summer, Winter and Mid-season days to be compared with mean radiant temperatures in the same time period. If temperature shape and magnitude differ in 24hs period flag a link to patterns involving sensitivity analysis. If temperature shape and magnitude are similar over a 24hs period the building is assumed to be lightweight so can proceed to analyse air heat balances. 3) Heat Energy flows for the 24hr period for each air heat balance component, on days when operative temperatures rise above the comfort zone. 4) Contribution of convective heat transfer from surface to air (or vice-versa) on days when operative temperature rise above the comfort zone, discriminated by type of surface, i.e. external walls, internal walls, roof, floors, ceiling and windows.
Information Display	**Metrics**: Performance assessment metric: A) Frequency distribution of operative temperatures above the comfort zone or degree hours above the comfort zone or number of hours above the comfort zone. Identification of causes: B) Comparison between inside air and mean radiant temperature profiles for typical summer, winter and Mid-season days - flagging link to other pattern or proceeding to air heat balance analysis. C) Resulting energy flows for each air heat balance component summed for each day when

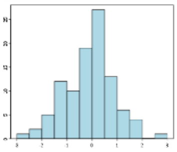
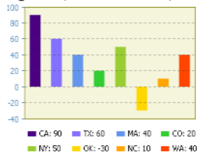
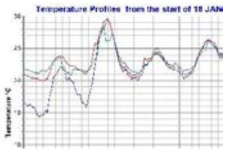
	inside air temperature rises above the comfort zone. D) Resulting energy flows for each type of surface when inside air temperatures are above comfort zone (floors, ceiling, roof, external walls, internal walls and windows). **Type of representation**: Coloured floor plan, floor plans with numbers and strings of text, histogram, bar chart, pie charts, exploded axonometric, line graphs (time series).     **Overview:** *Location* *Metric:* A for typical year, for all overheating zones in typical floor plan – highlighting zones with best and worst performance and grouping zones with very similar performances. *Type of representation*: Coloured floor plan + histogram. *Causes:* *Metric*: B using flagging link to other patterns or leading to air heat balance analysis (C). C for typical year, for all overheating zones in typical floor plan – highlighting main contributor in each zone. *Type of representation*: Time series for B and Floor plan + text (naming the major contributor to overheating) for C. **Zooming and filtering**: A) Zooming into user selected time frames (seasonal and monthly) and floor plans. B) Filtering information by zone (e.g. all zones adjacent to the south façade). C) If B leads to air heat balance analysis - Rank ordering the contribution of each type of surface to inside air temperatures above comfort zone (e.g. show relative contribution of external walls for each zone in contact with the outside) (exploded axonometric with figure in percent). D) If B leads to air heat balance analysis - Rank ordering the contribution of each type of air heat balance component to inside air temperatures above comfort zone (e.g. show relative contribution of ventilation to overheating (exploded axonometric with figure in percent). **Details on demand**: To be decided. **Comparisons afforded**: Comparisons between different zones, different orientations, different floor plans, different time periods, different inside air heat balance components, different types of surfaces.
Simulation Quality Assurance Procedures	- Auditing all simulation inputs (automatically as much as possible). - Audit all modelling and simulation assumptions and requirements (automatically as much as possible).
Usefulness to building designers	The pattern is presented to building designers in a workshop and designers are asked to comment on its perceived usefulness and every aspect involved in it – including proposals about new metrics and representation systems to be addressed in further development.
Comments & further development	To be completed after a workshop as development would depend on feedback from building designers.
Link to other patterns	This pattern could link to a pattern in which causes of overheating due to building fabric are refined through the use of sensitivity analysis. This other pattern would enable designers to know what in the fabric is actually causing overheating (e.g. levels of insulation, mass, G-value). AND / OR patterns exploring the design of shading devices, exploring the effects of ventilation, exploring the effects of different spatial arrangements.

Table 3. Example pattern 2: Understanding the main causes of overheating in a passive building.