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Multi-parameter sensitivity analysis: A design methodology applied to energy efficiency in temperate climate houses

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ABSTRACT

Quantified sensitivities of heating and cooling loads to different variables that influence heat gain and loss in a building provides a valuable basis for energy efficient design, especially in temperate climate zones where particular parameter settings could be beneficial in one season while reducing performance or neutral in the other. In doing so it is important in this multi-parameter design space to consider impact of changes in each parameter when other variables also change. Such 2-variable up to n-variable correlation is called factorial analysis. The methodology is introduced using three variables (roof solar absorptance, air exchange rates, and sub-roof *R*-value) in a simple structure with all other parameters fixed. Sensitivity is via impact of changes on each of heating load, cooling load and annual total. Knowledge of factorial effects is shown to be important and lead to simple strategies that provide large benefits in both seasons. They also show that some standard approaches to saving energy (e.g. raising *R* significantly), while useful are often unnecessary, unless poor settings are made in other parameters.

1. Introduction

Energy efficiency has become a central issue in building design, but cannot be considered in isolation from a variety of other issues including available funds, aesthetic appeal, occupant well being, and overall environmental benefits. The latter can involve more than the reductions in CO_2 emissions from reduced energy use, which from an atmospheric impact perspective can be strongly outweighed by other direct thermodynamic benefits for several years [1]. Local exterior impact might also be factored into such an analysis, including ability to aid in reducing the local urban heat island [2–4], and impact of building energy systems on precinct pollution levels including humidity. Finally the feedback from improved or degraded exterior air can add to or detract from interior energy savings. While this paper is focused on interior energy efficiency and thermal comfort, the options emerging from our analysis can be further evaluated or ranked in terms of some of these broader issues, which turn out to be prominent discriminators in temperate zones. We will with one key example demonstrate how the seasonal bias from just an energy efficiency analysis is reversed when total environmental benefits are considered.

Various simple strategies for minimizing or eliminating the use of energy for heating or cooling of buildings are known, but how best to integrate is less well understood. In climate zones where reductions in energy use for heating and cooling are both important integrated approaches which achieve both are an ideal goal. There are many design and material parameters to consider. Some impact significantly year round, some mainly in summer, others mainly in winter. A design or operational setting that saves considerable energy and enhances comfort in summer may have a variety of impacts in winter; including an undesirable raising of heating load, a marginal impact, or a worthwhile benefit. Achieving an optimum overall design in temperate climates, and cost benefits, for each parameter setting is made easier if the sensitivity to parameter variations of heating, cooling and year round energy loads (or comfort) is better understood.

Changing one design parameter at a time may give insights into relative impacts of different parameters and the sensitivity of energy use to their variation. This though useful, gives an incomplete picture and may yield sub-optimal, or erroneous solutions. This is because these sensitivities may change as other key parameters change and the seasons shift. The additional consideration here is thus changes in relative sensitivities in summer and winter. A simple example is raising roof or ceiling thermal insulation to lower *U*-value (or raise *R*-value). This often brings year round improvements especially if winter heating loads dominate overall energy usage. However, optimum *R*-values for good summer performance can be much different to that for good winter savings. For roofs in summer the optimum *R*-value setting depends also on roof solar absorptance (A_{SOL}) and emittance, and may be quite low [5], so two obvious questions in the context of this paper are; how adverse in winter is a reduced solar absorptance and what is the best year

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round setting for R-value. Before proceeding to answer it is useful to grasp the main seasonal impacts, otherwise key variable parameters may be left out of the study. Minimising the impact of solar irradiance by raising solar reflectance is the well known core function of "cool roofs" [6–8] for reduced summer cooling loads, though thermal emittance can play a significant role as well [5,9]. Windows may have a major influence in both seasons but can be managed to have low impact and we assume that is the case in this introductory study for simplicity. The main origins of excessive winter heating loads, when they exist in temperate climates such as in Sydney and Melbourne in Australia, is excessive infiltration rates. That is the core problem parameter in winter is air exchange rates per hour (ACH). Thus ACH rates are an essential variable in this study. Fixed wall vents, common in older homes, were designed to deal with summer heat and humidity, but their impact in winter was rarely considered until recently.

The roof two-parameter (R-value, A_{SOL}) co-variant impact noted above is one example of how energy efficient design in buildings is a multi-parameter factorial exercise. A factorial impact on energy use involves simultaneous changes in parameters, in the design process. It is often important. Energy savings however are not just about reducing fossil fuel usage. While savings and better comfort in each building adds value to its occupants and owners, it is the atmospheric impact of reduced CO_2 emissions from many such buildings that is most needed. But for multiple buildings one aspect of design, roof and wall solar reflectance, has a more direct and much greater atmospheric impact. Reflecting more solar energy directly back into space leads directly to less atmospheric warming. Using the methods developed by Edmonds and Smith [1] and Akbari et al. [6] it is easy to show that atmospheric cooling from raising the albedo of many roofs by a moderate amount outweighs by a factor of order 300–400 in year 1 the atmospheric cooling from the reduced emissions associated with the resulting energy efficiencies within those buildings. This large factor does decrease sub-linearly in subsequent years with further CO_2 buildup but it takes many years for reduced emissions to match and then overtake direct impacts. Thus while the MJ savings potential for winter heating in temperate zones may often dominate annual savings, total environmental benefits may be dominated by factors aimed at reducing summer energy use. Our focus will be on energy savings in single buildings but the environmental aspect needs to be kept in mind when making final design decisions. Ideally it would be nice to achieve all three goals in any one design; namely low summer cooling demand, low winter heating demand, and maximized environmental benefit. The multi-parameter methods we introduce here show that achieving all three is indeed possible.

A factorial approach to multi-parameter impacts in a two-season domain is needed since multiple solutions exist for a given energy goal. A better understanding of these relative impacts will help in design choice. Cost, aesthetics, lighting and air quality, can also then be more easily integrated to enhance the attraction of the final design without sacrificing energy savings. Computer simulation of building energy use is now sufficiently reliable and experimentally validated that one can perform acceptably accurate factorial experiments on the computer. The way these are done is outlined in the next section.

In this paper we will focus on variations within a limited factorial set to introduce the methodology and exemplify how to achieve good savings in both summer and winter. The relative importance of different joint pairs to getting individual parameter settings right emerges. Cross-seasonal anti-correlations, or insensitivity measures, play an important role in temperate zones. The factorial experimental principles for a building will be applied here with just three variables, roof solar absorptance, air exchange rates and ceiling or sub-roof R-values, with all others fixed. A simple geometric design and all other factors such as mass, internal loads, windows and wall insulation are thus fixed for this study. In a subsequent report we will examine a much wider multi-parameter set and hence more parameter pair-couplings, and higher order correlations. Once such studies have been carried out their generic outcomes can be used initially in design and the time consuming full set of computer "experiments" is no longer needed.

Example practical questions that can be addressed using factorial modulated parameter sensitivities covering each season and annually:

(i) Can the roofing recommendations for moderating cooling demand be retained without excessive gains to heating loads?
(ii) What impact do beneficial factors for heating load have on cooling load?
(iii) Which air exchange rate settings reduce benefits of cool roofs and which enhance them?
(iv) What is the best year round ceiling or sub-roof R-value if one has both cool roofs and low air exchange rates during winter?

2. Establishing parameter sensitivities and pair-factorial impacts

Two different but related approaches to systematic design optimization have been explored. Both can be extended in principle to any number of variables which a designer might wish to consider. If account is taken of the sensitivities that emerge from this analysis at the outset of a design exercise faster convergence to a final design and better end results will be more likely. The qualitative benefits arising from wider and deeper understanding of sensitivities to different building variables are also important and of value to designers and building materials producers. Factorial or co-varying effects are important for structures in a temperate zone given the widely different weather conditions that can occur over a year. We have explored two approaches to parameter sensitivity analysis including pair factorials. Both ultimately utilise a matrix of "experiments". In each "experiment" the variables of interest are fixed. From a sufficient number of such sets one can establish the energy-use sensitivity to each parameter's variation, along with its modulation by other variable changes. It is informative to have sets in which only one variable changes and then see how that sensitivity is modified when other parameters are changed simultaneously. The latter is called a "factorial" experiment.

For example from the data matrix the cooling load as function of roof solar absorptance is first quantified with all other parameters fixed. Then changes in response to A_{SOL} are examined when one another factor is altered, such as sub-roof R-value or air exchange rates (ACH). This allows net sensitivity to roof A_{SOL} to be refined to include pair wise impacts which is very useful to know and utilise. What is interesting for these three parameters from our study is the different seasonal impacts of pair-wise and three-way correlations. For example we shall see that the way A_{SOL}'s influence is impacted by ACH and R settings in summer and winter are quite distinct. Such information helps find the most attractive ways of achieving maximum total savings to be pinpointed more accurately. The alternate approach using the matrix of data involves statistical analysis, ranking and grouping parameters according to the outcomes of interest. The spread of possible energy outcomes in the climate zone of interest links to single parameter and factorial sensitivities. Using the matrix elements directly is better when the number of variables is large. This approach is well established in other multi-parameter contexts such as land surface sensitivity of global climate models [10,11] and industrial experimentation [12]. Energy outcomes can be ordered and mapped against parameters in each season and over a year. In this introductory report we use the direct sensitivity or rate of change approach since only three parameters are varied;