INTERACTIVE VISUALISATION AS A TOOL FOR INTERPRETING BUILDING THERMAL SIMULATION RESULTS

Yaqub Rafiq, Martin Beck, Pieter De Wilde

ABSTRACT: During building design there is a growing need to reduce energy usage whilst maintaining the comfort of the occupants. The latter is referred to as 'thermal comfort' and can be measured by the extent that the internal temperature of the building does not exceed a specified comfort level. Traditionally these two measures of building performance are seen as a trade off. Moreover, energy efficient building design is a complex process involving a large number of design variables each of which differentially affect both energy usage and thermal comfort. There is a vast search space to be traversed to find an optimal set of potentially good designs. This coupled with computationally expensive building performance simulation software leads to a problem which is potentially intractable. In the past the authors have used the Interactive Visualisation Clustered Genetic Algorithms (IVCGA) to address some of the complexities of multi-disciplinary building design problems. The aim of this paper is to apply the IVCGA to allow the building designer (physicist) to: Firstly discover a set of potential design solutions which meet the design objectives of minimal energy usage and maximal thermal comfort individually; Secondly discover a set of potential design solutions which are common to all objectives (mutually inclusive region); Thirdly present a means to understand the impact that particular design variables have upon each objective.

KEYWORDS: genetic algorithms, visualisation, design, thermal simulation.

1 INTRODUCTION

While there are many definitions of design and the purpose of each stage which makes up the whole design process, in essence design is a co-ordinated human activity. Simon (1969) defined design as a problem solving process and an activity of searching the solution space for a solution that satisfies client requirements and it is fit for purpose. It was Smithers (1993) who questioned the validity of this approach. Smithers argued that search implies a well defined problem from which a solution can be generated: At the early stages of the design process (i.e. conceptual stage) the design requirements (i.e. the 'problem') are often ill-defined and the process should be viewed as one of exploration rather searching the solution space. This issue is also eloquently advanced by the work of Gero (1993), Maher et al (1995) and Maher (2000) who point the way to which conceptual design is both an exploration of the design requirements and the potential solutions to those requirements.

One of the key ideas underpinning this paper is the notion of 'design as exploration'. Hence, the focus is on exploring the design space where interest in the inter-relationships between design variables and / or objectives is primary. To achieve this exploration two interrelated aspects of visualisation techniques and human involvement play a key role. By combining these two aspects an interactive user interface and human-driven search process is developed which goes beyond the predefined algorithmic procedure and aids the designer to freely explore the design search space in a creative way. Unlike analysis tools it is not intended to yield one single solution, but rather to supply the designer with stimulating, plausible directions (Bentley and Corn 2002). This enables the designer to widely explore design requirements and corresponding solution spaces, evaluate merits of computer generated solutions by considering non-quantifiable non-encoded criteria in order to drive the search to a designer preferred direction.

1.1 *Design space visualisation*

A number of systems described in the literature are applicable to visualisation and manipulation of engineering design data. Robert Spence from Imperial College has used extensive experience of human computer interaction in engineering design to develop the Influence Explorer (Tweedie et al 1996) and the Prosection matrix (Spence – "The Acquisition of Insight"). The Influence Explorer is designed to help in the decision making process during engineering design; input parameters and output performance measures are shown in parallel displays, the colour of the solutions changes during interaction so that the user can assess which solutions are within specified tolerances.

Visualisation of alternative coordinate systems has been extensively researched and implemented by Andeas Buja, Diane Cook and Deborah Swayne at AT&T Labs (Swayne et al 1998 & 2001). After a number of design changes GGobi (Swayne et al 2001) was developed which presents data in a variety of ways using window cloning and supported by brushing (Becker & Cleveland 1987). The data can also be viewed in different coordinate systems using the projection pursuit technique (Friedman and Tukey 1974). Gilbert et al also use principal component analysis to visualise biological data in Space Explorer (Gilbert et al 2000) using the first principal components to visualise the 'natural' clusters in the data. The systems described above use static and pre-classified data whereas the IVCGA described in this paper allows arbitrary data to be clustered in alternative coordinate systems, refinement of clustering by the user is also possible.

1.2 *The interactive visualisation clustering genetic algorithm*

Most architectural and engineering design problems are multidisciplinary, multivariate and multi objectives so visualising and understanding interaction between design variable would lead to better understanding of the search and solution spaces as well as understanding of the design issues. The main aim of engineering design is to provide a number of design alternatives (Dym 1994) and check the suitability and robustness of the design by evaluating neighbouring solutions (Phadke 1989). In this study the Genetic algorithm, GA, (see Goldberg, 1989, for overview) was chosen as it is capable of widely searching the design space in order to generate design solution by random sampling method that attempts to converge on good design solutions. Because of the GA's optimisation strategy, it is capable of returning a number of local optima (or clusters) that are good candidates as robust design alternatives.

Packham and Denham (2003) argue that the clusters should be presented to the engineer in terms of the original design variables or a coordinate system that can be easily related to the original variables. This approach enables the user to get a solid understanding of the search and solution spaces. It is also necessary to check that the regions of the search space indicated by the clusters are robust (not sensitive to changes in variables). Therefore a novel clustering algorithm based on kernel density estimation (Silverman 1986) was used in the Interactive Visualisation Clustering Genetic Algorithm system (IVCGA) by Packham (2003) which identifies high performing clusters in terms of a given coordinate system. The IVCGA as a whole combines the diverse research areas of engineering design, multivariate visualisation and evolutionary computing. It was developed as a combination of these research areas as a means to improve understanding and wider exploration of the solution space in modern engineering design activity. The overall goal was to create an interactive visualisation system that generates data and provides analysis of the data by indicating regions of the search space that are worth investigating (Packham & Denham 2003).

An important feature of the IVCGA is that it allows the user to interact with the data and search process, and using domain knowledge the user is able to choose a number of possible actions, i.e. to choose the next action such as to perform a more detailed search inside a region or try to find other high performing regions.

While IVCGA is discussed in more detail in Packham (2003) and Rafiq et al (2005), however some of the features of the system can be summarised as:

1. Fast Exploration of the search space using an automatic clustering procedure that identifies clusters of good solution both in variable or objective space. Colour is used to highlight important clusters, enhancing perceptual understanding of the data.
2. An easy to use interface that allows direct manipulation of the data and views. Various high dimensional visualization techniques are supplied to enable understanding of the data from different viewpoints and combination of parameters.
3. Extensive interaction is supported allowing the generation of further data with the GA inside or outside regions identified by the user or clustering algorithm. The definition of clusters can be modified by the user or even created manually, ensuring complete freedom of search and human-led exploration of the search space.

The majority of these techniques discussed in the design space visualisation section are incorporated as interactive visualisation tools with the IVCGA and are used in this paper.

1.3 *Discovering inter-relationship between parameters and objectives*

In order to demonstrate the capabilities of the IVCGA, the technique is applied to a relevant problem in building engineering: The analysis of robustness and adaptability of domestic houses towards climate change scenarios. Obviously, such an analysis requires a deep insight into the interrelationships between different building design parameters, environmental conditions, and thermal performance. A typical single two storey terrace house in the UK is used to investigate the effect of four essential design parameters (building orientation, floor insulation, wall insulation and attic insulation) on the objectives of energy consumption and thermal comfort (criteria for energy consumption and thermal comfort are presented in the methodology section)

In the context of this building engineering problem, the aims of this paper are to allow the building designer (physicist) using the IVCGA to: Firstly discover a set of potential design solutions which meet the design objectives of minimal energy usage and maximal thermal comfort individually; Secondly discover a set of potential design solutions which are common to all objectives (mutually inclusive region); Thirdly present a means to understand the impact that particular design variables have upon each objective. This latter aim achieves an enhanced understanding of the inter-relationship between design parameters and objectives, thus potentially discovering less important parameters which play minimal role in energy usage or thermal comfort.

Taken together these three aims allow an exploration of differing design requirements: By providing designers with an enhanced understating of the differential effects of the design parameters and coupling this with domain knowledge, the designer is helped to find compromise design alternatives which partially satisfy minimum energy consumption and maximum thermal comfort.

An interesting aspect of this research is that these three facets are achieved through post-processing and maximal use of information already generated during the individual runs of the GA search for each objectives separately thus reducing computational expense.

These four design parameters (i.e. orientation, floor insulation, wall insulation and attic insulation) are used as their effect upon building performance are relatively well understood, and provide a means to confirm the results of this study. For example building orientation is directly linked to solar access, and insulation layer thickness is directly linked to transmission losses.

As these parameters are generally fixed at construction time[1] it is thus instructive to understand the impact these parameters have upon the objectives before design or construction details are firmed. Moreover, given the longevity of a typical building and the current world-wide attention on climate change, where the consensus of opinion being that of a warmer climate in the UK, it would be informative to see how the design parameter-objective interaction generalises if the building was in a warmer climate. To this end, objective performance is assessed under two typical western European climatic conditions: That of Birmingham (UK) and Rome (representing potential future UK climate).

2 BUILDING THERMAL MODELLING

The building used in this paper is a three bedroom terraced dwelling. This is the most common type of housing in the United Kingdom (approximately one third of all houses are terraced; and approximately half of all houses have three bedrooms). The dwelling is assumed to have a floor size of 84 m^2, and modelled as a three zone building: With one zone for each of ground floor, first floor and attic. The ground floor and first floor are heated; the attic is not. None of the zones contains an active cooling system. Façade lay-outs have been based on a range of existing dwellings in England. A wireframe image dwelling is shown in Figure 1, below.

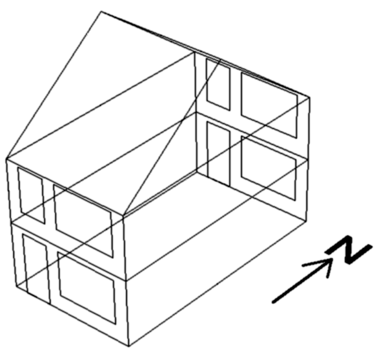


Figure 1. Wire frame model of dwelling used in simulation.

A model of this building is developed based on common construction practice, materials and dimensions for the United Kingdom (e.g. insulated cavity wall, double glazing, wooden internal floors, insulated attic, and slate roof on felt membrane). Of the wide range of building parameters four have been chosen for this study:

- The orientation (rotation) of the building. With 0 degrees representing North-South facing (as shown in Figure 1). Rotation is performed in a clockwise direction.
- Three parameters relating to insulation: Ground floor insulation; wall insulation; and attic insulation (also known as loft insulation).

The ranges of these four parameters are shown in Table 1, below.

Table 1. Building uncertainty parameters and their investigated range.

Name	Description	Range
X1	Building orientation	0 to 90 [degrees]
Insulation levels		
X2a	Floor	0.02 - 0.100 [m]
X2b	Wall	0.05 - 0.120 [m]
X2c	Attic	0.03 - 0.150 [m]

For this study three objectives (termed here Performance Indicators, PI) are used:

- PI1: Indicates the energy use of the dwelling as measured in GJ/year. Note that PI1 relates to required end-use heating energy only, and does not take into account: The type or the efficiency of the heating system; any energy conversion or transport factors.
- PI2 and PI3 : Are the thermal comfort of the ground floor (PI2), and the first floor (PI3). Thermal comfort is measured by the number of hours per year that the mean air temperature in the respective zone exceeds a threshold value of 25°C. This threshold value is in common use (i.e. Hacker et al, 2005). A lower PI2 and PI3 value indicates better thermal comfort, with values below 100 hours per annum being considered acceptable (DeWit, 2001).

Assessment of the three objectives was performed using EnergyPlus version 1.2.3. Other than the four design variables, all other design parameters remained fixed with values taken from ASHRAE (2005) Handbook of Fundamentals, chapters 25 and 38 and the CIBSE (1988) Design Data Guide, Appendix 2. For other calculation parameters (i.e.. time step) the default settings of EnergyPlus have been used. For a fuller discussion of the model used see DeWilde et al (2006)

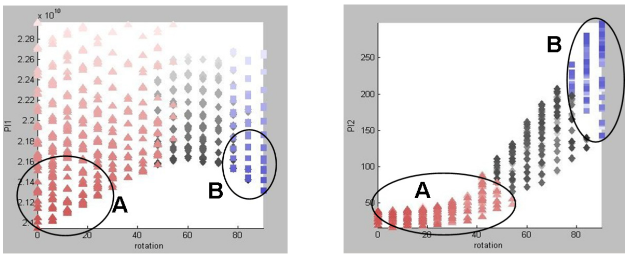
3 RESULTS

For all cases presented in this section, clustering was done in objective space and three clusters identified using Kernel Density Estimation. Initial inspection of the effect of building orientation (rotation) upon energy usage (PI1) would tend to suggest two possible ranges of rotation associated with low energy those shown as areas A and B in Figure 2. However when one of the thermal comfort objectives (PI2) are considered, it is clear that only lower values of rotation provide good thermal comfort also,

[1] Admittedly insulation can be added after construction, but except for attic insulation this can be a costly and inconvenient process.

with a marked increase as rotation increases[2]. This example demonstrates the significance of a trade-off between energy consumption and thermal comfort when deciding on building orientation. Area A represents the presence of windows in the North and South faces of the building while in Area B these windows are in East and West faces of the building. During the summer time (when days are longer) the latter will result in more heat entering the building, which adversely affect the thermal comfort. These results meet the first two aims of the paper:

- Firstly discover a set of potential design solutions which meet the design objectives of minimal energy usage and maximal thermal comfort individually. The areas A and B represent solutions of minimal energy usage, where as area A represents maximal thermal comfort.
- Secondly discover a set of potential design solutions which are common to all objectives (mutually inclusive region). In this case only area A represents a region which is common to both objectives.

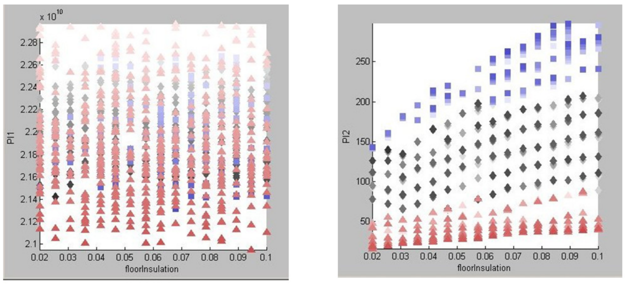


(a) Rotation vs. PI1 **(b) Rotation vs. PI2**

Figure 2. Showing relationship between rotation of building and (a) energy usage, PI1; and (b) ground floor thermal comfort, PI2.

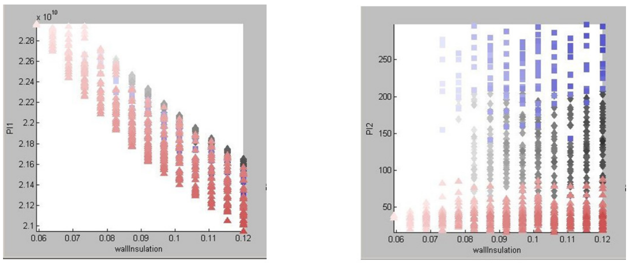
When floor insulation is considered, results shown in Figure 3(a) indicate no apparent relationship between floor insulation and PI1. This indicates that omitting floor insulation will not greatly affect the energy consumption. This is partly caused by the physical model used within EnergyPlus, where the soil temperature is kept at a constant level throughout the year. In contrast Figure 3(b) demonstrates a that a lower value of floor insulation is associated with a marginally better value of thermal comfort for solutions in area A, but that more marked increases are achieved in area B. This leads to the conclusion that omitting floor insulation improves thermal comfort. This is caused by the accessibility of the thermal mass in the ground slab, which dampens overheating peaks in the summer. Note that a different built-up of floor layers will show a different behaviour.

Looking at the effect of varying levels of wall insulation it can be seen that higher levels of wall insulation are associated with lower levels of energy usage, Figure 4(a), whereas wall insulation has a very marginal impact on thermal comfort (Figure 4 (b)). In this case the insulation is positioned in a cavity wall. As the inner wall provides thermal mass and dampening to the indoor climate, a change in insulation thickness here does not show any impact on thermal comfort. However, it now has a significant impact on energy use, impacting the transmission to the outside air.



(a) Floor Insulation vs. PI1 **(b) Floor Insulation vs. PI2**

Figure 3. Showing relationship between levels of floor insulation: and (a) energy usage, PI1; and (b) ground floor thermal comfort, PI.



(a) Wall Insulation vs. PI1 **(b) Wall Insulation vs. PI2**

Figure 4. Showing relationship between levels of wall insulation and: (a) energy usage, PI1; and (b) ground floor thermal comfort, PI2.

Investigating the relationship between the objectives of energy usage, PI1, and thermal comfort, PI2 (see Figure 5) indicates that at lower energy values (less than approximately 2.14×10^{10} GJ y-1) there is also a significant number of correspondingly good thermal comfort levels. Above this 2.14×10^{10} value, the thermal comfort is far more variable. To understand this more, when Figure 5 is compared with Figure 2 it can be seen that the dramatic increase of PI2 values (those shown by diamonds and squares) are due to the increased rotation of the building. From these initial exploratory results, three general heuristics can be made:

1. Lower rotational values are associated with lower energy usage and better thermal comfort, Figure 2 (a) and (b)
2. Floor insulation levels play no apparent role in energy usage, and have only slight impact on thermal comfort: with lower floor insulation bringing better thermal comfort, Figure 3 (a) and (b)
3. Increased wall insulation dramatically reduces energy use, but has no impact on thermal comfort, Figure 4 (a) and (b).

These results meet the third objective, namely: Present a means to understand the impact that particular design variables have upon each objective.

These observations are made with the dwelling assumed to be located in a typical current UK climate range (Birmingham). With the current world-wide attention for climate change and with the scientific consensus predicting a warmer climate in the UK, it would be informative to see how the performance of the dwelling and the extent to which the heuristics developed above are influenced by a warmer climate. To this end a second performance analysis of the dwelling was undertaken, but this time assum-

[2] Similar results are found for PI3, but are omitted for brevity

ing the dwelling is being operated within a Rome type climate.

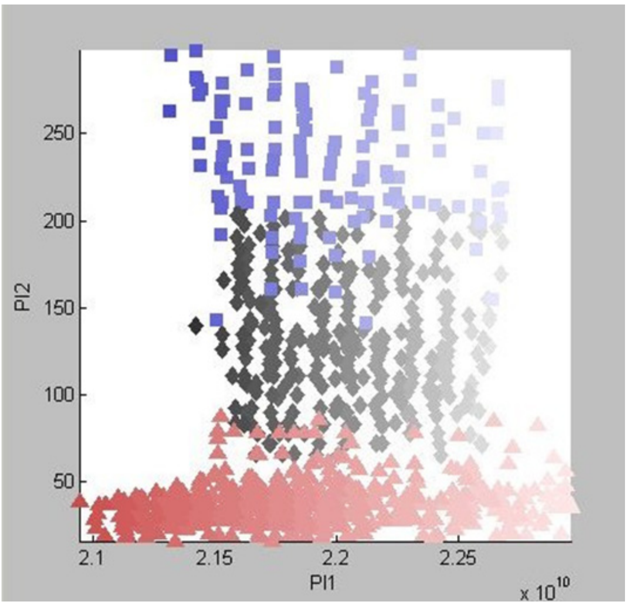
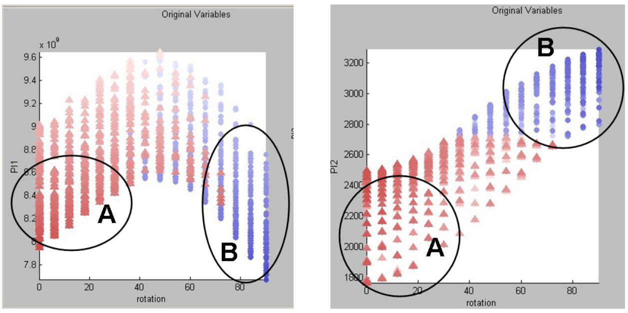


Figure 5. Showing relationship between energy usage, PI1 and ground floor thermal comfort, PI2.

Reference to Figure 6 shows a similar patterning of the effect of rotation of building to energy usage (Figure 6 a) and thermal comfort (Figure 6 b) to that found in Figure 2. Again it is evident that two areas of low energy usage, A and B are present. There are, however, some marked differences in performance across the two climates:

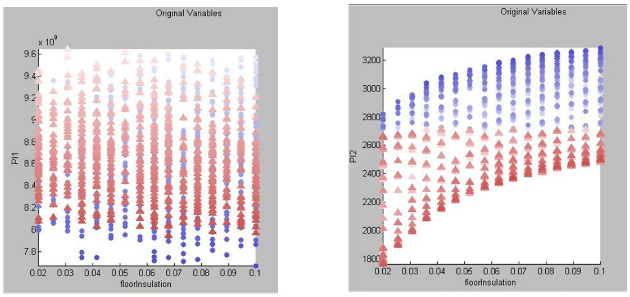
- Firstly the magnitude of the performance indicators with energy usage for Rome being a factor of 10 less than for Birmingham (i.e. Some 10^{10} GJ yr-1 for Birmingham versus 10^{9} GJ yr-1 for Rome). Also the level of thermal comfort has dropped dramatically for Rome when compared to Birmingham (i.e. Ranges of 1,800 to 3,300 hours above 25^{o}C for Rome and 0 to300 hours for Birmingham). It should also be noted that the best values of thermal comfort for Rome (circa 1,800 hours) are way in excess of the 20 hours recommended.
- Secondly, the better minimal energy usage for Rome is now to be found at higher rotational values (Figure 6 a, area B). In contrast this was found to be at lower rotation for Birmingham (Figure 2 a, area A).



(a) Rotation vs. PI1 **(b) Rotation vs. PI2**

Figure 6. Using Rome climate the graphs show the relationship between rotation of building and (a) energy usage, PI1; and (b) ground floor thermal comfort, PI2.

When the effect of floor insulation is considered, again there is no apparent relationship between energy usage and levels of floor insulation, Figure 7 (a). However the marginal improvement in thermal comfort with lower floor insulation levels found earlier, see Figure 3 (b), has been replaced with quite a dramatic improvement, Figure 7 (b). This again is contributed to better access of thermal mass contained within the floor (PI2).



(a) Floor Insulation PI1 **(b) Floor Insulation vs. PI2**

Figure 7. Using Rome climate the graphs show the relationship between levels of floor insulation: and (a) energy usage, PI1; and (b) ground floor thermal comfort, PI2.

4 DISCUSSION / CONCLUSION

Interactive visualisation clustering genetic algorithms (IVCGA) have the advantage that they can work on the existing data, or can use the GA to explore the search space to generate a population of design solutions. The IVCGA has proved to be efficient in rapidly identifying clusters of good design solutions. It uses colour to distinguish between clusters of good and unsuitable design solutions, using user defined objectives. Users' interaction with the system and using their expert domain knowledge enable them to quickly assess the merits of solutions for the intended design requirements. In this paper an example of thermal performance of a three bedroom terraced dwelling is presented.

Using IVCGG it was possible to discover sets of design solution which are satisfy both for minimal energy consumption and for maximal thermal comfort. It was possible to clarify to the designer that clusters of design alternatives within a solution space, which may appear desirable for one objective could have a detrimental effect on other objectives, which may not adequately satisfy the overall design requirements.

A bi-product of using interactive visualisation tools such as IVCGA was the discovery of new knowledge and increasing designers' confidence on their existing knowledge. This new knowledge could be interrelationship between design parameters or understanding the impact of particular design variable on the various objectives and on the suitability of overall design. For example by using IVCGA it became clear that wall insulations has a dramatic effect on the energy consumption but less effect on the thermal comfort. Similarly floor insulation had no significant impact neither on energy consumption nor on thermal comfort. These observations enable the designer to develop a set of heuristics particular to the specific problem at hand, and to interpret these using their own extensive domain knowledge. Furthermore the IVCGA allows the designer to test the generalisation of these heuristics across different scenarios (i.e. Birmingham climate vs. Rome climate), and to assess the overall impact that particular design variables may have across scenarios.

It is the discovery problem specific heuristics which provide a better understanding of the design requirements, and may be instrumental in a reformulation of these requirements, thus allowing the notion of 'design as exploration' to be realised.

5 CONCLUSIONS

Systems such as the IVCGA help exploration of design spaces, aiding understanding and interpretation of results. However, they do not eliminate the need for domain knowledge and expertise, rather they compliment and add to it. As an example, understanding the impact of floor insulation levels on thermal comfort is only possible if one has detailed knowledge of the sequence of material layers in the underlying EnergyPlus model. The knowledge discovery and visualisation techniques presented in this paper are not intended to contribute to automated design rather they support informed design decision making enabling the designer to more effectively explore the design space.

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