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An energy-balance model for the optimal design of tall office buildings

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Abstract: Energy efficiency differs by building use and type as well as prevailing climatic conditions. This study examines the energy efficiency of tall office buildings in a Mediterranean climate by developing an energy balance for a typical level (or storey) of the building that may be of any form or style. The availability of, and ability to harness, renewable energy in the form of wind and solar power contributes positively to the balance against energy consumption. The latter includes the contributions of a variety of technologies used to support the working environment. These range from traditional constructions through to modern energy-efficient designs of building form and systems. The model that results has the potential for widespread use as a design tool that can be integrated with the architectural and construction-based execution of building projects.

In order to quantify efficiently the effects of a large number of parametric permutations that characterise different building forms and systems, mathematical modelling and simulation are adopted to construct a virtual prototype for each building and its associated systems. Modelling programs are used to calculate the building-energy loads resulting from solar gains and occupancy, while Computational Fluid Dynamics (CFD) is used to assess detailed air flow within the building, wind patterns and pressure profiles which may be harnessed to provide supplementary energy to the building.

Parameters assessed for their impact on the energy consumption for each typical level include: the floor-plate geometry; façade construction; glazing positioning; fixed and operable shading devices; various Heating Ventilation and Air-Conditioning (HVAC) systems; building-management profiles and occupant comfort-tolerance bands. These parameters are varied to assess their impact on the energy consumption of the building over a typical reference year while maintaining occupant usability ratings such as availability of daylight, temperature and comfort bands within acceptable limits.

The results of the study indicate that the appropriate selection and optimisation of building form, HVAC system, and shading devices can significantly reduce building energy consumption with little or no additional cost to the overall project. By considering opportunities to harvest renewable energy sources such as solar and wind and integrating these with modern building systems, a cross-over point can be reached where energy consumption for a given floor area balances the harvestable renewable energy for each typical level. The results of these investigations can be used to optimise and maximise the area of the floor-plate which may yield an energy and carbon-neutral outcome while maintaining occupancy comfort limits.

Keywords: *Green building, optimisation, energy balance*

1. INTRODUCTION

Sustainable or “green” buildings are developments which focus on the efficient use of resources throughout their design, construction and operation. The desired outcomes, as defined by the United States Office of the Federal Environmental Executive (OFEE, 2003) are to: a) increase the energy efficiency with which buildings and their sites use energy, water and materials; and b) reduce the impact of human health and the environment through better siting, design, construction, operation, maintenance, and removal throughout the complete life-cycle. Although green building design has become increasingly popular over the past decade or so, the origin may be traced back to the late 19th century.

The most obvious direct benefit of green building design is to reduce energy and water consumption as well as waste and landfill generation. In 2006, the US Department of Energy (DOE, 2007) reported that buildings consumed 40% of the energy in the United States and 12% of the water. Buildings are also attributed to generating up to 40% of air emissions and 40% of waste that goes to landfill. The importance of reducing these figures has been highlighted by the recent encouragement of the Australian and United States federal governments to improve insulation in residential housing. Further to this, an aspect of green building which is often overlooked is that “Green Buildings” often provide a more pleasant environment and promote good health. There is evidence by (HeathCanada, 1993) that providing higher levels of natural ventilation, increased daylighting levels, reduced volatile compounds, and cycling or alternative transport facilities have definite health benefits in reducing sickness such as sick building syndrome.

This paper presents the methodology and some preliminary results from a study that is being conducted into using a combination of computer modelling and an evolutionary non-linear optimisation algorithm to assist in the holistic development of green building design in the early stages. Existing computational fluid dynamics (CFD) and energy modelling packages are used to assess the energy availability due to wind and solar. This available energy is balanced with the energy required to maintain a set indoor environment quality. This energy balance, constrained with the requirements to maintain set internal conditions, yields a complex multiple-input-multiple-output optimisation problem which has application in the early design stages of a building project.

There have been many previous related studies on the optimisation of green buildings using a variety of optimisation algorithms. For a thorough review refer to (Wang et al., 2005).

1.1 The anatomy of a green building

There are other factors to consider beyond simple energy and water efficiency in the design of a building in order for it to be considered sustainable. Figure 1 shows some of the categories that are used in the “Green Star” rating tool (GBCA, 2008) which is a voluntary tool developed by the Green Building Council of Australia for the rating of sustainability of commercial office buildings in Australia. In this rating tool, water and energy efficiency only make up a few of the categories on which the building is assessed.

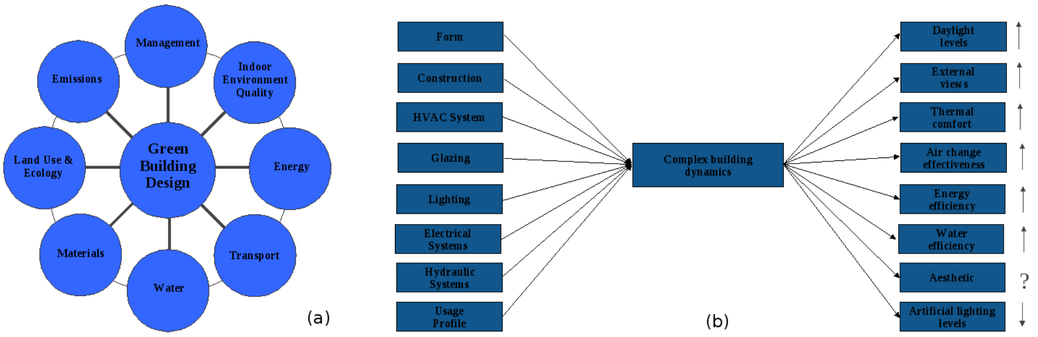

Figure 1: a) Categories used to assess green building design from the Australian “Green Star” rating tool (GBCA, 2008). b) some of the input parameters and measurable outputs in the design of a building.

Categories such as Management recognise that even a well designed building can perform poorly if it is poorly managed such as: leaving the air temperature set point too low; leaving windows and vents open with air conditioning on, etc. The transport category recognises the potential to reduce emissions through site location, provision of cycling facilities, small car and motorbike parking and proximity to public transport.

The “Indoor Environment Quality” (IEQ) category recognises the fact that Green Buildings cannot be truly sustainable unless its occupants are comfortable and satisfied with the environment in which they reside. This category establishes metrics for the assessment of indoor conditions on occupant health and comfort. Measurable conditions such as temperature and humidity, radiation, air velocity and movement contribute towards a predicted mean vote (PMV) which attempts to assess human occupant comfort. Other parameters such as penetration of natural daylight and proximity to external views are important metrics for assessing occupant comfort.

1.2 Green building features

Modern day green building design is seeing a return towards passive design features which take advantage of naturally available energy to offset artificially generated energy requirements. Passive design features are able to use naturally available renewable energy resources without the inefficiencies of energy conversion through active systems. For example, the simple use of skylights within a building is generally a more efficient means of lighting a space than using active systems to convert available outdoor solar energy into electricity that may then power internal lighting equipment.

That said, there are many cases where actively harnessing and storing renewable energy is the only practical means. This is often the case with wind energy where, aside from use in a passive flow-through system, that energy would otherwise be wasted without harvesting with a wind turbine. Many modern building designs use a combination of passive and active systems to harness the maximum of renewable energy that may be available on site.

Typical features which are included in current green buildings include: operable louvres; skylights; high efficiency air conditioning systems; the use of phase-change materials; integrated wind turbines and photovoltaics; increased outdoor (fresh) air supply and optimised facade construction and glazing selection.

1.3 Numerical modelling in building design

Numerical modelling is a central tool in the design of green buildings. Physical prototyping in the building industry is prohibitive in time and expense, therefore computer modelling is commonly adopted to model the various components of these buildings and adjust the design accordingly.

Generally on a large development there will be many members on a design team who all use various systems, packages and methods to achieve their part of the design. Communication and knowledge-sharing between all members of the design team is essential and generally laborious. This paper presents the initial work in the development of an holistic design tool which may be adopted in the early design phases to efficiently inform the team of the optimal broader design strategy.

2. IDENTIFICATION OF THE OPTIMISATION PROBLEM

Figure 1(b) summarises a few of the inputs and measurable outputs that may be considered in the design of a building. There are many factors beyond simple building shape and orientation which all contribute simultaneously to the outcomes. It is a complex Multiple-Input Multiple-Output optimisation problem.

Currently, the optimisation of this complex system is performed manually through the design phase of the building. Individual aspects of the design are generally handled by many different people throughout the process such as hydraulic, structural, mechanical and electrical engineers and architects. This process is very labour intensive which leads to only a few design iterations being performed prior reaching final design solution. Input and output parameters may be influenced by multiple disciplines and changes made to optimise one outcome (such as increase daylighting and reduce artificial lighting) may penalise another design aspect (such as ventilation system energy consumption).

The work presented in this paper combines some of these analytical tools in the framework of a non-linear optimisation algorithm. The initial model explores the variation in a few of the parameters defined in Figure

1(b) such as: glazing type; wall construction; and basic building floor plate geometry of a typical level of a tall office building.

3. MODEL CONSTRUCTION

The modelling described in this paper involves the combination of two simulation approaches and integration into an evolutionary optimisation algorithm to achieve an holistic design model. The two modelling approaches involved are: a) energy and solar modelling and b) computational fluid dynamics. These two approaches are described briefly below.

3.1 Energy modelling

Energy modelling is an important tool in building design used to determine solar loads and size air conditioning systems. The energy modelling software used adopted in this paper is the EnergyPlus software developed by the US Department of Environment. The EnergyPlus software is ideally suited for this type of development, as is noted in the documentation (DOE, 2008):

> It is intended to be the simulation engine around which a third-party interface can be wrapped. Inputs and outputs are simple ASCII text that is decipherable but best left to a GUI (graphical user interface). This approach allows interface designers to do what they do bestproduce quality tools specifically targeted toward individual markets and concerns. The availability of EnergyPlus frees up resources previously devoted to algorithm production and allows them to be redirected interface feature development in order to keep pace with the demands and expectations of building professionals.

EnergyPlus is used to assist in the calculation of: external solar loads on the building facade and glazing; thermal transport throughout the building zones; daylight factors within the internal space; and HVAC system energy consumption.

3.2 Computational fluid dynamics

Computational fluid dynamics (CFD) is used to calculate the wind pressures and wind energy availability on the exterior of the building. CFD may also be used to assess temperature and humidity distribution, detailed spatial comfort modelling, and air change effectiveness on the interior of the building, although this is noted for future work.

In this case, external flow modelling is handled by a simple boundary element method with solves for the potential flow around the exterior of the building form. This facilitates simple modification of geometry without the need for a complex mesh. However, it does lack in assessing pressure fields and wake dynamics in the lee of the building. Future work may involve incorporating grid-based finite-volume solution of the full Navier-Stokes equations through the open-source OpenFOAM CFD package.

4. EVOLUTIONARY OPTIMISATION

In varying even simple parameters such as wall construction, glazing type and building floor plate geometry there are a very large number of parametric variations which become possible. It is clear that conventional trial-and-error search methods are not suitable for dealing with the vast number of combinations possible. A Genetic Algorithm (GA) searches this space very efficiently to converge towards the optimal solution. The GA was selected over other optimisation techniques, such as steepest-gradient methods, for its: simplicity to implement in problems with a large number of independent variables; proven efficiency on problems with heavy non-linearity; and robustness at finding global maxima in problems where many local maxima may exist.

The field of GA's is vast and to derive the algorithm here is beyond the scope of this paper. Excellent reviews of GA's and their architecture may be found in Chambers (1995); Buckles (1992); Gen and Cheng (1997). Given that the architecture of a simple GA may be obtained from these references, only the evaluation of the score through the scoring function and a brief overview of the components of a GA will be described below. For brevity only the pertinent details that are common to most GA's are described here.

4.1 Elements of a GA

Genetic Algorithms are a stochastic non-linear search method that is based on the principles of natural selection or 'survival of the fittest'. It is a very effective method for finding the globally optimal solution (within a finite search space) for non-linear problems.

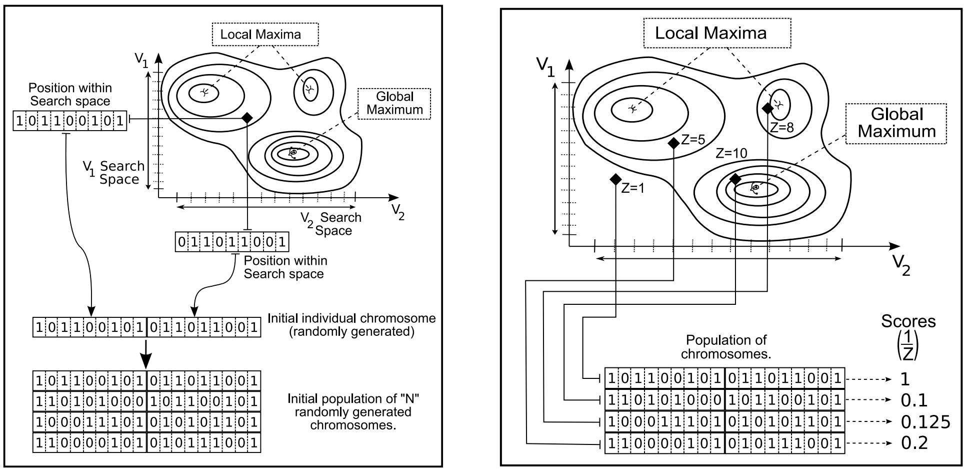

Figure 2: Left) Schematic diagram illustrating the development of an initial population of a GA for a two-dimensional problem. (Right) Schematic diagram illustrating the weighted scoring of individuals within one iteration (generation) of the GA optimisation.

A GA can be likened to a population of individuals, where each individual maintains a binary 'chromosome' that contains variable parameter information that is associated with a possible solution. This is depicted schematically for a two-dimensional problem in Figure 2. At each generation (iteration) of the GA, the older (parental) set of individuals is replaced with the newer (children) individuals. The life of a set of individuals in a generation then follows the following operations: translating the binary string (chromosome) of each individual into real variable parameter values; evaluation of the 'strength' of each individual; 'breeding' the individual solutions together to create a new generation of individuals; and mutation.

The translation of the binary string into variable parameter values is simply a matter of defining a number of bits to each variable, then performing a binary-to-decimal conversion of the groups of bits to give decimal parameter values. Evaluation of the strength of each individual is done through a scoring function by assigning a single numerical value to each individual. The score is obtained from the results of applying the variables of each individual to the non-linear function. The final process of 'breeding' the solutions together is done by preforming a random swap of bits in the binary string between two parents. The resulting 'children' carry with them some characteristics of the parents. The score of each individual from the scoring function is used to determine the *probability* of it breeding with another individual. Therefore, stronger solutions have a higher probability of breeding with other individuals and to carry good characteristics of the solution to future generations. Breeding is performed with binary strings by simply assigning probabilities that bits will be swapped between the two parents. Finally, to avoid solutions from converging towards a local maximum, it is important to assign a probability that each bit within an individual will be changed. This mutates some bits in some individuals and will place those individuals within other points of the search space where a stronger solution may exist.

This is only a general description of GA's. It is important to realise that there are many methods by which to perform each operation. Swapping of bits for breeding, assigning scores and selecting individual for breeding can be done in a variety of ways. For this investigation, very simple 'roulette wheel' type calculations are used to assign probabilities to each event. And, for simplicity, the GA used herein stayed true to the description above, adopting simple binary strings, simple scoring functions and uniform binary crossover for breeding.

4.2 The scoring function

Selecting an appropriate scoring function is often the most complex part of any non-linear optimisation problem. It is necessary to select a scoring function that is both robust and simply implemented. In this method, wind energy availability, solar energy availability, ventilation system energy consumption, and internal daylighting levels are measured throughout a simulation of the building over a typical Meteorological Reference Year (MRY). Various weightings may be given to the output (based on the designers wishes) and the relative energies are summed over the year-long simulation for the particular climate in question. The final resulting weighted year-long energy consumption is the final score which must be minimised.

5. PRELIMINARY RESULTS

Presented here are some preliminary results from the CFD analysis of the external wind conditions as well as solar energy availability at the facade and HVAC system energy consumption obtained through the EnergyPlus simulation package. Conservative assumptions were made regarding the construction of wall and glazing materials and efficiencies of using available energy. The MRY used in this case is based on the city of Perth in Western Australia, which is representative of a typical Mediterranean climate.

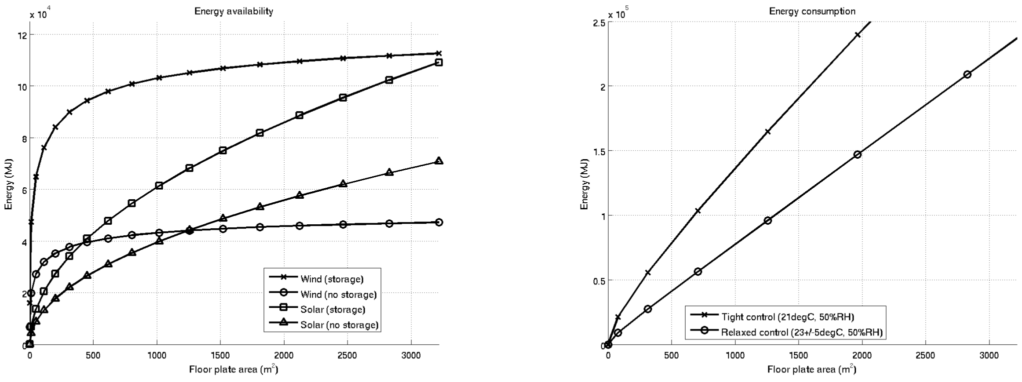

Figure 3: Left) Energy availability from wind and solar on the exterior of a typical level of a cylindrical building throughout the Reference Meteorological Year (RMY) and (Right) energy requirements with tight and relaxed air conditioning set-points throughout the RMY.

Figure 3 is a plot of the energy that is directly available to a typical level of a tall office building, that is, wind and solar (left) as well as energy requirements for heating and cooling and basic lighting and equipment needs (right). It is important to note that this analysis treats the the single level of a tall office building as a 'closed system' with simply 2 sources of energy (wind and solar) in a 2 dimensional context. While building integrated renewable energy harvesting may not be a practical, or even most efficient means of acquiring energy, the analysis of a tall office building in this sense reveals much of the passive design potential towards carbon neutrality regardless of whether renewable energy is finally harvested on-site.

The graph on the left indicates the energy availability due to solar and wind for a typical year with and without storage. On the abscissa is the net lettable area of the cylindrical building floor plate while on the energy availability, assuming conservative efficiencies for wind and solar harvesting potential, throughout a typical year is on the ordinate. It can be seen that as the building area increases and prevailing winds are forces around the perimeter of the building then energy availability due to wind within 3 meters of the facade increases toward a limit with increasing NLA. Conversely, as the building area, hence building surface area, increases then the available solar energy grows with the square root of the floor plate area.

The graph on the right indicates the energy required to condition and power the base-build using tight and relaxed control bands respectively. It can be seen that relaxing the temperature control set-point to allow a float of 5 degrees Celsius makes a significant difference to the air conditioning energy requirements year-round.

Putting the two curves of energy availability with and without storage over the top of energy requirements with and without tight control one can assess the carbon-neutral potential of the building in terms of net lettable area.

That is, the potential floor plate area of the building which has the potential to be carbon-neutral in operation.

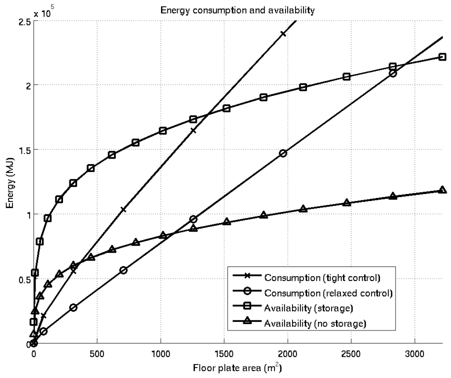

Figure 4: Total of Figure 3 shown plotted on the same axis for comparison.

It can be seen that by adopting energy efficient measures to condition the space with relaxed temperature comfort bands and integrating passive (or active) design features which make use of the naturally available energy resources with storage to capture overnight conditions then the carbon-neutral potential based on NLA is nearly 3000m2. This is a large floor plate area for commercial office buildings.

Conversely, the use of tight control bands along with use of available renewable energy without storage reduces this figure dramatically to less than 500m2. This would be considered a rather small floor plate area for a commercial office building.

6. CONCLUSIONS

A framework has been developed for the holistic analysis and optimisation of pertinent building properties that may be of use in the early design stages of a building project.

Preliminary results indicate that the method is capable of assessing energy consumption and availability using a combination of CFD and energy modelling packages. This establishes a basis for the optimisation problem once consideration of internal conditions such as daylight are incorporated into the weighted accounting of energy.

Preliminary results have shown that through adopting: a) passive design features which are able to harvest and store renewable energy at all hours of the day, even when unoccupied; and b) energy efficient features such as light fittings, HVAC systems and relaxed temperature bands, then the carbon-neutral potential of the building can be dramatically influenced.

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