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Pedestrian access modelling with tree shade – won't someone think of the children…

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Abstract

Australia has one of the highest rates of skin cancer in the world and school children are amongst the most vulnerable to harmful UV exposure. Australia also has one of the world's highest levels of childhood obesity and much research has focused on encouraging active modes of transport to and from schools.

This research aims to answer the following questions: How do we balance the need for protecting school children from excessive UV exposure whilst encouraging active modes of transport? And, how can innovative strategic approaches to urban transformation increase the potential for school children to walk to school maximising exposure to sun, and hence vitamin D, in winter but minimising UV exposure in summer?

The method used for this study involves bringing together "PedCatch", a novel animated pedestrian catchment modelling tool that can exclude busy roads or intersections, with high polygon 3D proxy-object tree modelling, flexible 3D precinct modelling, and temporal solar impact analysis.

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The results of the study demonstrate that by using these tools, it is now possible to assess a school's walkable catchment given specified sun and shade parameter requirements, taking into account the time of year, the solar impact of street orientation, urban form, street tree size, spacing, species and location. The study also describes how the tools can be used to rapidly test potential impacts of urban interventions and modifications to street design such as increasing canopy coverage, adjusting street setbacks for future urban development.

This research has far-reaching implications for schools, school children and their parents, policy makers, planners and urban designers. The tools have the potential to contribute to the development of more walkable and accessible communities that minimise over exposure to the harsh Australian sun whilst encouraging an increase in children's level of physical activity.

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Keywords: Accessibility; catchment modelling; tree shade;

1. Introduction

Overweight and obesity is estimated to cost Australia over $55 billion in total every year [1] and has overtaken smoking as the country's leading cause of premature death and illness [2]. Physical inactivity is the fourth leading contributor to the burden of disease globally [3]. Increasing physical activity is a critical priority for the future of Australia and its citizens particularly its younger population which has seen the steady decline in active transport used by children to go to and from school and growing incidences of childhood obesity in recent decades [4–6]. Children walking to school is critical for an active and healthy community with not only health, but environmental and social benefits [7].

The likelihood of children walking to school regularly is much higher if children live in well-connected neighborhoods with good pedestrian accessibility or "Pedshed" ratings [7,8]. It follows that urban designers need to carefully consider school siting and street design in school neighborhoods to encourage children to walk to school [7–9].

In addition to proximity to school, it has been shown traffic volume and perceived safety significantly impact on the likelihood of children walking or cycling to school [7,10] with parents being concerned for children's safety due to traffic driving their children to school thus contributing further to the traffic, in a vicious circle.

Although it is important to encourage children to walk to and from to school, prolonged exposure of children to direct sunlight in summer can be problematic. Australia experiences summer temperatures that can exceed 40°C [11] and has one of the highest rates of skin cancer in the world [12] with over 440,000 Australians treated for skin cancer each year [13]. School children are amongst the most vulnerable to harmful UV exposure [14]. Effective UV radiation protection during childhood is necessary to control both immediate and long-term harmful effects on children's skin [14].

It is advisable to limit sun exposure to just a few minutes in summer [15] and wear sunscreen, hats and shirts to limit UV impact on skin. Apart from clothing and sunscreen, tree-shade provides "supreme protection" from UV exposure [16,17] and is an important aspect of the design of streets for providing a comfortable walking environment [18], with closely-spaced shade trees described as an essential ingredient for designing "walkable communities for pedestrians" [19].

Conversely there is growing concern for protecting streets from overshadowing in the cooler months of the year as nearly one third of Australian adults are currently suffering vitamin D deficiency [20]. To gain a healthy amount of vitamin D from the sun, people need to be exposed to direct sunlight for two to four hours per week from May to August [15]. It is therefore important when designing for accessibility to schools and walkability of streets to consider the amount of solar exposure, not only maximising shade in summer, but minimising shade throughout winter.

This paper will outline a novel, animatable approach to modelling pedestrian accessibility that measures proximity in the form of a pedshed or catchment taking into account street networks (excluding dangerous roads), but also accounts for solar exposure time.

2. Background

2.1. Background to pedestrian catchment modelling - accessibility and proximity assessment

2.1.1. Modelling proximity – calculating 5, 10 and 15 minutes' walk

Until very recently, modelling walking proximity to services has been limited [21], with 'Euclidean buffers' or 'circular catchments' (as-the-crow-flies distance from services such as schools) being the most commonly adopted approach [22]. Here, a circle of a given radius is drawn on a map, to indicate a theoretical catchment for an approximation of a chosen walking time from a chosen node. For example, a 400m or 800m radius may be drawn to indicate an approximation of five or ten minutes' walk to the central node. This Euclidean buffer method has been used since the 1940s [23] and is still common practice despite criticism for being inaccurate, not accounting for street networks, barriers to walkability such as rivers or railway tracks, and its tendency to overestimate catchment areas [21]. This modelling technique is very quick but has very low accuracy as it fails to consider street grid layout, busy roads and crossings. The circular catchment method also ignores aspects of the physical environment that may influence walking distances, perceptions of safety and climate [24].

2.1.2. Service Area Approach with Network-Analyst

Recent development of proprietary GIS software with additional network analysis plugins (ESRI™ Arc Map with Network-Analyst™ plugin) makes a dramatic improvement on accessibility catchment modelling [22] with the vector distance based Service Area Approach (often referred to as "pedsheds") and Network Buffer Approach. These methods calculate vector distances travelled for each path from a central node and, using the shoelace formula (Gauss's area formula), create a convex hull catchment shape or network offset buffer catchment shape respectively of known area [25].

This method can produce more accurate and useful accessibility analysis but can be prohibitively expensive, requiring high-end GIS software. Sophisticated tools that build on this modelling approach exist such as the

Singapore University of Technology & Design and MIT's City Form Lab's add-on to the Network-Analyst™ plugin called "Urban Network Analysis (UNA) toolbox for ArcGIS" [26]. This plugin provides a range of tools to compute network centrality and proximity measures. The tools have also recently been recompiled as a plugin for McNeil's Rhino 3D™ program and can begin to work in 3D. This approach is sophisticated but is not animatable nor does it take into consideration environmental factors such as shade.

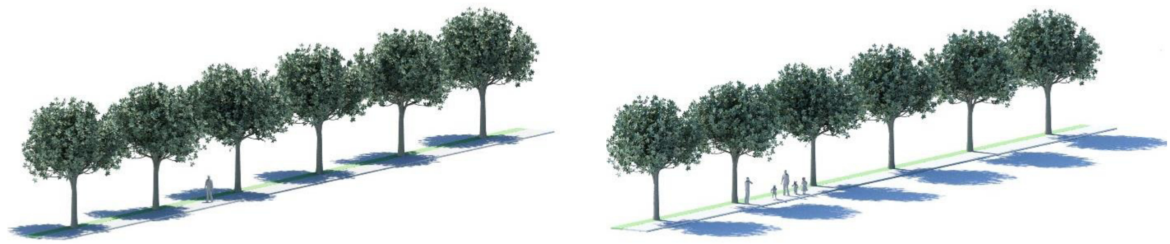
2.1.3. Simple agent based modelling (PedCatch)

Due to improvements in both software and hardware, agent-based modelling is increasingly in use for assessing human movement [27]. PedCatch was a simple agent-based catchment analysis model used to animate and calculate the ratio of the pedestrian network area to the area of a Euclidian buffer (eg. 800m as the crow flies) [28]. The simple agents moved at average human walking speeds navigating the street network from a central node (eg. railway station or school) to assess existing catchment for 5 and 10 minutes walking distances.

The tool was later rewritten to work with web-based GIS road center line vector data from the AURIN portal. Here the impact of waiting time at traffic lights through an additional crossing wait time variable was added. An updated version of PedCatch using crowd-source data and open-sourced elevation data is available at PedCatch.com. This tool has been presented in workshops to researchers and policy makers generating a great deal of interest and suggestions for further development such as to introduce important environmental variables such as solar amenity and shade [29] which inform the aims of this project.

2.1.4. Algorithmic botany modelling

The modelling of street trees and their shade has seen significant improvements [18] and it is now feasible to digitally simulate large scale urban scenarios with geometrically accurate high-polygon trees within flexible 3D precinct models. Solar and shading impacts can also be projected with a level of accuracy suitable for urban scaled analysis [18]. This analysis can now be done taking into account temporal change of sun position at different times of the year, and times of day (Fig. 1) and exported in a range of formats including baked shadow map images (raster images including shadows only).



a **b**

Fig. 1. This figure shows the different positions of shadows on footpaths at different times of the day and the different levels of solar exposure for pedestrians traversing a footpath. (a) shows 3D rendering of a row of juvenile *Ficus Rubiginosa* at 12pm, 1st December; (b) shows 3D rendering of the same row of juvenile *Ficus Rubiginosa* at 3pm, 1st December.

3. Aims

This research aims to answer the following questions: How do we balance the need for protecting school children from excessive UV exposure whilst encouraging active modes of transport? And, how can innovative strategic approaches to urban transformation increase the potential for school children to walk to school maximising exposure to sun (and vitamin D) in winter and minimising UV exposure in summer?

4. Method

The method used for this study involves bringing together the approach used by “PedCatch”, a novel animated pedestrian catchment modelling tool that can exclude busy roads or intersections, with high polygon 3D proxy-object tree modelling, flexible 3D precinct modelling, and temporal solar impact analysis.

4.1. Road network data sets

Road network, and in some cases footpath data, can be exported from the Australian Urban Research Infrastructure Network (AURIN) data portal [29] filtering out major busy roads and freeways to exclude non-pedestrian trafficable roads. Another option is to download pre-filtered data from the PedCatch.com website which excludes freeways and can also exclude streets that exceed specified gradients (useful if calculating catchments for children riding to and from school).

For the experimentation described in this paper, a simple fictional rectangular grid on 100m x 200m has been used so to improve legibility of resulting catchments.

4.2. Calculating distance, travel time and exposure

Typical walkable catchment analysis accounts only for distance travelled within a certain time at a certain speed and hence is only modelling for a single-objective. Modelling walkable catchments if accounting for two disparate factors, in our case solar exposure and distance travelled, requires reconciling objectives that may have conflicting optimal solutions. Our method to address this conflict uses an approach of unifying these two separate metrics to create a single, dimensionless, synthetic metric of the relative cost of a pedestrian traversing a particular road with solar irradiance and length properties.

The relative cost of solar exposure is calculated by sampling a raster image or shadow bitmap. The bitmap used in the process described here was generated using algorithmic botany tree models arranged in Autodesk’s 3ds Max™ as procedurally arrayed proxy objects as described by White and Langenheim [18] [Fig. 1]. The trees are then rendered from above using a camera clipping plane so as to exclude the tree canopy and just capture the shadows cast by the trees along the footpath to create a ‘shadow bitmap’ [Fig. 2 to Fig. 4].

Points along the pathway are sampled from the shadow bitmap by assessing the pixel intensity (darkness of the pixel) to calculate the level of shade. For our prototype model, we have simplified this exposure sampling to a Boolean reading of either in full direct sun (0), or in some level of shade (1). Using this sampling method, we are able to specify a maximum solar exposure as a pedestrian walks along a pathway at a specified speed. For example, if a pedestrian moves at a speed of 1 meter per second with a maximum exposure of 10 seconds and a maximum time of 60 seconds, without any shade, the maximum distance a pedestrian will get is 10 meters before they exceed the maximum exposure time [Fig. 2 a]. If the pedestrian is in full shade for the duration of their walk, they will move a full 60 meters [Fig. 2 b] as they have not been exposed to direct sunlight at all.

Furthermore, if in our test a pedestrian is in full shade for the first part of their journey, they will travel 38 meters before exceeding solar exposure limit [Fig. 3 a], whereas if there are trees on the second part of the path, but the pedestrian is exposed to direct sun for more than 10 seconds before they make it to the shade, the distance traveled would be 10 just meters [Fig. 3 b].

When the trees were dispersed at 10 meter centers the pedestrian would move 38.5 meters before exceeding the specified maximum exposure [Fig. 4 a]. The resulting distance is significantly reduced when the shadows are rendered at school 'home time' of 3.30pm with shadows falling on the road and not the footpath [Fig. 4 b].

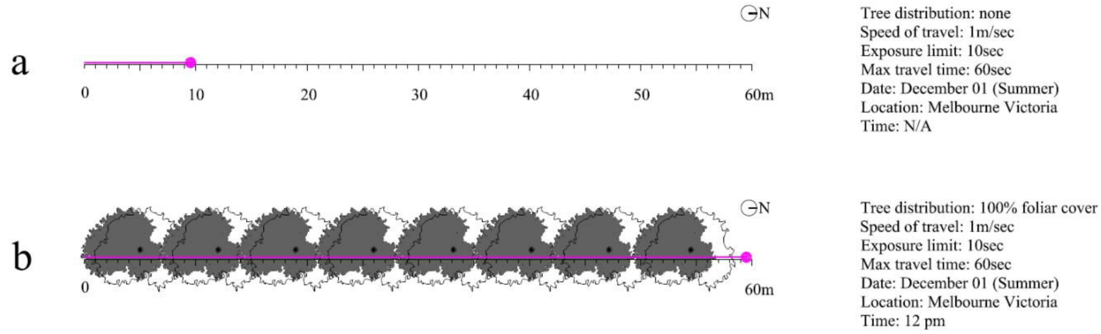


Fig. 2. This figure shows different levels of solar exposure for a pedestrian traversing a single footpath moving at 1 meter per second, with a maximum walking time of 60 seconds, and maximum exposure time of 10 seconds at 12pm, 1st December; (a) shows a path with no trees resulting in a walking time of 10 seconds with distance of 10 meters; (b) shows full foliar cover row of juvenile *Ficus Rubiginosa* resulting in a walking time of 60 seconds with distance of 60 meters.

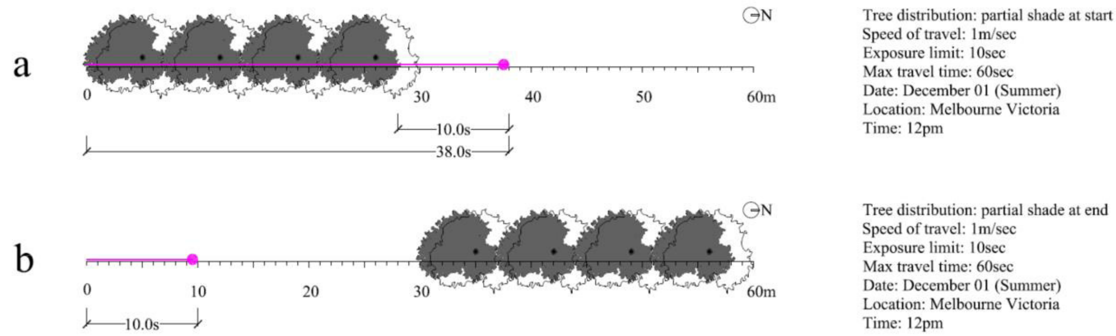


Fig. 3. This figure shows different levels of solar exposure for a pedestrian traversing a single footpath moving at 1 meter per second, with a maximum walking time of 60 seconds, and maximum exposure time of 10 seconds at 12pm, 1st December; (a) shows the first half of the path with full foliar cover row of juvenile *Ficus Rubiginosa* resulting in a walking time of 38 seconds with distance of 38 meters; (b) shows the second half of the path with full foliar cover resulting in a walking time of 10 seconds with distance of 10 meters;

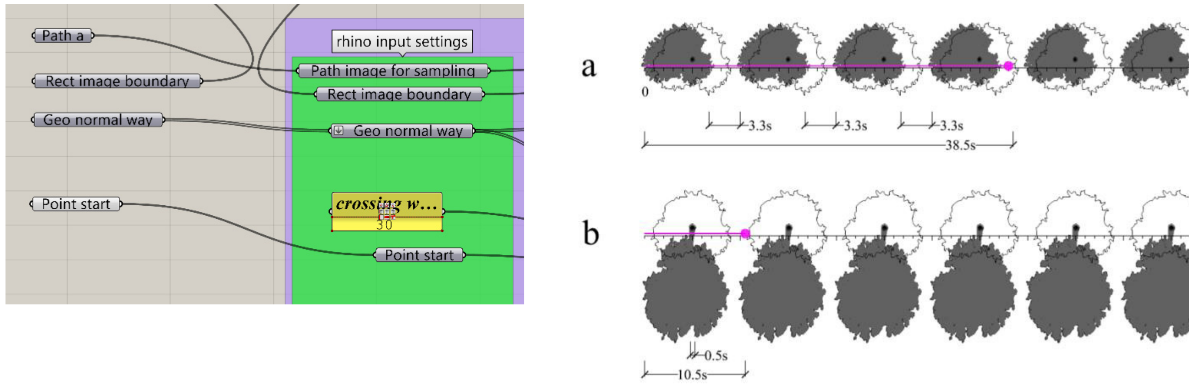


Fig. 4. This figure shows different levels of solar exposure for a pedestrian traversing a single footpath moving at 1 meter per second, with a maximum walking time of 60 seconds, and maximum exposure time of 10 seconds, with trees spaced at 10 meter intervals, at different times of the day on 1st December; (a) shows analysis with shadows for 12pm, resulting in a walking time of 38.5 seconds with distance of 38.5 meters; (b) shows analysis with shadows for 3.30pm, resulting in a walking time of 10.5 seconds with distance of 10.5 meters.

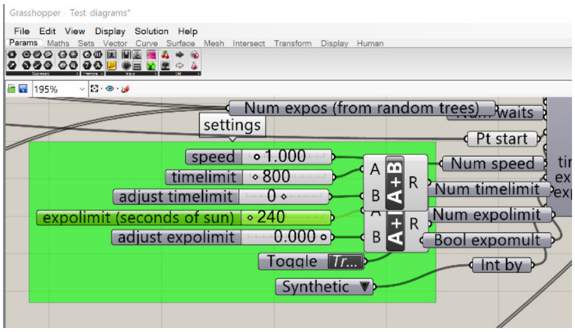
4.3. Calculating catchments

To calculate the catchments, we have used Rhinoceros 3D with the Grasshopper visual scripting plug-in to prototype the tool as it provides a flexible environment for rapid development and testing of extensible solutions. The Python programming language was used within Grasshopper to implement more-complex parts of the solution and to allow for iterative steps to be performed.

The synthetic metric is applied within an algorithm which, given in descriptive terms, performs the below steps to find a walkable catchment [Fig. 5]:

- The script is initialized with a street network and corresponding shadow bitmap (as described above), a start point on the street network, pedestrian walking speed, and time and exposure limits [Fig. 5].
- A list of untraversed streets is created, with shadow intensities stored for each street by sampling the shadow bitmap.
- A notional 'frontier of movement' is established to contain the extent of the expanding pedestrian catchment in the road network. At the start of the simulation this extent is merely the start point provided to the script.
- The following steps are undertaken while there are still untraversed streets at the frontier of movement:
    - The street with the lowest cumulative cost according to the synthetic metric, and that has not exceeded the time and solar exposure limits, is traversed.
    - The traversed street is moved to the list of traversed streets.
    - The frontier of movement is expanded to include the newly-traversed street.
- The list of traversed streets is output with associated time and distance information.

Although the metric itself is dimensionless, the actual solar exposure and distance travelled at any point of the scenario simulation output can be quantified. Further, the metric can be configured for increasing or decreasing solar exposure for winter and summer respectively.



a **b**

Fig. 5. This figure shows user variables for the prototype model; (a) shows user input parameters including specifying the file path for the shadow bitmap image, geo-referencing rectangular image boundary (where to place shadow bitmap), selection of street network and catchment start point; (b) shows user inputs including walking speed, total time limit, and total limitation on sun exposure.

5. Initial diagrammatic test results

5.1. Abstract pattern shadow bitmap tested on 100x200m grid

To test the catchment modelling method, we used a simple 100 x 200 meter orthogonal street grid network with a centrally-located start point, with speed set to 1 meter per second, maximum time of 800 seconds and maximum exposure of 240 seconds [Fig. 5 b]. We tested the tool using a series of simple black-and-white patterned shadow bitmaps where black represented full shade while white represented full sun exposure. These patterns included a checker pattern [Fig. 6 a] and a kite pattern [Fig. 6 b]. When not considering solar exposure, the catchment for a rectangular grid such as this one is a rhombus shape.

As expected, the shape of the catchment for the checker patterned shadow bitmap test [Fig. 6 a] resulted in a deformation of the pure rhombus shape due to pedestrians in the north-west and south-east quadrants being exposed to full sunlight and thus reducing their total distance, reducing the overall catchment. The impact of exposure on catchment is further illustrated in the kite pattern example [Fig. 6 b] where pedestrians travelling towards the north, east and south are exposed to sun far more than those travelling in easterly directions and consequently the catchment shape spreads primarily to the east.

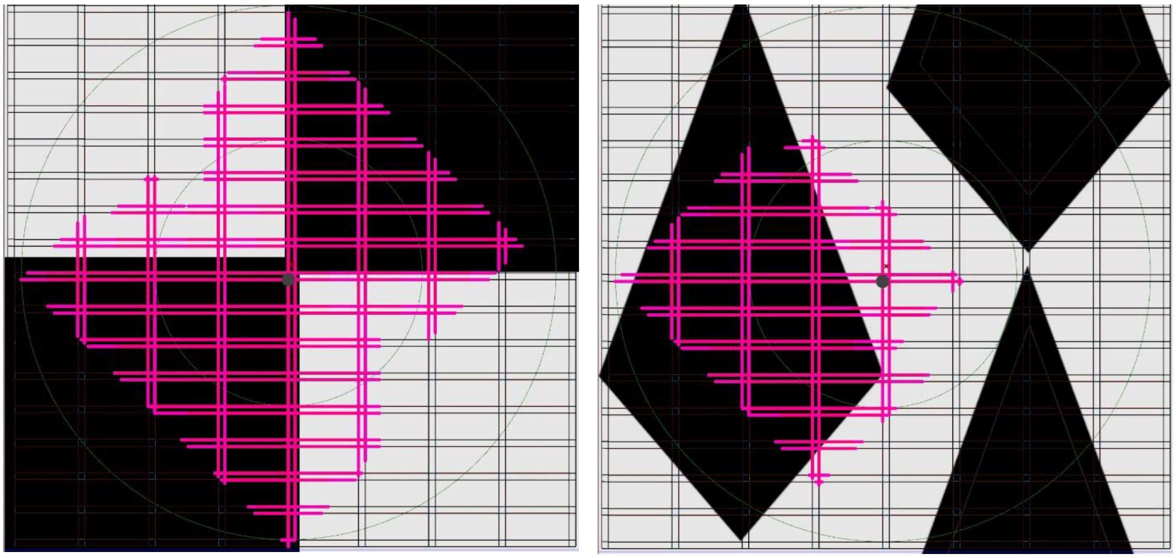
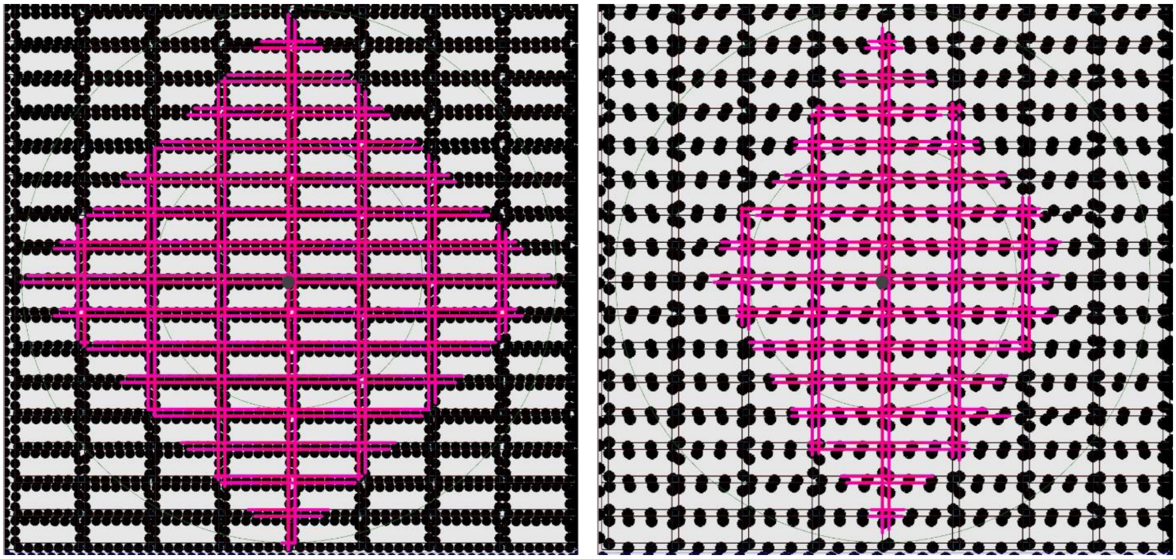


Fig. 6. This figure shows examples of catchment analysis calculated with simplified shadow bitmap diagrams; (a) shows a simple black and white checker distribution; (b) shows a staggered black and white kite shadow bitmap.

5.2. Rendered street tree shadow bitmaps on 100x200m grid

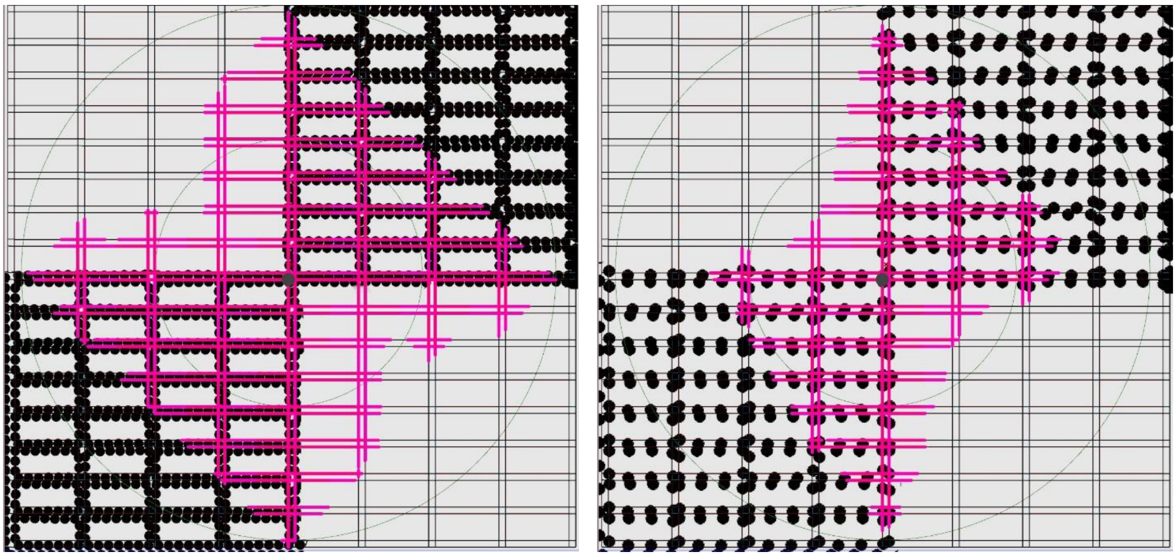
We then tested the catchment modelling method using more-complex tree shadow bitmaps whilst maintaining the same orthogonal street grid network, start point, speed, maximum time and maximum exposure. Two patterns were used; one of dense tree cover providing full or near-full shadowing for pedestrians, and one of dense tree cover with interspersed exposed areas that have directional-variation in intensity causing pedestrians travelling in the east-west axis to be relatively more exposed than those travelling in the north-south axis. To verify, the modelling method was tested with these patterns uniformly covering the entire orthogonal road network. As expected, a regular rhombus catchment was formed for the full-shadowing pattern [Fig. 7 a], and, for the intermittent-shadowing pattern, a rhombus catchment constrained in the east-west axis was formed [Fig. 7 b]



a b

Fig. 7. This figure shows uniformly distributed tree coverage; (a) shows full tree shading producing a regular rhombus catchment; (b) shows partial, direction tree shading with a constrained rhombus.

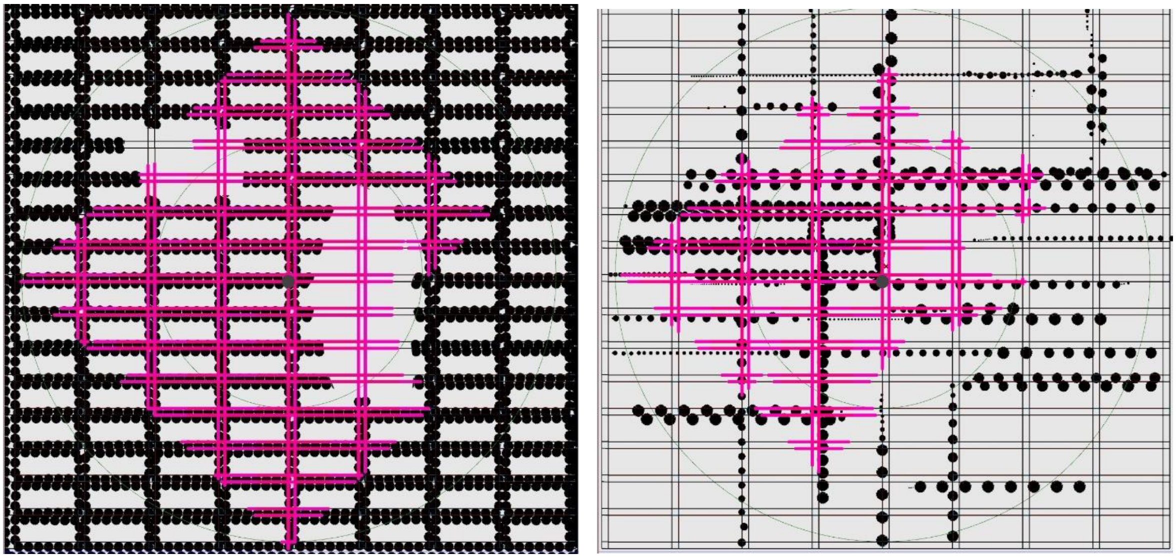
The two tree patterns were verified against the checkered distribution used above [Fig. 6 a], and we expected the full-shadowing pattern to, and saw that it did, create the same deformed rhombus as the pattern provides pedestrians in the north-east and south-west quadrants with the same solar shelter [Fig. 8 a]. The intermittent-shadowing pattern was also applied to the checkered distribution, and, as anticipated, the deformed rhombus catchment was both constrained in the east-west axis and its incursions into the fully-exposed quadrants were limited due to the pedestrians' increased exposure in the shadowed quadrants [Fig. 8 b].



a b

Fig. 8. This figure shows more detailed tree shade bitmap version of the simple checker distribution described earlier; (a) shows expansive catchment in the north-east and south-west quadrants due to tree shading; (b) shows partial, directional tree shading producing a rhombus constrained in the east-west axis and all quadrants due to increased solar exposure.

The method was tested against two more-real-world scenarios. First, the area of the default rhombus catchment for a fully-shaded street network was disrupted with clearings of solar-exposed zones, resulting in the catchment in these zones being reduced as pedestrians 'exhaust' their allowance of solar exposure [Fig. 9 a]. Second, a street network of dispersed but interconnected tree-lined avenues was modelled, resulting in a catchment that is closely-contained to the spread of the interconnected avenues as the more-shadowed roads are selected [Fig. 9 b].



a b

Fig. 9. This figure shows detailed tree shade bitmap with more complex tree arrangements; (a) shows reduced catchment under a full-shading pattern due to clear areas increasing solar exposure; (b) shows a catchment closely contained to the spread of tree-lined avenues.

6. Discussion and conclusion

The results of the study demonstrate that by using this modelling approach it is now possible to assess a school's walkable catchment given specified sun and shade parameter requirements, taking into account the time of year, the solar impact of street orientation, street tree size, spacing, species and location.

We have, in the examples used for this paper, limited the study of solar exposure to purely that affected by trees on a very simplified urban network. The tool is however capable of being applied in highly-complex urban situations and can take into account shade provided by awnings and sun sails, buildings, and even topography. This capability will be explored further in future research, and the validity of the process will be tested in real-life case studies.

Though in this study we have treated tree shade as a binary input — a location is either fully shaded or fully exposed — the tool can be configured to read not only black or white, but also shades of grey. This means that if suitably prepared shadow bitmaps are produced, the model can take into consideration different levels of ambient and reflected light as well as intensities of shade provided by different trees, such as variation due to tree leaf emissivity, and urban enclosure or canyons.

This study also draws attention to the dramatic effect the time of day has on footpath sun exposure. The experiment described in Fig. 4 clearly illustrated the difference for north-south streets at distinct times of day and suggests novel approaches to street tree placement should be considered if shade at school home-time in summer is a key objective, but also suggests that the typical layout of Fig. 4 may be ideal for winter sun exposure. Further testing is required to confirm this hypothesis. The study also suggests further research is required that looks at a range of times of year along with different tree species including deciduous and evergreen species.

The method's ability to moderate solar exposure by selecting routes in a street network — such as staying on a tree-lined avenue in summer or traversing an open area in winter — requires further testing, particularly with real-world case studies. The possibility of a suite of routes to and from a destination such as a school for different seasons, weather conditions, or even UV indexes, and how these routes could be managed, merits further consideration.

The aims of this research were informed by the interest in and suggestions for further development of the PedCatch.com walkability tool, in particular to introduce environmental variable analysis. Though further testing is required, there is great potential to integrate the outcomes of this research into the PedCatch.com platform. The approach may also be suitable to include walkability indexes with a specific focus on childhood walkability.

This research has far-reaching implications for schools, school children and their parents, policy makers, planners and urban designers. The modelling approach facilitates testing of potential impacts of urban interventions and modifications to street design that affect solar exposure such as increasing canopy coverage or controlling connectivity of pedestrian networks, and potential for testing the adjustment of street setbacks for future urban development. By aiding rapid, iterative urban analysis and design of street networks, the tool has the potential to contribute to the development of more walkable and accessible communities. By combining pedestrian access modelling with solar exposure, this novel tool has the potential to inform street designs that minimise over exposure to the harsh Australian sun in summer, maximize exposure to the sun in winter, encouraging an increase in children’s level of physical activity.

Acknowledgements

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