THERMAL SIMULATION SOFTWARE OUTPUTS: WHAT DO BUILDING DESIGNERS PROPOSE?

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ABSTRACT

This paper describes the process used to develop a framework to produce thermal simulation post-processed information and data representation systems meaningful to design decision making. The framework comes from reverse engineering an empirical data set in which designers were invited to propose meaningful building thermal physics information to design decision making when requested to solve a design problem specifically tailored for this purpose. A combination of: Interaction Design, Information Visualization and Qualitative research methods from Social Science were used to undertake the analysis. This enabled theoretical aspects involved in how building designers solve design problems also to be taken into consideration.

INTRODUCTION

The aim of this paper is *to describe the process used to develop a framework* to produce thermal simulation post-processed information and data representation systems meaningful to building designers so that they can be used in design decision making.

Early design stages, clients not willing to hire consultants, small practices that cannot afford specialist advice, design education willing to incorporate physics in the design decision making process are just few examples of why there are still many initiatives from software developers (Open Studio 2012, See et al 2011, AutoDesk Project Vasari 2012) to better integrate dynamic thermal simulation tools to design decision making.

However, "current outputs from dynamic simulation tools tend to be unrelated to concepts that are meaningful to the building designer. They are incompatible with his constructivist / experimental 'learning by doing' way of approaching problem solving." (Bleil de Souza 2013).

Metrics and representation systems composed of time series and graphs with temperatures and loads are more effectively connected to decisions related to HVAC systems rather than to elements building designers manipulate. These outputs rarely provide direct useful information about *how and where to act in the building itself* so that envelope and spatial arrangements can be manipulated to improve building thermal behaviour.

The systematic and scientifically based approach required to set up, run and analyse dynamic thermal models differs from the building designer constructivist approach to problem solving. The latter is composed of organising principles, sets of rules, formal languages, functional spatial typologies and various analogies and metaphors coming from references and precedence (Bleil de Souza 2013).

The result is dynamic thermal simulation tools end up being proper 'engineered systems' which deliver specific functions effectively but do not support the way designers communicate and interact with their pieces of design. This means much still needs to be done if the building designer is to be considered a proper 'user' of these tools.

From contrasting how buildings designers design with how building physicist solve problems (Bleil de Souza 2012) and analysing building design problem-solving in action (Bleil de Souza 2013), this research concludes on what could be a suitable framework to produce post-processed data representation systems meaningful to building design decisions making. The framework has a user-centred approach, in which the building designer is the dynamic simulation tool user. It was developed from a combination of Interaction Design, Information Visualization and Qualitative research methods from Social Science. These methods were applied to an empirical data set in which designers were invited to propose meaningful building thermal physics information to design decision making when requested to solve a design problem specifically tailored for this purpose.

BACKGROUND

The vast majority of studies that propose solutions for dynamic thermal simulation tools to be used by building designers tend to be empirical. They do not take into account the fact that there are fundamental differences in the worldviews of building designers and building thermal physicists / simulationists.

Studies that propose to integrate simulation tools throughout the building design process through new output interface data display systems tend to present an interesting source of visualization techniques to display overall results. However, they do not inform designers specifically on how and where to act[1].

Design advice systems can focus on: (i) target oriented design decisions that come from regulations or performance based standards, (ii) provide multi-criteria evaluation strategies to explore design changes, (iii) database structures to query several design alternatives, (iv) use statistics to derive cause/effect relationships[2] or (v) automatically generate design alternatives to be evaluated based on a series of predefined design criteria[3]. In any case, they assume a large number of design alternatives need to be produced for decisions to be made. This generally does not correspond to the way designers work and does not attempt to understand how, and based on what, designers generate these design alternatives.

Propositions that focus on producing different interfaces for different design stages[4] can dangerously restrict design possibilities as well as simulation possibilities. Design stages tend to be used by practitioners for management purposes as well as to set up budgets and deliverables to clients. They are not an absolute map of the design process[5] and the use of them as such by simulation tool developers show a clear misunderstanding on the way designers think and act.

Differences in knowledge and praxis derived from knowledge (Bleil de Souza 2012) illustrate fundamental difficulties designers face when trying to use dynamic simulation tools without being acknowledged as 'proper' users:

- In the constructivist way of thinking of building design, product and process are interrelated. Problems are 'ill-defined'[6] meaning they cannot be solved by using purely a systematically and scientifically based approach.
- Building designers construct their 'design hypothesis' based on the uniqueness of a situation. They use leading ideas to define and derive rules to assess and criticise their actions / 'moves', through 'a reflective conversation with the situation' (Schon 1988 and 1991). Designers generally *do not* identify physical phenomena in their design problems. They do not simplify reality into a predefined heat balance structure to construct a reference model with desire states to be achieved. Their test methods *tend not to be* based on sets of actions structured as model perturbations from which decisions are made mainly based results from cause/effect relationships.
- The variables and metrics building designers are used to manipulating are mainly developed in space. and are suitable to be visually represented. These professionals can struggle to deal with phenomena developed over time which are mainly mathematically represented.

On one hand, these differences probably explain why there are many initiatives focusing on creating collaborative environments, rather than for enabling building designers to directly use simulation tools. As fundamental differences in worldviews are acknowledged a priori in this case, research in this area tends to focus on setting up guidelines to create design teams with experts or in expanding tool capabilities with regards to information exchange[7].

On the other hand, these differences are fundamental to explain that a building designer might have a very distinct way of thinking compared to software developers, HVAC engineers and consultants in general. This also illustrates the possibility of using interdisciplinary research methods to address this difference. Case studies, interviews, on-line surveys, questionnaires on design decision making and reports of experiences in interacting with building designers[8], are conventional research methods which address only part of the problem. They describe user's needs without providing any hints to what could be potential solutions to the problem.

An attempt to break this is presented in Bleil de Souza 2013. This empirical study reports and experiment in which building designers were recruited to propose meaningful metrics and representation systems for design decision making when requested to solve a design problem specifically tailored for this purpose. The idea of making designers design solutions to their own problems, once provided with basic training of building thermal physics, is highly likely to make these solutions to be consonant with their way of thinking and 'modus operandi'. The qualitative Social Science research method of Thematic Analysis was used to analyse the sample of design journals collected. From this, examples of potential meaningful building thermal physics metrics for design decision making were recorded.

The research was useful to highlight how a different method could provide examples of building physics data to design decision making. However, its

[1] See comprehensive in Bleil de Souza 2009 and 2013
[2] Ibid.
[3] Ibid.
[4] Ibid.
[5] The design literature is full of examples about the design process and how it does not follow prescribed design stages (Schon 1988 and 1991 are classics, more is discussed in Lawson 1997, Rowe 1987)
[6] 'Ill-defined' problems are wicked problems with loose objectives or boundaries and incomplete sets of requirements (Buchanan 1995). Approach to problem-solving in these cases tend to happen through a co-evolution of problem and solution (Cross 2004) rather than following a set of predefined steps to achieve specific goals.
[7] See comprehensive in Bleil de Souza 2009 and 2013
[8] Ibid.

empirical nature, limited data sample, design and physics data manipulated were far from covering broader aspects of a user-centre approach.

A proper structure or framework to address the problem of making thermal simulation outputs meaningful to building design decision making is still necessary. This framework should include theoretical and empirical aspects of how designers design in order for it to provide a comprehensive user-centre approach. It should be developed using an interdisciplinary set of research and design methods to cover as much as possible the theoretical and empirical aspects mentioned.

This paper intends to provide a step further in this research area. It concludes on what could be a suitable framework if the data sample proposed in Bleil de Souza 2013 was expanded, and analysed using a combination of: Interaction Design, Information Visualization and Qualitative research methods from Social Science to include theoretical aspects of how designers design. Even though there are still limitations with regards to design and physics data manipulated in this sample, much can be achieved if the aforementioned research methods are used in the analysis of it.

METHODOLOGY

The key methodological aspect of this study was how to combine the three aforementioned research methods coherently.

Interaction Design methods provide means to address user's needs with regards to how they communicate and interact with machines. Interaction design as a discipline emerged from the activity of developing computer software and hardware interfaces. It is seen as a design discipline separate from but connected to engineering and science (Cooper et al 2007).

Basic activities from Interaction Design include (Rogers et al 2011);

- Establishing requirements for user experience
- Designing alternatives to meet those requirements
- Prototyping alternatives for communication and assessment
- Evaluating at all stages for user experience

Cooper et al (2007) point out that while engineering has methods and procedures to follow, and business has methods for assessing commercial viability of products; digital technology industries do not have a complete and reliable process that would link the needs and wants of users in the design of their 'products'. The professional designing the 'product' needs to decide who 'the users' are and have some idea about their goals and why these might be.

This means, it seems plausible to invite 'the users' (building designers) to propose what they think are meaningful metrics and representation systems for building physics to be used in design decision making. This idea is likely to make these users' requirements match with the design alternatives proposed. It also enables prototypes to be evaluated by the users themselves. Moreover, it would assure the knowledge and 'modus operandi' of the building designer could be preserved in whatever is proposed.

This research uses the same data collection procedures described in Bleil de Souza 2013, but expands the data sample to 140 design journals. These journals narrate all steps building designers used when solving a design problem which included thermal comfort, energy efficiency and the testing of passive design alternatives.

A combination of Social Science research methods is then employed in the analysis of the data sample. Grounded Theory is used together with Thematic Analysis to *extract information and assist in the development of a theory* about how designers make sense of building thermal physics information throughout their design process.

Thematic analysis is one of the most common approaches to qualitative research in Social Sciences (Bryman 2008). "It consists in the search for themes in written pieces of data that can be further detailed into groups of codes that break the major themes into subthemes" (Bleil de Souza 2013). "The themes and subthemes are essentially recurring motifs in the text that are then applied to the data" (Bryman 2008).

This approach is complemented by the use of Grounded Theory, another Social Science research methods in which one of the key tools is also coding. This time coding is used to identify concepts, categories and properties to develop hypothesis from which "a theoretical framework that explains some relevant social … or other phenomenon" (Strauss and Corbin 1998 in Bryman 2008) can emerge. In Grounded Theory, theory is derived from data, "systematically gathered and analysed through the research process" (Strauss and Corbin 1998 in Bryman 2008).

These two Social Science research methods were employed in the data sample aiming at the following:

- To confirm and acknowledge aspects about knowledge and 'modus operandi' of building designers highlighted in theoretical studies (mainly Bleil de Souza 2012) are properly taken into account in the process used to develop a framework
- To extract themes from the data sample that could be linked with the four aforementioned Interaction Design activities to be addressed in the process used to develop a framework
- To directly assist in the process used to develop a framework as "grounded theory is not a theory – it is an approach to the

generation of theory out of data" (Bryman 2008).

Methods from Information Visualization were used to extract information from the data sample so that formal knowledge on categories, types, hierarchies, relationships and filtering could be applied in cataloguing and producing meaningful displays.

Finally, the concept of 'patterns' (originally coming from architecture, Alexander et al 1977 and Alexander 1979, but also used in software design), was used to extract and propose combinations of different elements found in the analysis. Patterns are abstract descriptions of a problem statement with its respective solution for designers to create form from them. Once collected and properly catalogued, they can be used as building blocks to construct unique problem-solving sequences.

RESULTS ANALYSIS

Designing the behaviour of interactive software requires an understanding of *how and why the user wants to use the software* (Cooper et al 2007).

It is reasonable to expect the ultimate aim for building designers to use thermal simulation packages as design advisors is to aid in the design of low energy buildings. However, as Cooper et al (2007) point out, considering user's aims also implies considering their unspoken goals. These are potentially difficult to be identified and require a subtle approach to understanding user's needs.

As the user was invited to solve a design problem which included the use of building thermal physics in it, one assumes he/she will do it not only aiming an ultimate objective of designing a low energy building but also aiming to fulfil a series of other design/performance goals. Many of these happen unconsciously throughout the design process[9]. However, if they are properly mapped, they could inform specific types of building thermal physics assessment to aid decision making. These goals were inferred from the sample, by applying Thematic Analysis to the data.

Recurrent motifs on the data were listed and coded using qualitative research software (NVivo, 2012) from which three main themes consistently emerged:

Theme 1 – Strategies to approach the design of low energy buildings (e.g. use of passive solar heating, use of natural ventilation as free cooling in Summer, etc)

Theme 2 – Sequence of design decisions and analysis (e.g. exploring different opaque façade panel compositions and analysing their U-values to comply with part-L, optimizing combinations of U-values and SHGC for windows per façade orientation, etc.)

Theme 3 – Examples of visualization of meaningful building physics data to building designers (e.g. floor plans coloured to illustrate different levels of internal gains, facades drawing indicating where thermal bridges are likely to happen, floor plans with resultant cooling demands per room, etc)

Themes 1 and 2 enabled user's goals to be inferred, as these goals would be the drivers of strategies and sequences of design decisions undertaken. These inferred goals seemed to be recurrent in the data sample even when strategies and sequences of design decisions were actually different. Table 1 shows the goals inferred with their respective characteristics implying what kind of information needs to be displayed.

Inferred Goal	**Special characteristics of the goal**
Understanding a specific performance result	Understanding *where* a specific performance result is happening and *what building elements are responsible for causing it*.
Exploring a specific design strategy	Undertake a specific design action and assess the consequences of this action in the overall performance.
Meeting a target	Quantify how far a specific type of performance result is from a prescribed benchmark and inform the user which building design variables are the responsible for this mismatch.
Assessing a specific product	Assess the performance result of integrating a specific system or product in the design of a building.
Optimizing	Find the optimum quantities for a specific set of parameters to achieve a best performance target.

Table 1 – Examples of inferred goals found on the data sample

Themes 1 and 2 also confirmed what was highlighted in Bleil de Souza 2012 about how designers tend to solve design problems. Even when undertaking a constrained design exercise, designers approached problem-solving of it from distinct ways without necessarily using a systematic and scientifically based procedure. Design hypothesis were many and dependant on many factors and constraints, not necessarily related to building thermal physics. Designers would then decide on when and which building thermal physics processes were more appropriate to be used depending on the specific design action they would be undertaking or evaluating.

Paths of design actions and analysis were clearly different from designer to designer but

[9] For design thinkers (e.g. Schon 1991) the design process is a conversation with the materials of the situation in which sequences of moves are directed by *reflection in action*. Designers think ***in*** the process ***not about the process***, meaning actions undertaken or goals to be achieved are mainly unconscious and have to be inferred.

commonalities about the types of actions and analysis processes undertaken by them were quite evident. One could see for instance that Subject X started his façade design by exploring different construction systems assessing their compliance with part-L. Subject Y decided to start his project by exploring the design of efficient solar shading checking building envelope compliance with Part-L only halfway in his design process. Both undertook similar types of actions and analysis processes in different design stages.

This confirms the idea that *there is not 'a' common design process but a series of common design actions* informed by or assessed through potentially specific common analysis processes. This finding is important. It means design actions and analysis processes need to be listed as isolated entities in a framework to enable the following things relevant to the design process to happen:

- For sequences of actions to differ depending on the designer and on the design problem at hand.
- For one action to be connected to more than one analysis process.
- For several actions to be connected to only one analytical process.

From the examples collected in theme 3, it was possible to see designers need location based representation systems and abstract representation systems for building thermal physics metrics to be related to the entities they manipulate.

Location based representation systems, mean representation systems used to inform *where* a specific parameter or performance result would happen or *which specific building design element* is the main one responsible for causing specific resultant behaviour. These representation systems connect building thermal physics metrics to commonly used building design representation systems (plan, section, elevation, detail or relevant 3D representation).

As not all building thermal physics phenomena can be related to or represented in space, abstract representation systems such as graphs, tables and charts cannot be excluded. They need to be used as a complementary set of tools when phenomena need to be represented over time and parameters need to be correlated.

Classification systems from Information Visualization were applied to theme 3. A list of types of visualization systems (based on Ward et al 2010, Mazza 2009, Spence, 2007, Card et al 1999) was developed together with a list of building thermal physics metrics relevant to design decision making. Approximately 30 pieces of information were identified, from heat flows to specific design parameters that affect them.

Relevant metrics and representation systems were combined on non-exhaustive tables with the purpose of each combination highlighted (Table 2). The tables were flexible enough to account for the fact that one representation system was suitable to more than one metric and vice-versa.

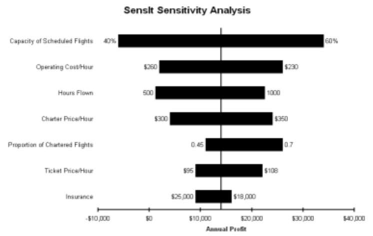
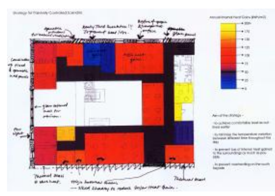
<table>
<tr><td colspan="2">Type of representation: Tornado Diagram

</td></tr>
<tr><td>Metric: Overheating</td><td>Metric: Heating energy use</td></tr>
<tr><td>Purpose: To assess the contribution of each different design parameter to the overheating performance.</td><td>Purpose: To assess the contribution of each different design parameter to the heating energy use.</td></tr>
<tr><td>Output Variable: Hours of overheating for altering each design parameter.</td><td>Output Variable: Heating energy demand.</td></tr>
<tr><td>Unit System: Number of hours of overheating</td><td>Unit System: kWh or kWh/m2</td></tr>
<tr><td colspan="2">Metric:
Free Float Environmental Temperatures</td></tr>
<tr><td>Type of Representation:
Diagram
</td><td>Type of Representation:
Coloured Floor Plan
</td></tr>
<tr><td>Purpose: To compare and rank free float mean environmental temperatures for a working day over a user selected time period (typical Summer, Winter, Mid-season days)</td><td>Purpose: To locate and compare mean environmental temperatures for a working day over a user selected time period (typical Summer, Winter, Mid-season days).</td></tr>
<tr><td colspan="2">Output Variable: Free float mean environmental temperatures for a working day over a user selected time period (typical Summer, Winter, Mid-season days)</td></tr>
<tr><td colspan="2">Unit System: Degree Celsius</td></tr>
</table>

Table 2 – An extract from a list of combinations between metrics and representation systems suitable to design decision making

Table 2 was expanded to include further methods of Information Visualization. These are data interaction techniques which allow the user to get an overview of data, zoom and filter on areas of interest, request details as needed, retrace steps and compare information (Scheinderman 1996).

Types of analysis afforded by each piece of information were added to the tables by following the criteria described in Table 3. This piece of information is seen by the authors as particularly relevant to establish further connections between visual displays and analysis processes.

Type of analysis afforded	**Purpose of the analysis**
Descriptive	To describe a model To remind the user of a base case or starting point To create a benchmark for comparison
Analytical	To compare 'n' different variables in a model To compare 1 variable across different models To compare 'n; variables across 'n' different models
Potential	Illustrates the 'ideal maximum' benefit one could get for a specific strategy
Optimization	Optimum combination of a group of pre-selected variables
Sensitivity of the system	The proportion of the system response to each variable variation
'Side Effects'	Remind the user of implications one action has in relation to other performance metrics in the model

Table 3 – Criteria for types of analysis afforded by each piece of information.

This stage of the research enabled the authors to conclude key parts of a framework could be:

- Inferred goals
- Design actions
- Analysis processes
- Database of metrics and representation systems

All of them could be listed as isolated entities suggesting the potential set up of databases for flexible and multiple connections among the parts to be enabled. The challenge then became identifying, collecting and producing connections among these parts to provide building physics information that is meaningful to design decision making. This should at the same time enable simulation software developers to apply appropriate post-processing routines to simulation output data for displaying the required information to building designers.

Prior to trying to identify connections among these parts, the authors decided to discuss the findings with simulation software developers. As the analysis processes contained in the data sample were set up by building designers themselves through the use of simplified methods, they could only be indicatives of what was needed as these were not based on full dynamic simulation. Experts would assist in further developing the analysis processes so they could be undertaken using dynamic thermal simulation tools. Formal knowledge about building thermal physics and dynamic thermal simulation was now taken into account. The analysis processes were refined and re-organised into the four following categories according to the type of simulation post-processing required:

- Simple post-processing, in which information to design decision making can be directly extracted from simulation outputs (e.g. magnitude and location of room temperature)
- Analytical post-processing, in which some type of analysis is needed for outputs directly extracted from simulation to be used in design decision making (e.g. percentage of hours of overheating in a year with a clear indication of its causes)
- Comparative post-processing, in which outputs from simulation need to be appropriately compared to be meaningful to building designers (e.g. comparing one design proposal with another for heating energy use)
- Virtual experiments, in which a specific type of modelling or model is required for simulation outputs to be useful to design decision making (e.g. determining 'effect of thermal mass' by modelling a heavy and a lightweight building under specific conditions)

The dataset was revisited so that analysis processes could be re-organised based on the new aforementioned categories. Performance variables meaningful to building designers were examined under these categories. Patterns of connections among inferred goals, design actions, analysis processes and visualization systems started to emerge. These patterns were abstractly described in terms of the following components:

- The context in which they happen, with examples
- The goals they address in connecting design actions with analysis processes
- Detailed information on the analysis processes, modelling assumptions, quality assurance mechanisms and simulation post-processing techniques required to extract meaningful data to building designers
- Links to databases with information display (metrics and representation systems meaningful to building designers)
- How they can be further developed and validated based on feedback from experts and building designers
- Their potential links to other patterns

These patterns can be seen as the building blocks to construct unique problem-solving sequences in which building thermal physics informs design decision making. They are fully discussed in another paper also presented in this conference, so that the appropriate level of complexity involved in their development can be addressed.

FRAMEWORK

From the analysis and development described above, it is possible to conclude that a framework to produce post-processed data representation systems meaningful to building design decisions making could be composed of the following parts:

1) Inferred Goals
2) Design Actions
3) Analysis Processes
4) Database of metrics and representation systems
5) Patterns for Decision Making

Each part of the framework is supposed to be an endless database which can be constantly enriched, populated and exchanged among designers and consultants.

Inferred Goals:

Inferred Goals reflect the range of uses dynamic thermal simulation has or can have in the design process (see Table 1 for examples). They provide important connections between design actions and analysis processes as they define the use of these analysis processes in assessing or undertaking an action.

Design Actions

These are records of different types of design actions designers undertake while designing (e.g. changing window sizes, changing construction systems of walls, etc.). They should be completely free for designers to decide about and described in a way to be easily stored and retrieved.

Analysis Processes

Analysis Processes are records of all types of analysis that can be applied on any type of design action. They are attempts to describe, map and categorise the comprehensive knowledge involved in analysing thermal simulation data and include not only a series of post processing techniques but also possibilities of doing specific virtual experiments to answer specific design questions. They act as a repository of formal knowledge that simulation experts provide to properly address physical phenomena involved in every specific design action.

Database of metrics and representation systems

Is a database containing information on metrics and representation systems meaningful to design decision making and could include the following components:

- Types of representation system (with an illustration)
- The metrics that can be represented
- The hierarchical / interactive level of representation provided (overview, zoom or detail on demand)
- The type of analysis it affords to easily link it with design actions and analysis processes.

Patterns for Decision Making

Patterns for Decision Making are abstract descriptions of connections between Design Actions and Analysis Processes established through Inferred Goals, displayed using appropriate metrics and representation systems. These patterns are the building blocks for designers to create their own sequences of informed design decisions. Once properly identified, mapped and validated by designers, these patterns become specifications for software developers to produce outputs containing meaningful building thermal physics information to design decision making.

CONCLUSIONS AND FUTURE WORK

The aim of this paper was *to describe the process used to develop a framework* to produce thermal simulation post-processed information and data representation systems meaningful to building design decision making.

The framework has been concluded from 'reverse engineering' several design processes which used building thermal physics information to aid design decision making. These processes were de-constructed and analysed using a combination of: Interaction Design, Information Visualization and Qualitative research methods from Social Science. A structure was developed to collect and propose alternatives to meet the requirements building designers have for using simulation tools.

Key aspects of the analysis and development that have resulted in the formulation of the framework are:

- Designers need to be completely free to undertake design actions.
- Inferred goals, recurrent aims found in the dataset reflecting the different uses building thermal physics has or can have in the design process, are used to connect design actions and analysis processes.
- Design processes are clearly unique and distinct from each other. However, they are composed of recurrent types of design actions and analysis processes that can potentially be recorded and stored to be retrieved or exchanged.
- Inferred goals, design actions, analysis processes, metrics, representation systems and patterns for decision making are open-ended. They need to be described using a format that enables constant update, enrichment and exchange

- Designers can provide useful hints about what metrics and representation systems can be useful to design decision making even if having a limited knowledge of building thermal physics
- The maximum level of prescription that can be achieved to connect inferred goals, design actions, analysis processes, metrics and representation systems are patterns for decision making. Once identified, structured and mapped, these patterns can be used as atoms or molecules of a design process as they can be assembled in infinite ways.

Future research should be focusing on the full development of this framework. Tables should be transformed into proper databases moving from a feasibility study stage into a proper pilot study stage, when information collected would be tested and validated by building designers.

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REFERENCES

Alexander, C. 1979. The Timeless Way of Building, New York: Oxford University Press, 1979.

Alexander, C., Ishikawa, S., Silverstein, M., Jacobson, M., Fiksdahl-King, I., & Angel, S. 1977. A Pattern Language, New York: Oxford University Press.

AutoDesk Project Vasari, 2012. AutoDesk Labs Homepage [online]. AutoDesk, USA. Available from: http://labs.autodesk.com/utilities/vasari/ [Accessed: Aug 2012].

Bleil de Souza, C. 2009. A critical and theoretical analysis of current proposals for integrating building thermal simulation tools into the building design process. Journal of Building Performance Simulation, 2(4), 283-297.

Bleil de Souza, C. 2012. Contrasting paradigms of design thinking: The building thermal simulation tool developer vs. the building designer. Automation in Construction, 22 (March 2012), 112-122, Elsevier.

Bleil De Souza, C. 2013. Studies into the use of building thermal physics to inform design decision making. Automation in Construction 30, pp. 81-93.

Bryman, A. 2008. Social Research Methods, Oxford University Press, New York, 2008.

Buchanan, R. 1995. Wicked problems in design thinking, in: V. Margolin, R. Buchanan (Eds.), The Idea of Design: A design Issue Reader, The MIT Press, Cambridge, pp. 3–20.

Card, S.K., Mackinlay, J.D., and Shneiderman, B. 1999. Readings in Information Visualization: Using Vision to Think, Morgan Kaufmann Publishers Inc.

Cooper, A. Reimann, R., & Cronin, D. 2007. About Face 3: The Essentials of Interaction Design, John Wiley & Sons.

Cross, N. 2004. Expertise in design: an overview, Design Studies 25 (5) 427–441.

Lawson, B. 1997. How Designers Think: The Design Process Demystified, 4th ed Architectural Press, Burlington, (1st edition 1980).

Mazza, R. 2009. Introduction to Information Visualization, Springer-Verlag London Ltd

Open Studio 2012. Open Studio Homepage [online]. Available from: http://openstudio.nrel.gov/ [Accessed: Aug 2012].

Rogers, Y., Sharp, H., & Preece, J. 2011. Interaction Design: Beyond Human-Computer Interaction, John Wiley & Sons; 3rd Edition.

Rowe, P. 1987. Design Thinking, The MIT Press, London.

Schon, D. A. 1988. Designing: rules, types and worlds, Design Studies 9 (3) 181–190.

Schon, D. A. 1991. The Reflective Practitioner: How Professionals Think in Action, Ashgate Publishing Limited, UK (1st edition 1983).

See, R., Haves, P., Sreekanthan, P., O'Donnell, J., Basarkar, M., Settlemeyre. 2011. Development of a user interface for the EnergyPlus whole building energy simulation program. Building Simulation '11, 12th International IBPSA Conference, Sydney, Australia, November 14-16, 2011, 2919-2926.

Shneiderman, B. 1996. The eyes have it: A task by data type taxonomy for information visualizations, Proceedings of the 1996 IEEE Symposium on Visual Languages.

Spence, R. 2007. Information Visualization: Design for Interaction, Prentice Hall.

Ward, M., Grinstein, G., & Keim, D. 2010. Interactive Data Visualization: Foundations, Techniques and Applications, A K Peters Ltd, MA.