Designing with Phenology: Tree Canopy Dynamics and Its Effects on Solar Exposure for a Residential Building

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Abstract: Trees and other vegetal materials are an integral component in urban or suburban environment, particularly in the residential landscape. In the literature, there are numerous studies on the roles that street trees and/or residential gardens play in shaping neighbourhood character, enhancing property value, mitigating urban heat island effect, and improving carbon sequestration of terrestrial ecosystems. However, these studies are mostly in a general sense and at relatively coarse spatial and temporal scales. In this study, spatially explicit models are developed to simulate the effects of tree phenology and the associated tree canopy dynamics on regulating solar exposure and natural thermal comfort in a typical residential building in Melbourne, Australia. Tree canopy dynamics are investigated and applied to simulate seasonal solar exposure and indoor temperature variations in a parametric environment. The outcomes from this study can be used to guide landscape planting design aiming at not only providing conventional ecosystem services but also reducing household energy consumption for heating and cooling, which will have enormous implications in landscape design in an era of climate change.

Keywords: Tree phenology, solar radiation, parametric modelling, climate change

1 Introduction

As the largest per capita emitter, Australia's energy supply heavily relies on fossil fuel. In Australia's energy mix, solar energy accounted for 2.4 % of all renewable energy use and around 0.1 % of primary energy consumption in 2007-2008 (BAHADORI & NWAOHA 2013), despite CSIRO (Commonwealth Scientific and Industrial Research Organization) predictions that 30 % of Australia's energy supply will come from solar power by 2050 (CSIRO 2012). Currently 50 % of Australia's GHG emissions result from electricity generation using black or brown coal (YUSAF et al. 2011). As Australia's population, as well as that of the world, continues to grow and live increasingly energy dependent, the future of energy supply is growing. In 2010, buildings across the world were responsible for 32 % of the global final energy use and 19 % of all greenhouse gas emissions (IPCC 2014). The transition from fossil fuel to renewable energy will have profound implications on our current endeavours in tackling carbon emissions and climate change.

Energy used for heating and cooling is the largest component among all energy uses (including cooking, lighting, hot water, appliances, whitegoods, etc.) in an average household in Victoria (SUSTAINABILITY VICTORIA 2014). Therefore, residential landscape design that facilitates harnessing renewable energy will be desirable. This paper seeks to ask basic questions in residential landscape design. Can tree plantings in the residential landscape be designed to improve the energy performance of the residential building? If so, what is the energy implication in the best possible residential landscape in terms of planting design for the sake of maintaining thermal comfort while minimizing household energy consumption?

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2 Methods and Workflow

In a parametric environment, trees phenological dynamics are used to simulate seasonal solar exposure of a residential building. Solar gain is widely recognised as the major natural regulator for indoor temperature and for natural thermal comfort.

2.1 Tree Phenology and Canopy Dynamics

The term phenology is derived from the Greek word *phaino*, meaning to show or appear. Plant phenology refers to recurring, seasonal plant life cycle stages, such as bud burst, flowering and leafing (SCHWARTZ 2013). Tree phonological timing and relationships with weather and climate provides opportunities to design with phonologies for low energy footprint housing.

2.2 Selection of an Ideal Tree Species

Deciduous trees are considered to differentiate the impacts of tree phonological stages on solar exposure. To facilitate the computational work, one single Golden Elm (Ulmus Glabra Lutescens) tree is used for simulating its solar filtering effect. That fact that it is a medium-sized, fast-growing deciduous tree makes it ideal for this study. Other information regarding this species is listed in Table 1.

Table 1: Golden Elm Factsheet

Size	Medium – large (max height 18-20 m, max canopy 20-25 m)
Form	First years vase-shaped, spreads as it matures to form a rounded canopy
Uses	Wide spreading, with golden foliage that provides good shade. Leaves are a bright green that turn a brilliant yellow in autumn. Provides good foliage contrast in larger gardens and parks. Adds great colour scheme in autumn and lovely filtered light in summer.
Position and Soil	Tolerant to a wide range of conditions (wind, salt, frost, sun), grows in cool, temperate or subtropical climate, but prefers moist, well drained soils in full sun
Other	Driveways & avenues, street tree, yard. The tree is normally grafted onto a rootstock; pruning not required

Evergreen species are commonly found in Victorian suburbs in the residential landscape either as street tree plantings or in households' private yards. However, evergreen trees are not used in this study because the lack of explicit morphological changes including less significant canopy dynamics in different seasons of the year.

2.3 Three-dimensional (3D) Tree Simulation

The geometry of nature (such as trees) displays fractal-like properties, which makes it possible to create digital 3D tree using algorithm such as Lindenmayer System (L-system). The well-established L-system provides a convenient theoretical and programming framework for modelling dynamic plant architecture (LINDENMAYER 1968; KURTH 1994). The 3D tree model presented in this paper used the L-system formalism and was implemented using the Rabbit plugin (L-System) in the Grasshopper (PAYNE & ISSA 2009) program, an increasingly popular add-in tool of the Rhinoceros software (COOK 2008). The relationship between various tools used in this study is shown in Fig. 1 below.

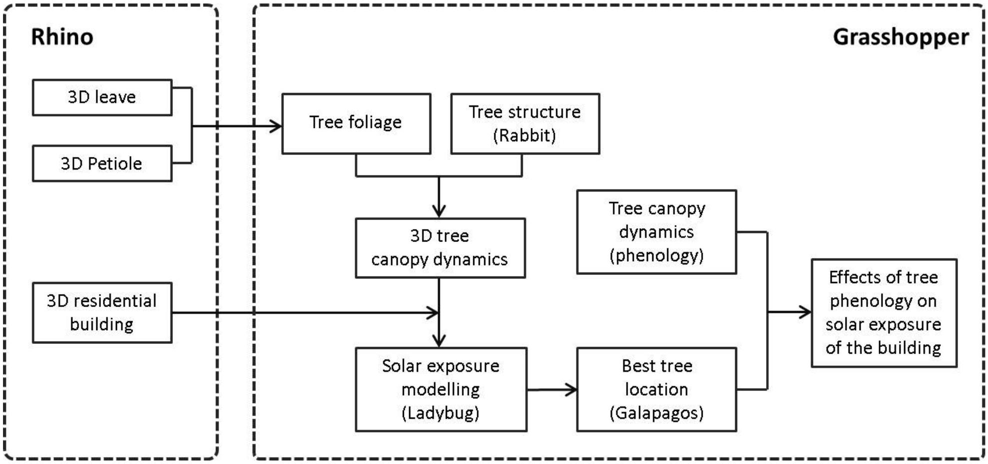

Fig. 1: Digital tools' interaction for simulating tree phenology and its impacts on solar exposure of building

2.3.1 Foliage Simulation

Three dimensional models of Golden Elm leaf and petiole were created in Rhino based on the natural characteristics of the foliage of the tree. L-system was used to create tree canopy shape and structure of the tree (Fig. 2).

2.3.2 Three-dimensional Tree Simulation

Based on the morphological and physiological characteristics of Golden Elm tree, the 3D digital tree was constructed in the Rhino and Grasshopper environment (Fig. 3a). Phenology stages are visualised through modelling canopy dynamics with different foliage amounts and the associated light filtering effects (Fig. 3b).

2.4 Three-dimensional Residential Building

A typical 3-bedroom, 2-bathroom residential building in the suburbs of Melbourne is used to construct the 3D model of a building (Fig. 4). The solar exposure of the building is simulated in response to tree phenology.

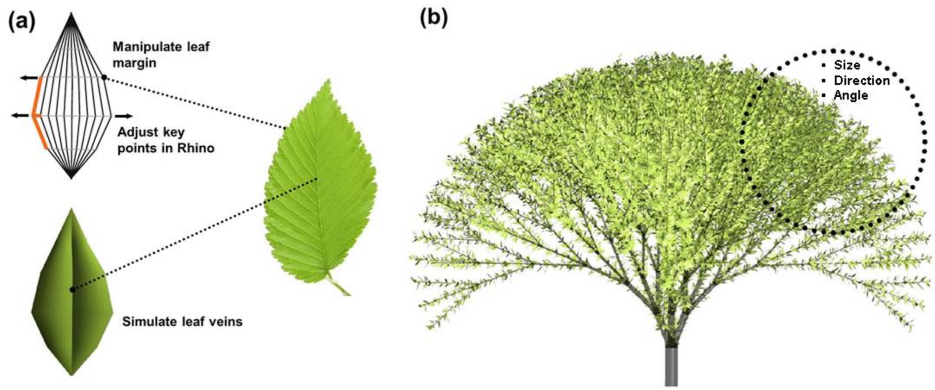

Fig. 2: Simulating Golden Elm foliage (a) and canopy (b)

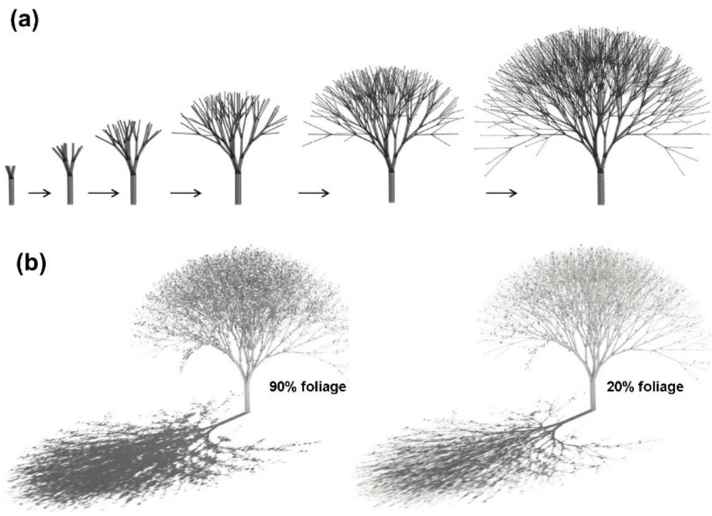

Fig. 3: Golden Elm tree structure construction (a) and canopy light filtering effects (b)

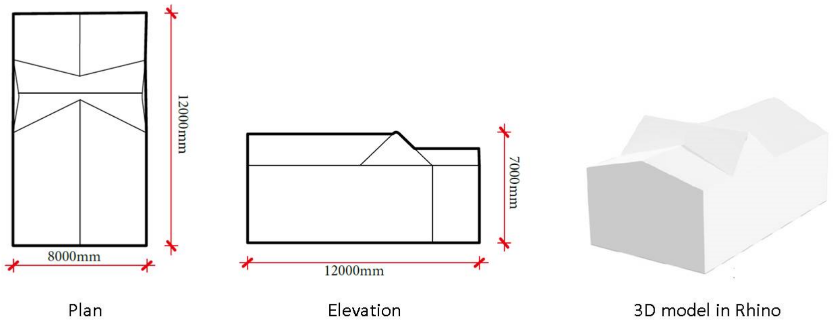

Fig. 4: Typical residential building in Melbourne suburbs

2.5 Solar Radiation Modeling

2.5.1 Identifying the Ideal Tree Location

To simulate the best effect that the golden elm tree could have in regulating solar exposure for the building, a grid of potential locations for the tree is established in Rhino using the following criteria:

- Offset building footprint by 5 m (this is reasonable for typical detached houses in Melbourne suburbs considering the location of the building footprint in a lot).
- Use the offset boundary to rebuild the grid of potential locations (2m distance).
- Analysis grid tolerance is 2 m.

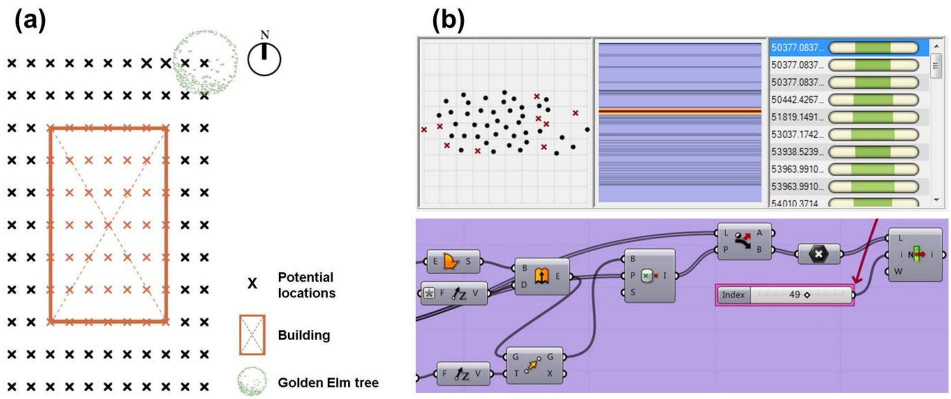

Fig. 5: Grid of potential locations (a) and identification of the best tree location using Galapagos (b). Point number 49 is identified as the best location.

Once the grid of potential location for the tree is established (Fig. 5), the following seasonal solar exposure of the building in response to tree phenology is simulated using the genetic algorithm (Galapagos) in Rhino/Grasshopper:

- Summer solar exposure in two scenarios: 1) Golden Elm tree in the ideal location; and 2) no tree.
- Winter solar exposure in two scenarios: 1) evergreen tree (using full foliage Golden Elm tree); and 2) deciduous tree (no foliage).

Once the ideal location is identified, the entire solar exposure for summer (1 Dec to 28 Feb) is calculated for the building. It is then compared with the total solar exposure for the building in the no-tree scenario (Fig. 6). This process is repeated to calculate solar exposure in winter (1 Jun to 31 Aug) in two scenarios: 1) evergreen tree; and 2) deciduous tree to differentiate the light filtering effect from different tree types (Fig. 7).

3 Results

The study aims to explore different tree planting schemes that can manipulate solar exposure of the building, i. e. in hot summer time, the tree can block as much solar radiation as possible to shade the building and keep it cool, while in cold winter time the tree could allow as much solar radiation as possible to penetrate the canopy and heat the building and keep it warm. Based on this study, the Golden Elm tree reduces the building's solar explore from 93,554 kWh to 48,567 kWh during the summer season. Based on this study, the tree's shading and cooling effect for the building is remarkable. The total solar radiation blocked (compared with the no tree scenario) is 44,987 kwh, which is the total energy consumption for 3 average households in Australia. In other words, the solar exposure for the building is reduced by 48% (Fig. 8) when a mature Golden Elm tree is planted at the best location in the residential lot.

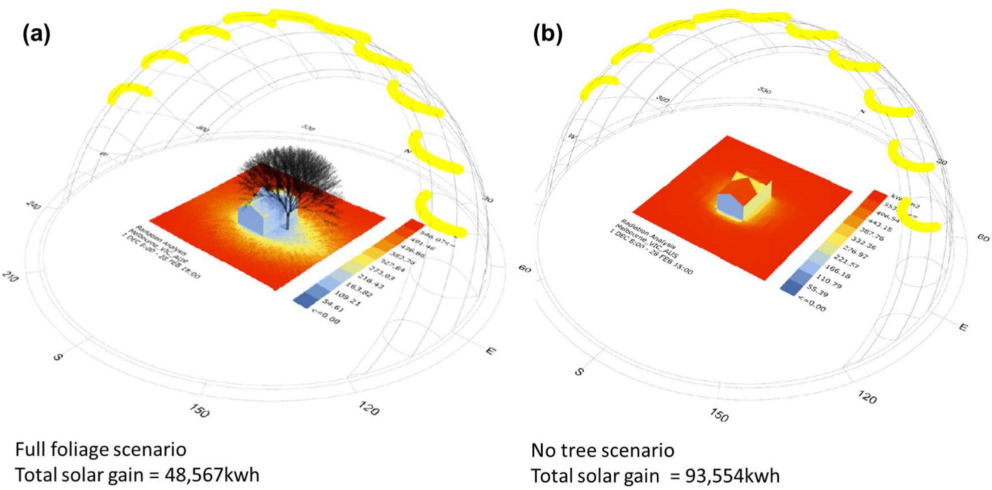

Fig. 6: Summer solar exposure in two scenarios:
(a) Golden Elm tree in the ideal location; and (b) no tree

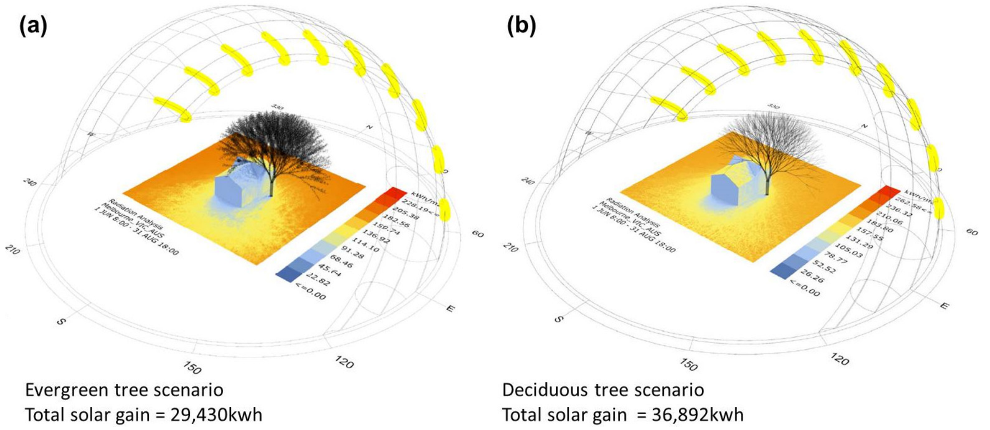

Fig. 7: Winter solar exposure in two scenarios: (a) evergreen tree; and (b) deciduous tree

Melbourne and most areas in Victoria have a long cold winter. The number of hot days (30 °C or above) is 35, while the number of cold days (18 °C or below) is 159. In fact, energy cost for heating is the largest component for households in Victoria (SUSTAINABILITY VICTORIA 2014). Therefore, natural heating strategies such as using deciduous trees to allow solar radiation to keep the house warm in winter are highly desirable. Based on this study, the solar gain increases by 29 % (7,462 kwh) for the period from 1 June to 31 August (Fig. 8). The amount should actually be much greater considering the winter in Victoria is longer than the time period used for solar radiation simulation in this study. The foliage dynamics through full (as an evergreen tree) to none (deciduous tree in winter) and its effects on solar exposure are also simulated (Fig. 8). There is a negative correlation between the amount of foliage and the amount of solar exposure for the building.

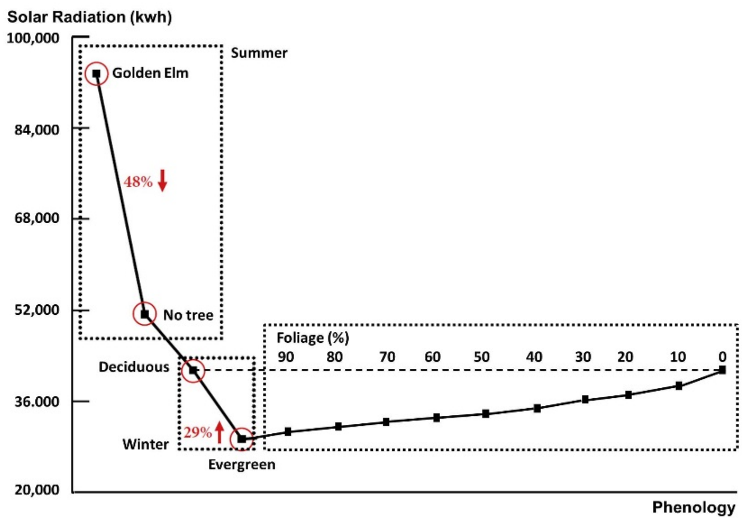

Fig. 8: Phenology of Golden Elm and solar exposure of the residential building

4 Discussion

4.1 Species and Ideal Tree Location in Relation to Tree at Different Ages

It must be noted that the results derived from this study are based on the specific tree species – Golden Elm. The ideal location and the solar filtering performance of the tree can be different for another tree species due to natural characteristics of the foliage, tree structure, and phenology. Despite this limitation, this study provides a quantitative feedback, which can be integrated into residential landscape planting design.

As the costs of transplanting mature trees are high, it is worth considering how a tree performs in regulating solar penetration in its life history from young to mature. The best location identified in this study is for a mature Golden Elm tree with specific height and foliage volume. However, since the elm tree can live up to 500 years and it only takes about 20 years for the tree to grow to maturity, the location for the mature tree is more important considering life-long benefits for the tree in regulating solar exposure for the building.

4.2 Solar Exposure and Indoor Temperature

This study only considers the solar exposure of the building and is yet to explore the indoor temperature for thermal comfort. Since the later involves many factors related to the architectural design (such as window-wall ratio) and construction material (wall, roof, insulation material, etc) and other landscape elements, it falls beyond the scope of this study. Further future research will involve indoor thermal comfort modelling with validation from data collected using thermal imager.

5 Conclusion and Outlook

This study explored the phenological dynamics of a mature tree in a residential lot and its effects on the solar exposure of the residential building through solar filtering in different seasons and phenological stages. The paper argues that natural thermal comfort may be achieved through residential planting design, instead of using heating or cooling systems powered by non-renewable energy sources. The methodology developed for this study requires very little data and can be easily applied in other situations. Studies like this are essential to promote solar energy use through the passive approach, in lieu of other approaches of harvesting solar energy such as electricity generating solar panels. This study provides an initial strategic outlook that sound planting design can achieve not only landscape aesthetic values, but also practical values such as reduced energy footprint, which is critical to tackling carbon emission and climate change.

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