OPTIMISING THE SOLAR ENVELOPE: UTILISING EVOLUTIONARY ALGORITHMS TO BALANCE SOLAR ENERGY AND DEVELOPMENT POTENTIAL IN AN URBAN PLANNING CONTEXT

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ABSTRACT

Solar energy systems are one of the most technically, operationally and economically viable renewable energy options available today. Despite high levels of installation, the overshadowing of solar panels by new developments in urban areas has emerged as a worrying problem for owners and a barrier to investment in small-scale solar energy generating assets.

In this study for the city of Melbourne, Australia, we have developed a methodology that attempts to find an optimal balance between maximising the development potential of land and protecting the solar access rights of surrounding properties.

Using Grasshopper, a visual programming tool, we have developed an optimisation methodology to enable decision makers and developers to navigate this balancing act of development versus solar access.

The report outlines a simplified methodology to create a set of solar envelope parameters that can easily be applied to proposed developments, and a number of case studies illustrating the application of those controls on real world examples.

The ultimate aim is to provide a solution enabling municipal bodies, businesses and residents to overcome barriers to installing solar and reduce the uncertainty around the continued efficacy of their solar investment.

INTRODUCTION

Historically access to sunlight and daylight has always been one of the key inputs of human urban forms. Ancient cultures practiced passive solar design in their buildings, in ancient Greece, and also in the United States in settlements such as the Acoma Pueblo, occupied continuously for over 1000 years (Knowles, 1974).

Knowles' concept was the solar envelope as a 3D surface on a given site that does not obstruct more than '*n*' hours of sun onto adjacent sites.

For the urban context in the City of Melbourne (CoM) the protection of solar access for energy generating assets such as photovoltaic panels was examined. New developments are not required to take into consideration the rights of adjacent properties to solar access for the purposes of energy generation.

There are no controls within the current Melbourne Planning Scheme that provide solar access guidance or constraints for the location of solar assets such as photovoltaics on buildings within the CoM.

This study investigates the calculation methodology for a solar envelope that aims to balance access to radiation for energy generation and development potential. An optimum solar envelope model is proposed that defines a set of parameters and built controls that can be used to guide the form of developments such that this balance is achieved. The following sections outline the approach used to calculate these parameters, and test them on 4 case study locations in the CoM.

CREATING THE SOLAR ENVELOPE

A solar envelope component for 'Grasshopper' (Vasanthakumar, 2013) based on Knowles' methodology was used to generate the solar envelope within a 3D model for our investigation sites. It is based on Knowles' methodology.

The module inputs are the envelope boundary, required hours of daylight and a month range for carrying out the calculations.

The monthly range investigated was from Winter Solstice on June 21 to Summer Solstice on December 21. This ensures that the envelope model covers the critical high and low points of the sun's movement over the year.

The solar envelope module calculates a solar envelope for the site for each of the specified dates. The resultant envelopes are then combined by Boolean intersection which solves for the maximum volume which will not cast a shadow between these times.

The solar envelope was compared against the maximum potential development envelope for the site.

SOLAR ENVELOPE DATA INPUTS

Calculation Height

The calculation height for the solar envelope is a parameter that is particular to each planning zone or area of similar maximum building height.

The calculation height has an impact on the solar envelope extents as the building areas beneath the height cut off are excluded from the calculation and hence may be shaded with no controls. A range of heights were considered to allow application of the model in high rise environments.

Boundary Offset

The boundary offset is a parameter that allows the model to manipulate the solar envelope extents beyond neighbouring buildings' cadastral boundaries.

Building Boundaries

Cadastral data and CoM building information was used as the basis for the solar envelope boundary line calculations.

ANALYSIS STRUCTURE AND SOFTWARE

The calculation methodology used is based on an open source, publically available and industry recognised method of sky calculation that is capable of simulating the effects of solar radiation distribution throughout a city.

The structure of the analysis carried out was as follows:

1. 3D model of CoM provided by CoM was processed and viewed in 'Rhinoceros' , a 3D geometry editor and complex algorithm modeller
2. 'Diva for Rhino' plug-in to Rhinoceros used as the platform to carry out solar radiation analysis on the 3D model
3. 'Grasshopper' plug-in to Rhinoceros used to create the geometry of the solar envelope for test sites, based on editable parameters
4. 'Galapagos' plug-in to Rhinoceros to automate optimisation of the solar envelope geometry and drive the radiation analysis by iterating between the output of 'Diva for Rhino' and the geometry generator in 'Grasshopper'

'Diva for Rhino' uses the software package 'Radiance' for its analysis.

Diva for Rhino and GenCumulativeSky

Diva for Rhino is a collection of tools developed by the Massachusetts Institute of Technology to carry out detailed analysis in the built environment.

The GenCumalativeSky, described by Robinson & Stone in 2004, generates a cumulative sky by adding up multiple individual sky conditions for any given period. The sky is divided according to the Tregenza scheme (Tregenza, 1987) and Perez luminance distribution model (Perez et al, 1993). The GenCumulativeSky method is incorporated in the 'Diva for Rhino' plugin. The GenCumulativeSky method combined with the overshadowing capability of Diva provides an accurate calculation methodology with fast processing times.

BASELINE METHODOLOGY

A model was created in Rhinoceros to test the solar envelope and its effects on neighbouring properties. A grid layout of representational rooftops was created to represent a central empty block where our test 'development' would be placed with surrounding buildings on each axis. Figure 1 shows the property grid and initial geometry with plot alignment running North-South.

An analysis of solar radiation on the roofs of all the properties without the new development was carried out to provide baseline solar radiation levels.

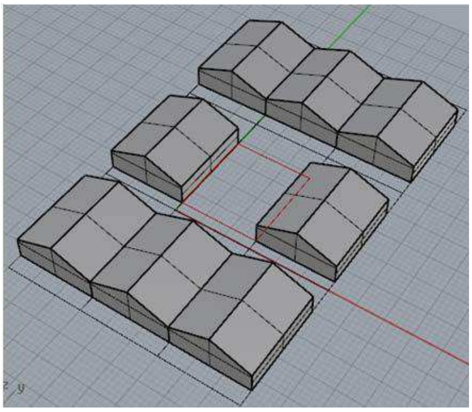

Figure 1 – Simple single storey buildings with central empty block ready for development

Creating the solar envelope "development"

The grid resolution for the solar radiation study was set to 1m^2 pixels.

This study investigated the solar envelope for 5 hours of uninterrupted direct light from Jun 21 – Dec 21, encompassing the shortest and longest days of the year and hence guaranteeing 5 hours for each day of the year.

Defining the envelope boundary

Firstly the envelope geometry at the ground plane is defined by the property boundary or building footprint.

Scondly the envelope is offset from the specified boundary, dependant on orientation. As this offset represents the most significant constraint on development potential, it is necessary to optimise this value to obtain a balance between solar radiation and the potential for development. For example, the initial offset for south facing elevations is based on CoM "Rescode" controls that protect existing north facing elevations. This offset is 3m.

Finally the envelope calculation height above ground level is defined. As this study is focussed on protecting the access to radiation for solar assets, this parameter addresses solar energy installations being at roof level and not on the ground.

These heights have been based on CoM Rescode guidance material and vary based on planning zone and building classification.

SOLAR ENVELOPE OPTIMISATION

To investigate multiple variations of the solar envelope and define the optimal combination an evolutionary algorithm solver was used.

This solver is called 'Galapagos' and is a plug-in to Grasshopper. It operates by applying a simulated method of natural selection of a geometric model to arrive at an optimal solution.

It works by altering a number of input parameters, or 'Genes', which form the basis of our model and then examining the result of a particular ratio, the 'Fitness' value. Rutten explains as follows:

"The fitness landscape takes place in the phase space which is created by the input parameters. The fitness landscape is an extrusion of the phase space. The higher the value on the fitness landscape the more fit it is, the lower the value the less fit it is. The fitness landscape is unknown and it's the job of the generic solver to find the highest peak on the fitness landscape by producing multiple generations. The generic solver does this by populating the landscape with random values of genomes. The genome values are then accessed; the higher on the landscape the better. The lower genome values die off while the higher genome values repopulate. The second generation genomes are created to find even higher values on the fitness landscape. This process of creating fitter generations of genomes continues until the highest peak is found."(Rutten, 2013)

For this model investigating the effect of a solar envelope model on available solar radiation to neighbouring assets, the genes are the calculation parameters for the solar envelope:

- Boundary offset
- Calculation height of the envelope

The maximum fitness value is given to the envelope solution that maximises both the radiation and the volume of the solar envelope.

To realise optimum solutions modifiers and penalties are used to affect the fitness outcome once the results go outside a desired realm.

For this project we used the following modifiers:

- Post-development Radiation Ratio Lower Limit of 85%
- Ratio of Solar Envelope to Maximum Developable Volume of 50%
- The importance of Radiation versus Development in the fitness values was 50%.

A baseline radiation study of an area was run the compared to the 'post-developed' state, represented by the solar envelope placed on the site. This shading reduction was then used as an input parameter for the evolutionary solver algorithm for envelope optimisation.

This optimisation process was carried out for every orientation and alignment of site to identify the optimum solar envelope to developable volume ratio.

Aggregate Optimum Envelope

The optimum solar envelope is the envelope that enables the largest volume of development to occur while protecting the greatest level of solar radiation access to the surrounding properties.

A Boolean intersection of the different envelopes was used to give a total developeable volume for the optimum solution.

SOLAR ENVELOPE CONTROLS

The solar envelope controls identified in this study are defined by the boundary of the proposed development site, the required offset from the boundary (x) and distance above ground level for the solar envelope calculation (h).

From these controls an orientation-specific vector angle (θ) is used to project the envelope boundary to form a 3-dimensional aggregate solar envelope.

The boundary offset (x) is described in Figure 2.

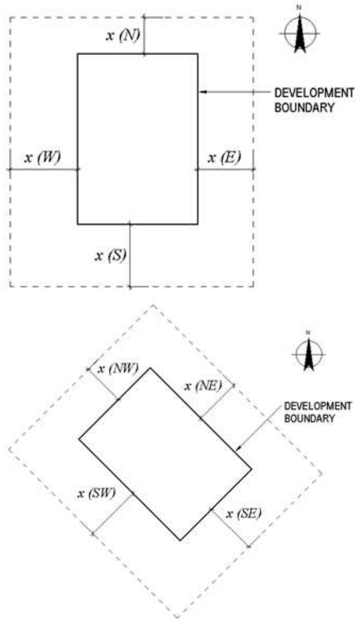

Figure 2 – Boundary Offset

An orientation specific offset and height is given for each boundary element, and then a line is drawn from this point at the vector angle specific to that orientation (Refer to Figure 3 & Figure 4). A plane is formed for each boundary orientation and the intersection of these planes defines the envelope.

The individual orientation-specific solar envelopes and the formation of the aggregate solar envelope are illustrated in Figure 5.

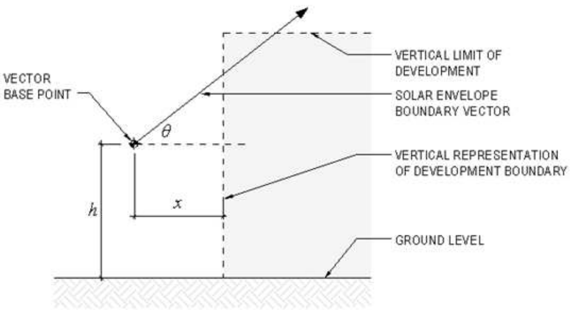

Figure 3 – Solar Envelope Calculation Height (h), Offset (x) & Vector Angle (θ) Example 1 of 2

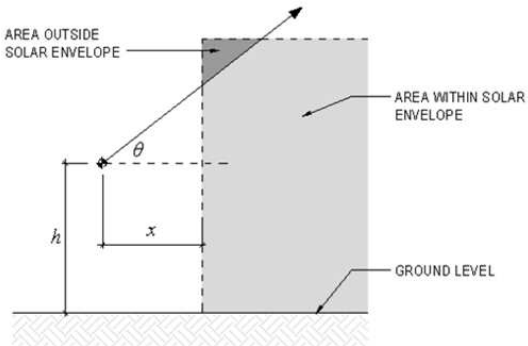

Figure 4 – Solar Envelope Calculation Height (h), Offset (x) & Vector Angle (θ) Example 2 of 2

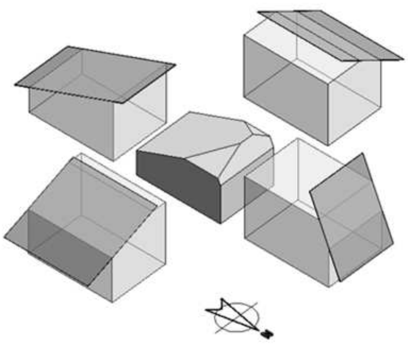

Figure 5 – Aggregate Solar Envelope Example

RESULTS FROM THE OPTIMUM SOLAR ENVELOPE

The following tables contain the parameters extracted from the optimum solar envelope model for use in the solar envelope control calculations.

Table 1 – Solar Envelope Vectors

BOUNDARY ALIGNMENT	VECTOR ANGLE (Θ)
N	98.48
NE	71.27
E	30.02
SE	19.31
S	23.44
SW	20.01
W	31.59
NW	68.11

Solar Envelope Parameters for Buildings up to 13.5m

The following tables show the Solar Envelope Calculation Height (*h*) and Offset (*x*) values for buildings up to 13.5m. The critical value for each site alignment has been highlighted.

Table 2 – Calculation Height for Buildings up to 13.5m

SITE ALIGNMENT	N-S	E-W	NW-SE	NE-SW
N ENV. (*h*)	13.5	13.5	13.5	13.5
S ENV. (*h*)	13.5	3.6	13.5	13.5
E ENV. (*h*)	8	13.5	13.5	13.5
W ENV. (*h*)	9	13.5	13.5	13.5
NW ENV. (*h*)	13.5	13.5	13.5	13.5
NE ENV. (*h*)	13.5	13.5	13.5	13.5
SE ENV. (*h*)	13.5	13.5	13.5	6.9
SW ENV. (*h*)	13.5	13.5	6.9	13.5

Table 3 – Boundary Offset for Buildings up to 13.5m

SITE ALIGNMENT	N-S	E-W	NW-SE	NE-SW
N ENV. (*x*)	0	0	0	0
S ENV. (*x*)	0	0	0	0
E ENV. (*x*)	0	0	0	0
W ENV. (*x*)	0	0	0	0
NW ENV. (*x*)	0	0	0	0
NE ENV. (*x*)	0	0	0	0
SE ENV. (*x*)	0	0	0	3
SW ENV. (*x*)	0	0	3	0

Solar Envelope Parameters for Buildings 13.5m to 21m

The following tables show the Solar Envelope Calculation Height (*h*) and Offset (*x*) values for buildings 13.5 to 21m. The critical value for each site alignment has been highlighted.

Table 4 – Calculation Height for Buildings 13.5m to 21m

SITE ALIGNMENT	N-S	E-W	NW-SE	NE-SW
N ENV. (*h*)	21	21	21	21
S ENV. (*h*)	21	13.5	21	21
E ENV. (*h*)	17.5	21	21	21
W ENV. (*h*)	17.5	21	21	21
NW ENV. (*h*)	21	21	21	21
NE ENV. (*h*)	21	21	21	21
SE ENV. (*h*)	21	21	17.5	13.5
SW ENV. (*h*)	21	21	13.5	17.5

Table 5 – Boundary Offset for Buildings 13.5m to 21m

SITE ALIGNMENT	N-S	E-W	NW-SE	NE-SW
N ENV. (*x*)	0	0	0	0
S ENV. (*x*)	0	0	0	0
E ENV. (*x*)	0	0	0	0
W ENV. (*x*)	0	0	0	0
NW ENV. (*x*)	0	0	0	0
NE ENV. (*x*)	0	0	0	0
SE ENV. (*x*)	0	0	0	0
SW ENV. (*x*)	0	0	0	0

CASE STUDIES

The following case studies were carried out to investigate the effectiveness of the optimum solar envelope parameters on real world cases and to investigate the impact of theoretical new developments in the case study locations.

Case studies were carried out for the following sites:

1. 436 Lygon Street, Carlton
2. Kensington Business Park
3. 278 Rosslyn Street, West Melbourne
4. 413 Macauley Road, Kensington

These locations have been chosen with CoM to provide an indication of the performance of the solar envelope controls across a range of building typologies and development zones.

The case studies investigate the effect of the following scenarios on the solar radiation resource:

- Pre-development baseline modelling for adjacent properties
- New development constructed using the proposed solar envelope controls

For Case Study 4 – 413 Macauley Road Kensington we present more detailed results and imagery.

Case Study 1 – 436 Lygon Street, Carlton

- This case study was located in a residential area with heritage overlay
- The maximum height for the zone is 9m
- Site orientation is E-W

Table 6 – Site 1 Results

PARAMETER	VALUE
Site Orientation	E-W
Envelope Boundary Offset	10m
S Neighbour Radiation reduction	**0%**
N Neighbour Radiation reduction	**0.2%**
Aggregate Envelope Volume	2583 m^3
% of Total Developable Volume	**98%**

The proposed solar envelope controls for the southern boundary of the site have successfully prevented the reduction of the southern neighbour's annual solar resource.

As expected, the northern neighbour experiences very little reduction in solar radiation, with the development height set to the maximum allowable as per the north boundary envelope controls.

Case Study 2 – Kensington Business Park

This case study was carried out to investigate the solar resource available at the Kensington Business Park site. The site consists of recently constructed buildings and would be a good candidate for a solar farm.

The effect of a theoretical 5-storey commercial development on part of the site was investigated.

Table 7 – Site 2 Results

PARAMETER	VALUE
Site Orientation	E-W
E Neighbour Radiation reduction	**1%**
S Neighbour Radiation reduction	**0.5%**
Aggregate Envelope Volume	35984 m^3
% of Total Developable Volume	**72%**

Case Study 3 – 278 Rosslyn Street, West Melbourne

- The West Melbourne case study was chosen due to its location in a Mixed Use Zone.
- Maximum building height of 4 storeys
- Buildings in excess of maximum height limit have been permitted in this area

Table 8 – Site 3 Results

PARAMETER	VALUE
Site Orientation	NW-SE
NE Neighbour Radiation reduction	**7%**
SW Neighbour Radiation reduction	**9.5%**
NW Neighbour Radiation reduction	**0.5%**
Aggregate Envelope Volume	1984 m^3
% of Total Developable Volume	**70.9%**

The results for this case study correlate with the optimal envelope results. The NE and NW neighbours experience less than 7% and 1% reduction in annual radiation respectively.

The solar envelope controls applied to the SW neighbour resulted in 9.5% reduction in annual radiation, however the aggregate envelope volume suffered a 30% reduction compared to the total potential site volume. The optimal balance between radiation protection and the maximisation of buildable volume requires further investigation.

Case Study 4 – 413 Macauley Road, Kensington

- Proposed maximum height of 20m
- Site orientation N-S
- Surrounding buildings predominantly single storey
- Chosen for more detailed analysis due to higlighting limitations of the model

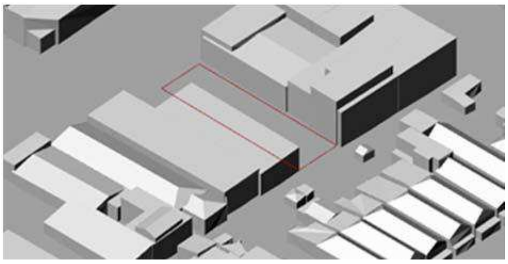

Figure 6 – Case 4 Model Context

Table 9 – Site 4 East Neighbour Results

PARAMETER	VALUE
Site Orientation	N-S
Envelope Boundary Offset	0m
Envelope Calculation Height	17.5
Maximum Building Height	20m
Predevelopment Radiation	805.4 kWh
Post-development Radiation	651.0 kWh
% of Predevelopment	**80.8%**

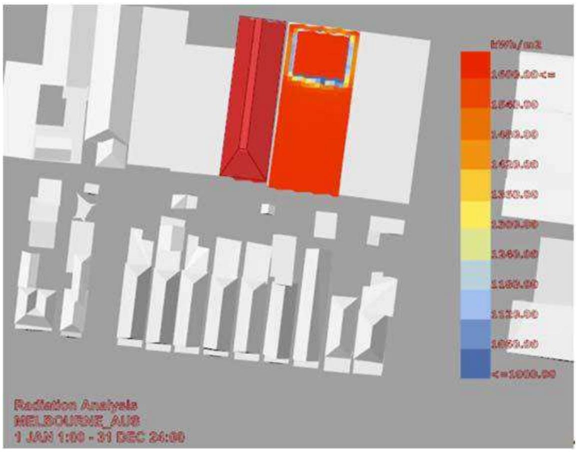

Figure 7 – Case 4 East Neighbour Predevelopment Radiation

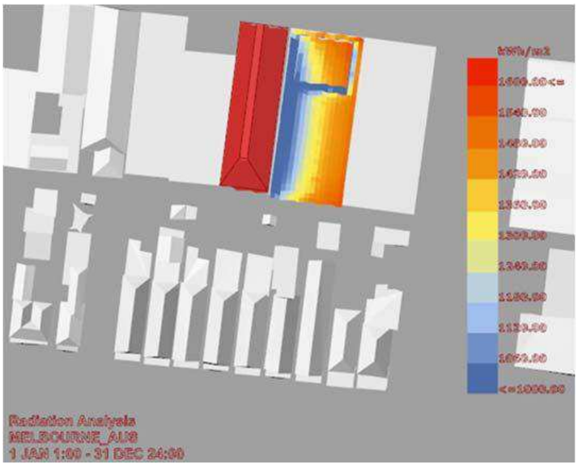

Figure 8 – Case 4 East Neighbour Post-development Radiation

The impact of the proposed development utilising the solar envelope built form controls clearly has an impact on the annual radiation falling on the roof surface of the East neighbour. The site typology for this case study highlights a limitation of the simplified envelope model for sites that have elongated shapes.

Table 10 – Site 4 West Neighbour Results

PARAMETER	VALUE
Site Orientation	N-S
Envelope Boundary Offset	0m
Envelope Calculation Height	17.5m
Maximum Building Height	20m
Predevelopment Radiation	421.7 kWh
Post-development Radiation	301.1 kWh
% of Predevelopment	**71.4%**

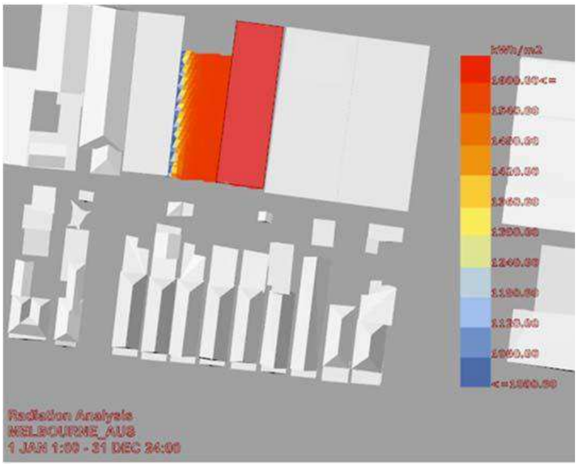

Figure 9 – Case 4 West Neighbour Predevelopment Radiation

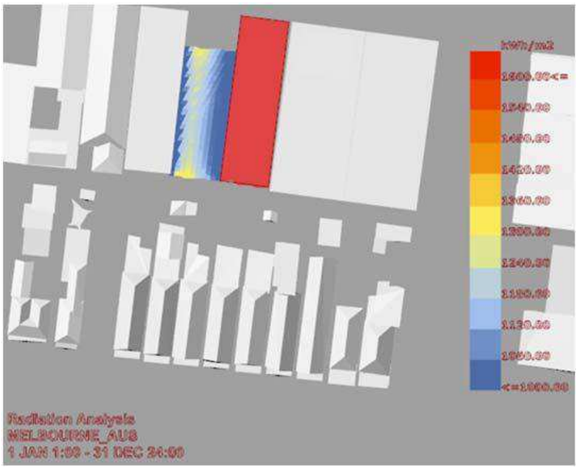

Figure 10 – Case 4 West Neighbour Post-development Radiation

For the West neighbour the overshadowing is more pronounced as there is a greater height differential between it and the proposed development under the proposed envelope controls. This highlights the need to investigate the adjustment of the envelope methodology to drive geometries via height differential rather than absolute building height, which would provide a more rigorous and adaptable tool.

Table 11 – Site 4 South Neighbours Results

PARAMETER	VALUE
Site Orientation	N-S
Envelope Boundary Offset	0m
Envelope Calculation Height	20m
Maximum Building Height	20m
Predevelopment Radiation	1554 kWh
Post-development Radiation	1520 kWh
% of Predevelopment	**97.8%**

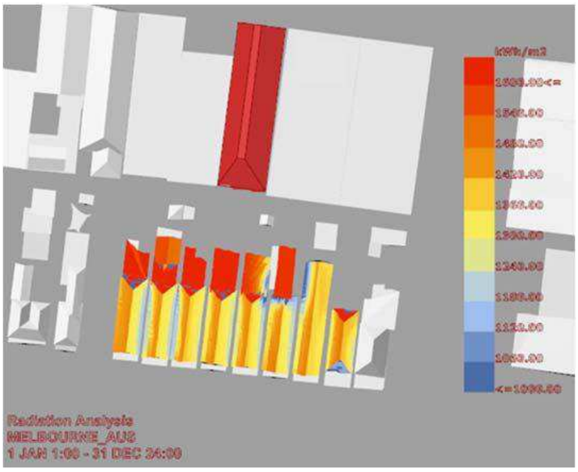

Figure 11 – Case 4 South Neighbour Pre & Post-development Radiation

The result for the South neighbours was a minimal reduction in annual radiation levels. In this case study this is primarily due to sufficient setback of existing buildings from the proposed development to avoid adverse impacts.

Table 12 – Site 4 Aggregate Envelope

PARAMETER	VALUE
Aggregate Envelope Volume	6430 m^3
% of Total Developable Volume	**94.8%**

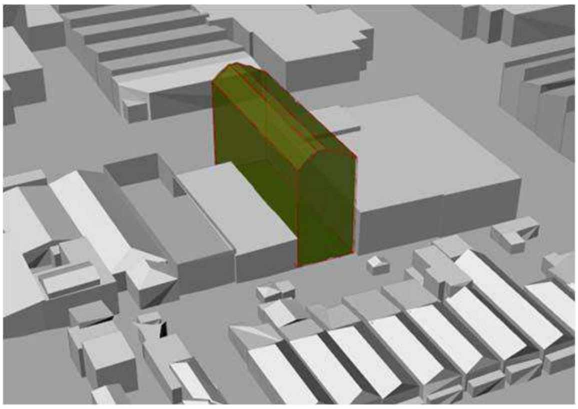

Figure 12 – Case 4 Aggregate Envelope Form

MODEL LIMITATIONS & IMPROVEMENTS

Narrow and long sites

Reductions in radiation for these sites was observed to be larger than for more uniformly shaped sites. This is due to the larger comparative impact on radiation on the site because of disproportional overshadowing when compared to a more 'squarely' shaped site.

Tall Buildings

Buildings over 21m in height could not be solved to determine a unique optimal solution for the envelope calculation parameters. As the height differential increased between the proposed development and the surrounding buildings, the algorithm became much less effective and the reduction in developable volume required to prevent small decreases in annual radiation was prohibitive.

The results suggest height differentials have a significant influence on the optimal balance and must be studied in detail in order for these proposed controls to be fair and useful to the industry.

Balancing Act

The critical area of future work needed is finding the balance between the potential for development and the degree of protection for solar assets to be provided from an economic perspective. Value could be found in studying the impacts of restricting developments versus the benefits of protecting small-scale solar energy generation.

PLANNING POLICY IMPLICATIONS

Development of *area specific* schedules which sit under the Design and Development Overlay planning instrument would appear to be the most appropriate planning tool in which to provide design guidelines / built form objectives to building designers where a planning permit is required for buildings and works.

Development of a local planning policy which gives rise to greater consideration of solar access which would in turn support the formulation of new schedules to the Design and Development overlay is recommended. This planning mechanism will provide guidance to built form outcomes in a manner which is then afforded statutory weight.

CONCLUSION

The simplified solar envelope methodology and methodology described and tested in this study aims to protect access to solar radiation of existing buildings from potential developments that may otherwise reduce their energy generating potential.

The optimal solar envelope found in the study varies depending on site orientation and maximum building height. Generally the model limits the reduction in solar radiation to 15% of predevelopment levels and aims to balance this with as large a developable volume contained within the solar envelope as possible.

It was found that as building heights increase beyond 13.5m, the optimal solar envelope as defined by the evolutionary solver used for this study, resulted in a reduction of radiation for neighbouring buildings. This highlights that building height alone is not the most important factor to examine but rather, the height differential of the surrounding buildings may be more useful to examine in future work.

When the proposed building controls were tested on the 4 case studies, the model performed well and results were numerically similar to those presented by the envelope optimisation process of the simple baseline model.

The results suggest that building form and its geometric relationship to surrounding buildings have the greatest impact on solar assets. As the solar envelope is based on the physical typology of a site, the actual building type is not relevant. Its physical size, orientation and alignment with other buildings is more important than if it is commercial or residential building for example

This study has shown that it is possible to develop a set of simple built form controls that is based on a large body of complex analysis, for specific orientations and building heights.

ACKNOWLEDGEMENTS

The author wishes to thank the staff at the City of Melbourne for their assistance, data sources and the opportunity to carry out this study.

This study was carried out under a professional consultancy agreement between GHD Pty Ltd and the City of Melbourne.

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