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Content

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On the Cul-de-Sac vs. Checker-Board Street Network: Search for Sustainable Urban Form

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Key words: Street network, connectivity, measure and neighborhood

Abstract: The study revisited the largely accepted idea to deal with sprawl by replacing cul-de-sac/curve-linear street with the traditional checkerboard system in community design. Recent discussions suggest that a neighborhood with cul-de-sac street pattern can promote accessibility and street connectivity, if it is designed integrated with open space and pedestrian paths, while creating safe and quiet residential environments. A good example is the discarded old wisdom, the Radburn. To date, the past researchers did not acknowledge the potential of the cul-de-sac neighborhoods in achieving the benefits New Urbansits strive to accomplish. This study tried to fill this gap by comparing a conventional suburban neighborhood, a neighborhood with creative cul-de-sac street pattern, and the grid street neighborhood.

1. INTRODUCTION

Cul-de-sacs and curve-linear streets present an iconic built environmental form of American suburban communities. Since the New Urbanism movement however, the cul-de-sac and curvature form has been under attack. Frequently the form features are used as visual illustration of suburban sprawl and are often tied to such sprawl-related problems as excessive driving and emissions, lack of place identity, and growing sedentary life style that increases obesity and health risks. In search for sustainable built environmental form, many planners/designers have advocated the traditional checker-board type of grids as an alternative to the conventional lollipop type of curvature; Grids are believed to improve connectivity and walkability that are largely lacking in the conventional cul-de-sac/curve-linear street network. Nevertheless, whether grids can outperform cul-de-sacs in achieving desired sustainable outcome (travel related) remains a topic of debate among scholars and practitioners. Better informing the debate motivated the study presented in this paper.

This paper first explains in retrospect the ideas of cul-de-sac and checker-board streets as vocabularies for community design. It then analyzes and compares their traffic and access characteristics through case study of three neighborhoods, Houston Heights, the Woodlands, and the Grand Lakes, all located in the greater Houston, Texas area. Houston Heights has a distinctive grid of street network, whereas the Woodlands and the Grand Lakes follow the conventional hierarchical street network full of cul-de-sacs. The Grand Lakes neighborhood differs from the Woodlands mainly in that the cul-de-sacs in the Grand Lakes have open ends leading to green and open spaces by pedestrian and bike paths. With applications of geographic information system (GIS) tools, the study calculates and examines the metrics of built environmental characteristics of the three neighborhoods using the following performance indicators: average trip distance among all households, average paved street length per person, alpha index of network connectivity, link-node ratio, directness of pedestrian/cyclist routes, and pedestrian catchments area. Implications are drawn from the study findings in regards to designing and developing sustainable urban form.

2. THE CUL-DE-SAC IN THE CONVENTIONAL SUBURBAN NEIGHBORHOODS

The neighborhood street is a multi-functional space that serves a variety of purposes. It has a traffic-carrying function to serve the movement of people and freight and the delivery of public services (e.g., fire, postal, and ambulance). It can be a place of social interaction for children and adults. Very often it functions as a border line delineating property rights and separating/linking different uses of land blocks. Furthermore, it has been a holding space for public facilities such as sewer and power lines and communication networks. To ensure proper functions of streets, local governments and professional organizations often establish rules or standards, for example, the subdivision ordinances adopted by most municipalities or the street design standards and guidelines provided by the Institute of Transportation Engineers. Reforming street network systems inevitably involves reform of these ordinances and design standards.

2.1 Cul-de-sac in the Radburn plan

Clarence Stein and Henry Wright first proposed the cul-de-sac in the Radburn design. The overall design of the Radburn was based on the concept of the neighborhood unit that Clarence Perry advocated. Based on Perry's concept, the Radburn was planned for 7,500 to 10,000 populations that is the most desirable number of pupils in a school. The whole community was laid out with a half mile radius, centering on elementary schools and playgrounds. Each section of the Radburn had its own shopping center.

The main concern of the designers of the Radburn was that the increasing automobiles made typical checkerboard street obsolete for living (Stein, 1967). Since drivers could see ahead on the uninterrupted road in the checkerboard pattern, the streets would equally invite through traffic into neighborhoods and threaten pedestrian safety. To mitigate the negative impact of automobiles on neighborhoods, Stein and Wright designed a hierarchical street system for each street to serve its own specialized function (Lee and Stabin-Nesmith, 2001; Lee and Ahn, 2003). The system consisted of express highway to connect outside communities, major arterials to connect sections of the community, collector roads around superblocks, and local streets (cul-de-sacs) only for accessing each house. The cul-de-sac streets were narrower and lighter (18-20 feet wide) than the collector roads.

Stein and Wright suggested cul-de-sacs strictly for car access to each house, and pedestrian paths were completely separated from vehicles. Pedestrian circulation system was formulated in the interior parks at the center of superblock and provided children with access to schools and recreations while protecting children from the danger of automobiles. the open spaces in each superblock were connected through underpasses, thereby creating a continuous pedestrian and open space system in the entire neighborhood (Parsons, 1990). Furthermore, the hierarchical street system was more cost-effective. Stein (1957) indicated that the paved area for the street and the length of utilities were 25 percent less than the grid street plan. The savings from less pavement costs were paid for acquiring land for the interior parks in the superblocks (Handy et al., 2003).

2.2 The Street Design Standards by the Federal Highway Administration (FHA)

The FHA provided series of suggestions for development layout in 1930s. Although developers were not mandated to follow those standards, the FHA could reject loans in areas where the prescription of the subdivision design standard set by the administration was not complied (Handy et al., 2003). The series of publications and bulletins of the FHA clearly demonstrated that the administration rejected the idea of the grid pattern for residential neighborhood (Southworth and Ben-Joseph, 1995; Southworth and Parthasarathy, 1996; Handy et al., 2003). Also, the gridiron street system would increase traffic accidents, since the traffic would disperse equally through the area. Additionally, the FHA was concerned about a monotonous and dull suburban landscape created by the grid street pattern (Southworth and Ben-Joseph, 1995).

Based on these reasons, the FHA expressed strong preference towards Stein’s concept in terms of street design, and the FHA recommended a hierarchical street system with cul-de-sacs for residential developments. Institute of Transportation Engineers (ITE) also exert strong influence on suburban street layout through series of standards and publications. The ITE supported the hierarchical street system of the FHA standards. Concerned with efficient vehicular movement and street safety, the ITE recommended 1) limited access to the perimeter highway; 2) discontinuous local streets to discourage through traffic; 3) street design with curvilinear cul-de-sac alignments; and 4) numerous three leg T intersections (Southworth and Ben-Joseph, 1995; Southworth and Parthasarathy, 1996).

The FHA standards failed to incorporate the key Radburn design concept of the public open space and separate pedestrian circulation system (Southworth and Parthasarathy, 1996). That is, while the main idea for the FHA street standards is originated from the Radburn plan, its comprehensive design concept was not incorporated into the FHA standards. The standards only focused on street designs. Exclusive pedestrian circulation system integrated with green open space was not adopted into the standards. Instead, the FHA and ITE put overriding emphasis on efficient vehicular traffic. It led to increase the lengths of streets and decrease sidewalk widths (Southworth and Parthasarathy, 1996). In most of post World War II suburbs, the cul-de-sacs are long and disoriented, and the sidewalks are often found on only one side of the street or not found at all. The minimization or elimination of the pedestrian paths indicates that pedestrian movement was not considered important.

While the whole innovate Radburn model was discarded, the developers adopted some parts that they could market from the Radburn design. The later new town development was considered a “piecemeal adaptation” of the Radburn design (Birch, 1980). Current typical suburban communities with the cul-de-sac provide quiet residential environments, but parts of a neighborhood are disconnected, and pedestrian access is severely restricted to various parts of suburbs.

3. MEASURING STREET CONNECTIVITY AND ACCESSIBILITY

Measures reviewed above evaluate slightly different aspects of street connectivity (Table 1). The measures using block size, length and density provide good proxy indicators of street connectivity, because those measures indirectly account for street lengths and intersection density. However, the block measures may not be appropriate for the analysis for neighborhood with superblocks. For example, it is likely that the whole neighborhoods could be composed of a few superblocks.

In terms of link node ratio, connected node ratio, Alpha and Gamma indices, the main disadvantage is that those measures are not related to the size of the blocks and the spacing of intersections. Thus, the measures do not reflect the distance between points in any way. It is possible to have the same values for the grid neighborhoods with small and large blocks (Dill, 2004). Nonetheless, those measures are easy to generate and use. All the information required for those measures are total number of nodes and links of the study area.

Dill (2004) stated that the Pedestrian Route Directness would be a better measure for pedestrian and bicycling friendliness, since the measure directly reflects the distance traveled that is a primary factor for discouraging walking or bicycling. Empirical evidence supports this argument at neighborhood level. Handy (1992) found that residents living in a traditional neighborhood that presumably have short distances between local destinations, are more likely to walk or bike than those living in car-oriented neighborhoods. However, Dill (2004) also pointed out that the measure is less attractive for policy making or large scale research, since analyzing all pairs of points requires additional computational capability or user’s judgment if not all pairs are analyzed.

The measure of the Pedestrian Catchment Area provides proxy indicator for pedestrian accessibility from a point. However, measuring the size of area does not consider the characteristics of the area. For example, an area created by the walkable network distance can be large. However, the primary land use of the calculated area may not be residential. Dill (2004) suggests Effective Walking Area (EWA) that is measured as a ratio of the number of parcels within a one quarter mile network distance from a point to the number of parcels within a one quarter mile radius from the node. While the EWA can remove the problem with the PCA, it requires parcel boundary information for the analysis.

Table 1 Measures and their definitions

Measure	Definition
Block Lengths	The block lengths are measured from the curb to curb or from the centerline of the street intersection to the other centerline.
Block Size	block size reflects two dimensions of the block that can be measu

	red by the width and length, the area, or the perimeter.
Block Density	the number of blocks per a certain unit area
Intersection Density	the number of four-way intersections per unit of area
Street Density	the linear miles of streets per unit of land
Length of Cul-de-Sac	the median length of cul-de-sacs
Connected Node Ratio	the number of street intersections divided by the number of inters ections and cul-de-sacs
Link Node Ratio	the number of links such as roadway or pathway segments divide d by the number of nodes being intersections or the ends of dead-end streets in a study area
Alpha Index	the ratio of the number of actual circuits to the maximum number of circuits. It is equal to (the number of links – the number of no des +1)/(2*the number of nodes – 5). Between 0 and 1, higher va lues indicate a more connected network.
Gamma Index	the number of links in the network divided by the maximum poss ible number of links between nodes (3*the number of nodes –6). By the construction of the index, this feature indicates a percenta ge of connectivity with range between 0 and 1
Pedestrian Route Directn ess	the distance using the actual network divided by the straight line distance for two locations
Pedestrian Catchment Ar ea (PCA)	an area created by the walkable network distance divided by a cir cled area by the Euclidean walkable distance

A number of researchers adopted the some of the measures suggested above for evaluating street connectivity in their analyses. Randall and Baetz (2001) developed GIS based methodology measuring Pedestrian Route Directness (PRD) between residences and local destinations. The authors used the value of 1.5 as a critical value for "acceptable" level of street connectivity. The results indicated that the neighborhoods with the grid street patterns had the values between 1.40 and 1.48, and the values for neighborhoods with curvelinear street patterns ranged from 1.63 to 1.88.

In addition, the study selected a suburban neighborhood in Canada and showed that as additional pedestrian connectors are proposed in the neighborhood, the PRD measure between residences and the elementary school in the neighborhood is increased. The authors suggested that the PRD measure using GIS based tool would be useful for comparing conventional suburban developments with traditional and neo-traditional neighborhoods and measuring the improvement by altering design of an existing neighborhood.

Similarly, Hess (1997) compared two neighborhoods in urban and suburban areas. Hess (1997) found 1.2 of PRD for the grid urban neighborhood and 1.7 for the curvelinear street neighborhood in suburban area. The reason for this finding is that street miles in suburban neighborhood are less than half of street miles in the urban grid pattern neighborhood. Furthermore, block sizes for multifamily housing and commercial uses are significantly larger in the suburban neighborhood because of private parking and the internal street circulation system. The author concluded that medium density suburban neighborhoods face serious deficit of street infrastructure, especially pedestrian network.

Schlossberg and Brown (2004) compared eleven Transit Oriented Developments in Portland, Oregon in terms of the connectivity of walking environment. The authors pointed out the limitations of the street connectivity measures previously adopted in past research studies: Overall, the measures do not differentiate the pedestrian friendly street and less pedestrian oriented streets, thus treating all road segments as equally attractive for walking (Schlossberg and Brown, 2004, p.4).

Their study accounted for this limitation and modified the measures of street connectivity tailored to pedestrian walkability. For example, in calculating the intensity of intersections, the impedance-based analysis excludes freeways and major arterial roads from the dataset and only accounts for intersections derived by neighborhood street crossings. If a neighborhood street reaches a major arterial road, the node becomes dead-end street. This makes intuitive sense, because the intersections and dead-ends obtained from the impedance based analysis would be more consistent with how a pedestrian view the walkability of the environment

The results indicated that not all Transit Oriented Developments are walkable at the same degree. The selected TODs varied to a great extent in terms of pedestrian walking environments. The pedestrian impedance analysis introduced in Schlossberg and Brown (2004) appears useful method to evaluate pedestrian walking environment.

4. CASE STUDIES: COMPARING URBAN FORMS OF THE NEIGHBORHOODS

4.1 Selected Neighborhoods

For this study, three neighborhoods are selected based on the physical configuration of the street pattern. The Grand Lakes located in Katy was developed on the 1,400 acre land. The Grand Lakes community is chosen as the Radburn-influenced neighborhood with cul-de-sac street pattern. The overall community is divided into two sections by a major arterial and consists of six neighborhoods. Each neighborhood has a park at the center, connected through green pedestrian paths separated from automobiles. In each two large sections, an elementary school and shopping center as well as various community services (e.g., church, daycare) are located to serve the residents. Figure 1 shows the Grand Lakes master plan combined with aerial photograph.

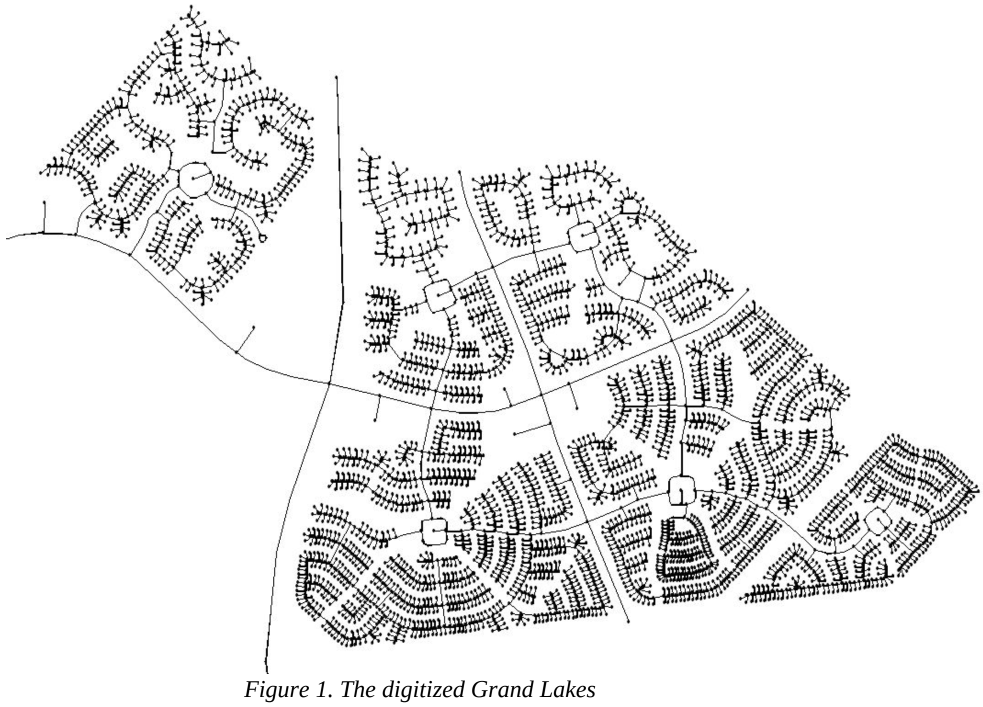

Figure 1. The digitized Grand Lakes

The street pattern and overall neighborhood plan of the Grand Lakes shows strong influences from the design concept of the Radburn plan. First, both communities are designed based on Perry's neighborhood unit concept. A section of both neighborhoods are centered on an elementary school serving residences located within each section. Also, in both cases, the hierarchical street pattern is laid out separating automobiles and pedestrians, and pedestrian paths are connected through public open space. The cul-de-sac streets are relatively shorter and less disoriented compared to the streets in current typical suburban residential developments.

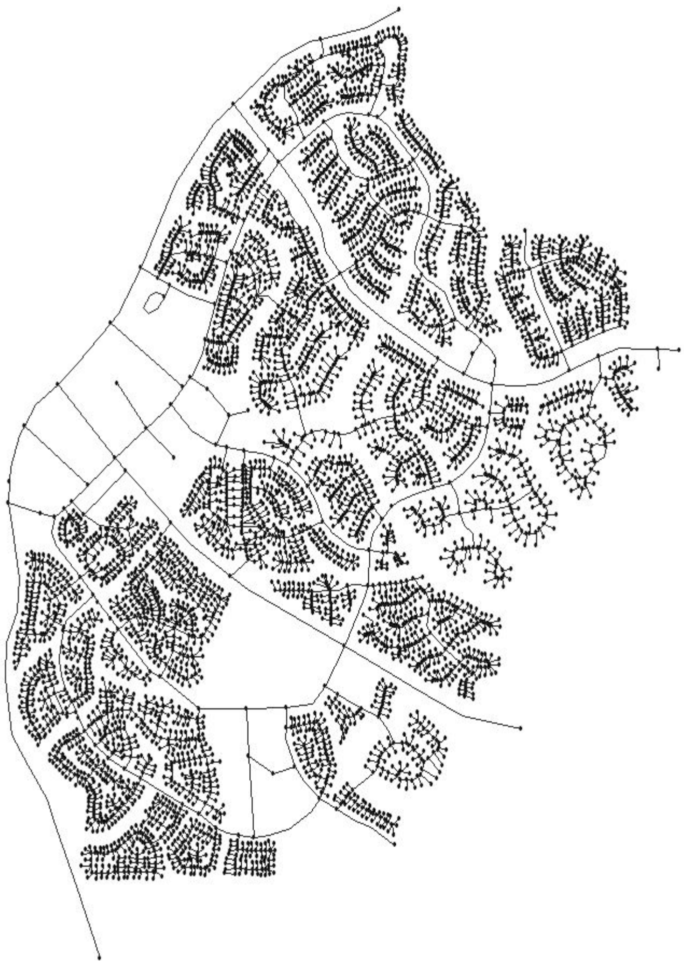

Figure 2. The digitized Woodlands

The Woodlands was selected to represent the neighborhood with conventional cul-de-sac street pattern. The Woodlands is one of the first master planned communities in the U.S. (ULI, 2003). The neighborhood was located on 27,000 acres of forest, 31 miles north of Houston. According to 2000 Census, its total population amounts to 56,000. The basis for the master plan of the Woodlands is a seven-village concept. As of 2003, six villages (Grogan's Mill, Panther Creek, Cochran's Crossing, Indian Springs, Alden Bridge, and Sterling Ridge) are completed. Each section contains major local attractions such as schools, shopping, community services and shopping, connected by a network of trails. In this study, we selected the 1,700 acre of Panther Creek Village to compare with other neighborhoods.

The cul-de-sac streets were generally more curvelinear and longer than those in the Grand Lakes. The community is famous for its ecological site planning by Ian McHarg. McHarg applied the concept of overlaying environmental constraints to identify the lands most suitable and vulnerable for developments. As a result, the overall neighborhood design accounted for the site's natural systems and their complex interrelationships. This ecological planning was the basis for creating land plan for the community. In particular, major arterials and collector roads were aligned away from drainage areas. (see ULI, 2003 for the detailed introduction of the Woodlands). Perhaps, McHarg designed the curvelinear and disoriented cul-de-sacs based on the environmental sensitivity analysis (Figure 2).

The Houston Heights in the inner city of Houston is selected as the grid street neighborhood. As a historic district of Houston downtown, it is located center of Houston, close to I-610. The neighborhood is distinguished from the other two neighborhoods in terms of street design: It has strict grid street pattern. Figure 3 shows the street network and location of Houston Heights.

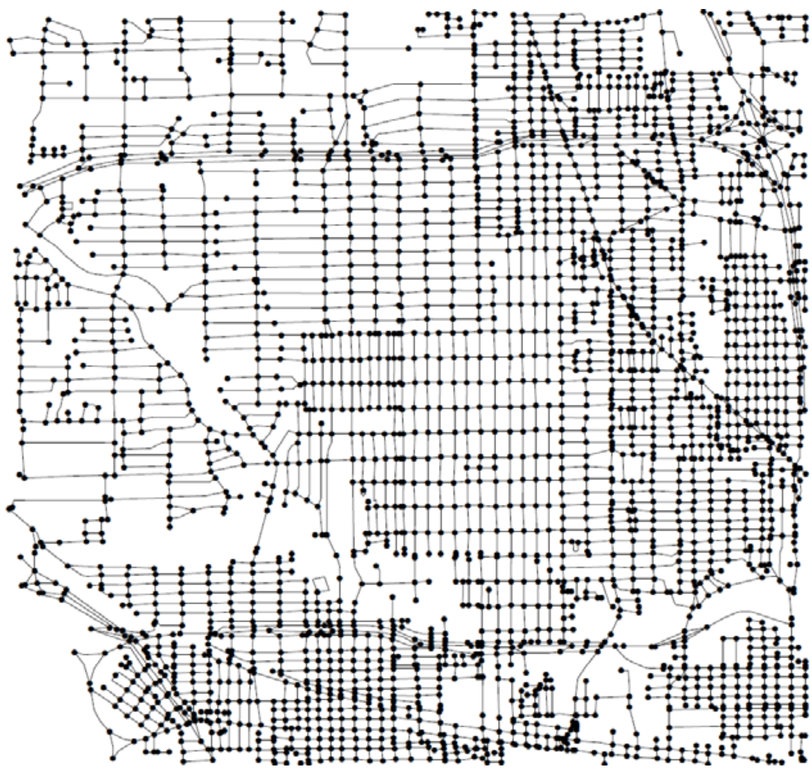

Figure 3 The digitized Houston Heights

4.2 Measuring Street Connectivity and Accessibility

From the studies reviewed in the previous sections, we adopted the following measures to analyze urban forms of the selected neighborhoods. The measures are selected because those are considered appropriate in applying to the neighborhood level analysis:

- Link-node ratio
- Percentage of cul-de-sacs
- Percentage of four-way intersections
- Street Density
- Alpha index
- Gamma index

- Pedestrian route directness (PRD)
- Pedestrian Catchment Area (PCA)

The eight measures above are selected to compare street connectivity and accessibility of three neighborhoods. The first six indices primarily measure street connectivity. In other words, the six indices measure the degree of "gridness" of the urban form. The indices of pedestrian route directness and pedestrian catchment area measure accessibility for pedestrians. Although both measures are highly correlated with street connectivity, they are based on the aerial and network distance from point to point. Using the two measures make more intuitive sense in comparing pedestrian and bicycle friendliness of the neighborhoods, because the distance has been considered as a major factor for walking and bicycling. In our study, the two measures are applied to each residence and major local destinations in the communities.

4.3 Preparing Data and TransCAD Functions used for the Analyses

To conduct analysis, three neighborhood plans are first digitized using the TransCAD GIS software. The links are considered to be along the centerlines of the roads, and centroids are assigned to all the residential lots. Dummy connectors are created to link each centroid and the street network. In the analyses, the length of dummy connector will be added when calculating the distances from residences to major neighborhood destinations. Theoretically, the dummy connectors are assumed to represent the distance from the front door of the residential unit to the street (Aultman-Hall et al., 1997).

To calculate street connectivity indices of link node ratio, Alpha and Gamma index, the required information is total number of nodes and the total number of links at the whole neighborhood. For measuring street density, we need to know the total lengths of the streets in a neighborhood.

To compute percentage of cul-de-sacs, we need to identify each line's starting and ending nodes (from-node and to-node). If a node is just once used either for starting point or ending point of a line, that node is the dead end of the cul-de-sac. The total number of such nodes means the number of cul-de-sac in the neighborhood. For the percentage of 4 way intersections, nodes that are used four times as a starting or ending point of lines. The number of such nodes is the same as the number of 4 way intersections in the neighborhood. Before computing percentages of cul-de-sacs and 4 way intersections, the external points that can be considered cul-de-sac should be removed from the digitized map.

For computing PRD, the centroids of the residences and major destinations are selected in TransCAD. Then, TransCAD can generate the distance matrix for measuring mean aerial distances and multiple paths matrix for calculating mean network distance from residences to local destinations.

4.4 Findings

Street Connectivity Indices

Table 2 presents the results of street connectivity in the three communities. Overall, the values of the measures indicate that the degree to which streets are inter-connected is higher in the Houston Heights than the Grand Lakes and the Woodlands. The result comes as no surprise, because the indices are proxy indicators for the level of "gridness" of the neighborhoods. Given that the physical configuration of the Houston Heights neighborhood are based on a strict grid street pattern, the street connectivity indices for the Houston Heights neighborhood should be higher than two other neighborhoods with cul-de-sacs.

Also, street density indicates that street miles divided by the size of neighborhood area are the highest in the Houston Heights. This reflects developer's concerns in the increase of infrastructure costs when developing the grid street neighborhood. The Grand Lakes neighborhood has shortest street miles among the three neighborhoods.

Table 2 Street Connectivity Index

	Houston Heights	Grand Lakes	Grand Lakes	The Woodlands
Street Pattern	Grid	Cul-de-Sacs without pedestrian paths	Cul-de-Sacs with pedestrian paths	Cul-de-Sacs only
Nodes	602	397	598	463
Links	365	353	432	509
Link Node Ratio	1.65	1.11	1.38	1.10
% Cul-de-Sacs	0.03	0.39	0.14	0.41
% 4-Way Intersections	0.82	0.06	0.10	0.08
Street Density	22.72	16.00	22.23	17.32
Alpha Index	0.33	0.06	0.19	0.05
Gamma Index	0.55	0.37	0.46	0.37

Accessibility Indices

Accessibility indices are calculated only for single family residences, since the multi-family housings only exist in the Houston Heights neighborhood. Mean aerial and network distances are measured from each residences (represented by the centroids of residential lots) to a major local destination. Based on the results, Pedestrian Route Directness (PRD) for each destination is determined.

First, accessibility scores of different land uses are compared within a neighborhood. Then, accessibility indices are compared between the communities in terms of land uses.

Accessibility: The Comparison within the Neighborhoods

Table 3 shows the accessibility indices for the Houston Heights neighborhood. In calculating the accessibility, local destinations within 0.25 mile buffer around the neighborhood boundary are also included.

Table 3 The Houston Heights Neighborhood Accessibility Scores (Miles)

Houston Heights	Aerial Dist	Network Dist	PRD	Median	Min	Max
Park 1	1.18	1.64	1.39	1.62	0.05	3.66
Park 2/Community 2	0.38	1.81	4.76	0.90	0.05	2.17
Park 3	0.99	1.21	1.22	1.19	0.04	2.97
Park 4	0.82	1.16	1.41	1.17	0.12	2.44
Park 5	1.11	1.43	1.29	1.42	0.16	2.76
Park 6	1.59	2.13	1.34	2.10	0.34	3.94
Park 7	1.13	1.43	1.27	1.46	0.10	3.05
Park 8	1.16	1.49	1.28	0.10	1.50	3.15
Park 9	1.25	1.60	1.28	1.60	0.19	3.30

Park 10	1.40	1.77	1.26	1.76	0.18	3.90
Park 11	2.09	2.36	1.13	2.34	0.29	3.98
AVERAGE	1.19	1.64	1.38			
School 1	1.38	1.90	1.38	1.93	0.05	3.98
School 2	0.92	1.21	1.32	1.08	0.05	3.21
School 3	0.87	1.08	1.24	1.04	0.06	2.69
School 4	0.79	1.04	1.32	0.98	0.03	2.38
School 5	0.91	1.17	1.29	1.04	0.04	2.84
School 6	1.02	1.32	1.29	1.36	0.19	2.98
School 7	1.85	2.29	1.24	2.28	0.30	4.01
School 8	1.02	1.31	1.28	1.28	0.09	2.62
School 9	1.04	1.32	1.27	1.31	0.06	2.64
School 10	0.84	1.11	1.32	1.13	0.01	2.32
School 11	0.88	1.25	1.42	1.24	0.20	2.54
AVERAGE	1.05	1.36	1.30			
Community 1	0.82	1.45	1.77	1.17	0.12	2.44
Park 2/Community 2	0.38	1.81	4.76	0.90	0.05	2.17
AVERAGE	0.60	1.63	2.72			
AVERAGE	0.95	1.54	1.63			

In terms of average mean network distance, all the land uses are located beyond walking distance from the residences. Mean network distances for elementary school are the shortest among other land uses. This trend also holds for PRD. The average PRDs for the elementary schools are higher than the average PRDs for community centers and parks. In sum, none of the land uses are within a walking distance on average from the residences. The elementary schools are the most accessible in the Houston Heights, but the network distance is longer than the distance pedestrians can easily walk. Especially, none of the residences are within an aerial walking distance from any of destinations in and around the community. It might be expected that automobiles would be dominant transportation modes to travel to major local destinations in the Houston Heights community.

Figure 1 shows the major local attractions in the Grand Lakes neighborhood.

Table 4 shows the results of accessibility analysis for the Grand Lakes neighborhood without considering separate pedestrian trails. For the sake of the analysis, the Grand Lakes community is largely divided into two sections (Section A and B in Figure 1) by the major arterial. The major arterials can be used for dividing the community, since they are major barriers for walking (Schlossberg and Brown, 2004). Section A is further divided into five parts in which a park is located at the center of the section. We assumed that residents are most likely to use the parks located in the section their residences belong to. Thus, accessibility indices for parks are calculated with residences in each section. Similarly, accessibility scores for two elementary schools and three retails are separately calculated for Section A and B. It makes intuitive sense that if qualities or amenities of the local destinations are similar, the residents are more likely to use the places that has the greater proximity from their homes.

Table 4 The Grand Lakes Accessibility Scores without Pedestrian Trails

Grandlake without Pedestrian Paths	Aerial Dist	Network Dist	PRD	Median	Min	Max
park1	0.20	0.35	1.75	0.35	0.15	0.59
park2	0.22	0.40	1.82	0.40	0.09	0.61
park3	0.26	0.51	1.96	0.49	0.11	0.93
park4	0.26	0.94	3.62	0.50	0.11	0.94
park5	0.18	0.33	1.83	0.32	0.11	0.56
park6	0.24	0.57	2.38	0.40	0.11	0.88
AVERAGE	0.23	0.52	2.29			
Retail1	0.75	1.18	1.57	1.18	0.29	2.32
Retail2	0.59	0.97	1.64	0.93	0.31	1.95
Retial3	0.50	1.10	2.20	0.99	0.67	1.31
AVERAGE	0.61	1.08	1.76			
school1	0.55	0.96	1.75	0.92	0.31	1.84
school2	0.42	0.82	1.95	0.79	0.29	1.15
AVERAGE	0.49	0.89	1.84			
AVERAGE	0.44	0.83	1.96			

Mean network distance for parks (0.52 miles) is the shortest compared to other land uses. In Figure 1, it may be obvious that a major design concept for the Grand Lakes is parks located at the center of each section of the community. Also, because of the way the measures are calculated, accessibility scores for the parks account for smaller area around the parks, while retails, schools, and church account for larger areas.

The average PRD value for parks is the highest, compared to other uses. It means that while the mean network distance to parks is the shortest, the locations of the parks are even more closely located within aerial walking distance (0.23 miles) from the residences. However, people need to travel more than twice of the walking distance (0.52 miles) perhaps because the hierarchical street pattern with cul-de-sacs makes pedestrian travels difficult despite the fact that they are closely located to the residences.

The mean aerial and network distances for retails, elementary schools and church serving larger sections of the community are far beyond the walking distance. Also, the average PRD for retails, elementary schools and church are similar and smaller than the mean PRD value calculated for parks.

When the separate pedestrian trails are considered in measuring accessibility in Grand Lakes, the values become smaller. Compared to Table 4 with Table 5, average network distance and PRD for parks, retails and schools are all significantly decreased. Also, the paired t-test between these differences in network distances are statistically significant with 99 percent confidence level.

Table 5 The Grand Lakes Accessibility Scores with Pedestrian Trails

Grandlakes with Pedestrian Paths	Aerial Dist	Network Dist	PRD	Median	Min	Max
park1	0.20	0.34	1.70	0.34	0.11	0.59
park2	0.22	0.39	1.77	0.39	0.09	0.59
park3	0.26	0.40	1.54	0.40	0.11	0.64
park4	0.26	0.42	1.62	0.42	0.11	0.88

park5	0.18	0.29	1.61	0.29	0.11	0.53
park6	0.24	0.39	1.63	0.38	0.11	0.88
AVERAGE	0.23	0.37	1.64			
Retail1	0.75	1.10	1.47	1.03	0.22	2.11
Retail2	0.59	0.87	1.47	0.83	0.19	1.74
Retial3	0.50	0.98	1.96	0.98	0.67	1.29
AVERAGE	0.61	0.98	1.60			
school1	0.55	0.89	1.62	0.24	0.84	1.68
school2	0.42	0.63	1.50	0.68	0.17	0.98
AVERAGE	0.49	0.76	1.57			
AVERAGE	0.44	0.71	1.60			

Overall, the parks in the Grand Lakes are located in each section are the most accessible, compared to other destinations. However, the network distance is two times greater than the distance pedestrians are generally willing to walk. Maybe this is because the hierarchical street pattern with cul-de-sacs is inefficient for pedestrian travels. The retails, schools and church are less accessible than the parks mainly because those land uses are serving larger areas. As was the case for the Houston Heights, it is expected that automobiles would be major transportation means for traveling to the local destinations except for the parks.

Table 6 presents the accessibility scores for the Woodlands community. The community is also divided into three sections by major arterials based on the same assumption employed in the accessibility analysis for the Grand Lakes: Pedestrians are most likely to use the local destinations located within the section they are living in, assuming that the qualities and amenities of the destinations across the whole community are similar.

It should be noted that the accessibility indices for Park 3 are separately calculated for Section 1 and Section 2, since Park 3 is located on the boundary of Section 1 and 2. Similarly, the accessibility scores for Elementary school 1 located in Section 2 are also calculated for all sections. Because Section 1 does not include a school, and Elementary school 1 is located at the center of the whole village, it might be expected that there are some children living in Section 1 or 3 attending Elementary school 1.

Table 6 The Woodlands Accessibility Scores

Woodlands	Aerial Dist	Network Dist	PRD	Median	Min	Max
Park1	0.42	0.79	1.88	0.61	0.15	1.69
Park2	0.49	0.77	1.57	0.78	0.16	1.29
park3_1	0.81	1.22	1.51	1.29	0.43	1.95
park3_2	1.01	1.41	1.40	1.50	0.31	1.95
Park4	0.55	0.82	1.49	0.78	0.09	1.71
Park5	0.58	0.94	1.62	0.96	0.36	1.76
Park6	0.59	0.93	1.58	0.94	0.07	1.81
Park7	0.56	0.94	1.68	0.92	0.03	1.74
Park8	0.46	0.74	1.61	0.73	0.09	1.23
AVERAGE	0.61	0.95	1.59			

school 1	0.59	0.85	1.44	0.80	0.09	1.81
school 2	0.51	0.81	1.59	0.81	0.09	1.32
school 1_ALL	0.77	1.18	1.53	1.20	0.09	2.17
AVERAGE	0.62	0.95	1.52			
Retail	0.91	1.32	1.45	1.31	0.40	2.41
AVERAGE	0.71	1.07	1.52			

On average, none of the local land uses in the Woodlands are within walkable distance from the residences. The mean network distances for parks and schools are both approximately 0.95 miles in length. Since the shopping center covers the whole Panther Creek village, the mean network distance is greater than parks and schools. In terms of PRD, the average PRD value for parks is the highest. Thus, while many parks are distributed along the village and closely located to the residencies on average, the ratio of the distance people need to travel to the aerial distance is the greatest.

Accessibility: The Comparison between the Neighborhoods

Accessibility scores produced for each community are compared. To do so, the accessibility scores are normalized using the following formula:

Normalized Distance
= (Average – Min)/(Max-Min)*

By this equation, all the network distances can be placed between 0 and 1, thus enable us to compare between neighborhoods. Table 7 summarizes average accessibility scores for the three neighborhoods. Accessibility scores for civic uses in the Houston Heights are excluded in Table 6, since the kind of uses do not exist in the Woodlands and the Grand Lakes.

Table 7 Accessibility Scores for the Three Neighborhoods

	The Houston Heights	The Grand Lakes without Pedestrian Trails	The Grand Lakes with Pedestrian Trails	The Woodlands
Parks Mean Network Distance	0.56	0.60	0.47	0.51
Elementary Schools Mean Network Distance	0.41	0.52	0.31	0.52
Retails Mean Network Distance	0.70	0.50	0.47	0.46
Total Mean Network Distance	0.56	0.54	0.42	0.50

Overall, total mean network distance calculated as average distance of all the mean network distance in a neighborhood is the shortest in the Grand Lakes with considering separate pedestrian trails. The mean network distances for parks and elementary schools are shortest in the Grand Lakes with pedestrian trails, while the Woodlands has the shortest mean network distance from its residences to retails. From the results, major findings can be summarized as follows:

- Separate pedestrian paths significantly increased pedestrian accessibility and street connectivity in a cul-de-sac neighborhood;
- Between the two cul-de-sac based neighborhoods, the neighborhood with design concepts focusing on better accessibility and interconnectedness has higher street connectivity and walkability than the neighborhoods without these design concepts; and
- Street connectivity and walkability of the cul-de-sac street design with separate pedestrian paths are comparable with or higher than those of the grid urban form.

5. CONCLUSION

The study revisited the largely accepted idea to deal with sprawl by replacing cul-de-sac/curve-linear street with the traditional checkerboard system in community design. Recent discussions suggest that a neighborhood with cul-de-sac street pattern can promote accessibility and street connectivity, if it is designed integrated with open space and pedestrian paths, while creating safe and quiet residential environments. A good example is the discarded old wisdom, the Radburn. To date, the past researchers did not acknowledge the potential of the cul-de-sac neighborhoods in achieving the benefits New Urbansits strive to accomplish. This study tried to fill this gap by comparing a conventional suburban neighborhood, a neighborhood with creative cul-de-sac street pattern, and the grid street neighborhood.

This study compares the three neighborhoods in terms of street connectivity and accessibility. The Houston Heights, the Grand Lakes and the Woodlands are selected based on their distinctive street patterns. The Houston Heights has a strict grid street pattern, while the Grand Lakes and the Woodlands are designed based on the hierarchical street pattern with cul-de-sacs. While the same concept of the hierarchical street pattern is used for the Grand Lakes and the Woodlands, the overall neighborhood designs show that the layout of the neighborhoods are different from each other. In the Grand Lakes, the cul-de-sac streets are designed centered around the parks in each section of the community, serving residences in internal blocks in the community. The cul-de-sacs are well-organized and integrated with public open space with pedestrian paths, as we have seen in the Radburn plan. In contrast, the overall neighborhood design of the Woodlands does not show any distinctive design concept or a pattern. The cul-de-sac streets in the Woodlands are more disoriented and culvelinear than the Grand Lakes, perhaps because the overall neighborhood plan is based on the environmental sensitivity analysis done by Ian McHarg.

The analyses of this study indicate that the neighborhood with cul-de-sac streets can provide higher accessibility for pedestrians than the grid street neighborhood. In other words, the benefits that New Urbanist proposal intends to achieve can be gained in a neighborhood designed based on the hierarchical street pattern with cul-de-sacs. This study shows that although the Grand Lakes utilizes cul-de-sacs, the degree of walkability is comparable with or better than the Houston Heights. Total mean network distance calculated as average of all the network distance is the shortest in the Grand Lakes. The mean network distances for parks and elementary schools are also shortest in the Grand Lakes. The mean network distance is considered the most reliable measures for indicating pedestrian accessibility, because the distance is a major factor for pedestrian travels.

This finding has an important implication for policy makers. For modifying our current development practices or proposing new development proposal to minimize automobile travels, developing the cul-de-sac street neighborhood in a way to increase pedestrian accessibility may be a better solution than proposing the New Urbansit grid neighborhood. Moreover, given that people have expressed preferences towards cul-de-sacs over the grid street pattern, it would be politically more feasible way to alter our urban forms. However, the street pattern alone cannot attain benefits such as high street connectivity and pedestrian accessibility. What is more important is the overall neighborhood design integrated with street network pattern. The grid pattern alone cannot promote pedestrian travels if local attractions are located far away from residences. Similarly, the cul-de-sac street community can encourage pedestrian travels if the street pattern is well-integrated with major destinations and public open space.

There exist several limitations in the present study, suggesting directions for improvement in the future. First, this study did not account for car free network, possibly present in the Grand Lakes and the Woodlands. Because pedestrian paths separated from automobiles are not necessarily form a linear way, it is difficult to digitize those paths. More data such as aerial photographs are required to properly digitize pedestrian only circulation systems. This study implicitly assumed that all road segments are as equally attractive for walking. Second, most residential cul-de-sac streets are car-oriented and not likely to have sidewalks. The sidewalk availability has been found as a significant l factor for encouraging non-motorized transportation mode (Rodriguez, 2004). Future study can overcome the limitations by incorporating more data.

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Moses: Planning for the Next Generation

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Abstract: The study of population changes has always been at the centre of public policy and planning. People's movements, interactions and behaviors will inevitably have an important impact on the society and environment that they are living in. At the same time, such changes will also lead to an evolution of the population itself over time. Advances in technologies and new tools often bring new visions to such studies. To facilitate strategic decision making and to plan developments for a more sustainable future, it is vital to study and understand the changes in our population. This paper introduces Moses, an individual based model that simulates the UK population through discrete demographic processes at a fine spatial scale for 30 years from 2001 to 2031. The modeling method is grounded in a dynamic spatial MicroSimulation Model (MSM), but also introduced Agent Based Model (ABM) insights to strengthen the modeling of movements, interactions and behaviors of distinctively different sub-populations. The MSM can not only produce projections of baseline population with rich information on individuals to facilitate various studies, it can be also useful in providing an assessment of multiple scenarios for different planning applications. In this paper, we will demonstrate three spatial planning applications in the areas of residential land use planning, public health planning and public transport planning. Whilst the demonstrations are deliberately made simple, the contribution of intelligent agents in the modeling of interaction, behavior and the impact of personal histories on demographic changes is clearly shown. Within this framework, it enables researchers to effectively model the heterogeneous decision making units on a large scale, as well as provide the flexibility to introduce different modeling techniques to strengthen various aspects of the model.

1. INTRODUCTION

It is in the nature of human beings to plan for their future. People, cities, and societies (and their past, present, and future) therefore have never failed to capture the fascination of researchers and modellers. Due to its vital role in human society, the population evolution patterns have always been at the centre of public policy and planning. Modern planning and policy making now demand detailed information on individual decision making units during a longer period of time to facilitate strategic decision makings. People's movements, interactions and behaviors will inevitably have an important impact on the society and environment that they are living in. At the same time, such changes will also lead to an evolution of the population itself over time. Advances in technologies and new tools often bring new visions to such studies. Computer based models have now been extensively used in modeling complex social systems, not only because they can provide valuable groundwork when it is too expensive or impossible (for practical reasons) to experiment in reality, but also new research methods enabled by the capabilities of modern computers can radically transform human ability to reason systematically about complex social systems. This has become increasingly important as our world today confronts rapid and potentially profound transitions driven by social, economic, environmental, and technological changes.

Simulation games of urban areas have been phenomenally popular in recent years. The underlying aim of the research reported in this paper is to translate such games into real world policy environments. If planners were equipped with the means (through simulation) to understand social and demographic changes in response to shifts in policy, such a device would have valuable practical applications as both a "decision support system", and as a pedagogic tool for understanding how cities work. Of course such interest is not unique: transportation and land use models such as URBANSIM project (Waddle, 2002), DELTA (Simmonds, 2001) and ILUMASS (Strauch *et al*., 2003); models of residential location and urban housing markets (Benenson *et al*., 2002) together with models of retail provision (Clarke *et al*., 2002), labor markets (Ballas *et al*., 2006), education (O'Donoghue, 1999) and health care systems (Smith *et al*., 2005). An increasing interest in models which represent the behavior of individual entities or 'agents' has generated policy-relevant applications to problems of disease control (Ferguson *et al*., 2005), transportation (Travelogue, 1996) and urban energy markets (Mozumder and Marathe, 2004).

Previous researches have pointed out that it is not possible to understand population changes properly without looking into the individual changes (van Imhoff and Post, 1998). At the same time, human activities have a strong spatial dimension, after all, "One cannot be at two places at the same time" (Hagerstrand, 1967). From a planning/policy point of view, "Means are to be employed somewhere" (De Man, 1988). Essentially, people have to live in a local area and they are affected by what goes on around them. Although certain demographic patterns have been found to persist in some geographical areas, it is difficult to identify the drivers as this is often the outcome of complex interactions between multiple factors. To capture all the factors within the modeling process can cause a series of theoretical and practical issues. Location provides a useful substitute when such information is hard to get and model, as the spatial variance can demonstrate to a degree of the impact of the demographic, social economic, environmental, as well as life style differences. Taking into consideration the spatial dimension, the population can be simulated within a local context and picks up on geographical characteristics.

In this paper an individual based model, Moses (Modeling and simulation of e-Social Science), will be introduced. To better model individual movements, interactions and behaviors, Moses adopts a hybrid modeling approach that combines the strength of both MicroSimulation Model (MSM) and Agent Based Model (ABM). Using the results produced by the model, three spatial planning applications have been described to demonstrate the potential usage of the model: One is to assist the planning of university student accommodation as part of the residential land use planning; the second is to assist health care resource allocation from the projection of mortality and morbidity in small areas; the third is to assist the transport planning through a simulation of interactions between the population changes and infrastructure changes to generate indicators of sustainability in terms of emission/air pollution.

2. METHOD

One of our central aims, and which forms the heart of this paper, is therefore to produce a simulation model of the UK population, as it now is and as it can be expected to develop over a thirty year time horizon. As a fundamental basis for our approach, the technique of microsimulation has been adopted. Microsimulation has a fifty year history as a technique within economic analysis (Orcutt, 1957), while more recent applications of spatial microsimulation have embraced problems such as transportation, healthcare and housing (Wilson and Pownall, 1976; Magne *et al*., 2000, Brown and Harding, 2002). The benefits of MicroSimulation Model (MSM) (in contrast to macroscopic modeling approaches with similar objectives) within a demographic modeling context have been argued persuasively and eloquently by van Imhoff and Post (1998). In short, an MSM describes each individual with its particular characteristics. Therefore MSM has obvious advantages over a macrosimulation model that is based on stochastic differential equations and the population is described in aggregated terms by the number of individuals in different states (Brown and Harding, 2002). In particular, these authors demonstrate the richness of microsimulation as a device for the representation of both relationships between members of a population, and of the transitions between states within a population.

Despite its many strengths and advantages, we argue that a microsimulation model of a spatially distributed population depends on good data about the important transitions which are experienced by individuals. Problems can therefore arise in at least two regards: firstly, when data is available, but only at aggregate scales; and secondly, when empirical data is difficult to access in any form. Agent Based Model (ABM) represents the individual decision making units as interacting agents with built-in intelligence. Such intelligence will then guide agents to make decisions and take actions during their interactions with other agents and the environment that they live in, according to their individual attributes and rules. The ease of introducing unique rules for different agents without affecting the remaining agents/components in the ABM helps us to improve the MSM when there is a knowledge gap or unavailability of data (Wu *et al*., 2008). ABM approach also enables the modeling of heterogeneous agents to represent individuals with distinctive characteristics and behaviors within the system (Axtell, 2000). This accommodates the need of the study of interactions within various sub-populations and the environment that they live in. This paper is therefore unique in its synthesis of the approaches of MSM and ABM.

Moses simulates the UK population through discrete demographic processes at a fine spatial scale for 30 years from 2001 to 2031. MSM projects population evolution patterns through the individual changes by applying transition probabilities according to individuals' demographic and spatial characteristics to update relevant attributes, using a Monte-Carlo simulation through six important demographic processes: Ageing, Mortality, Fertility, Household Formation, Health Change and Migration. The simulated output then becomes the base-population for the next year's simulation so that impact of previous year can be captured within the model. Each component of change is constructed separately but individual components can also interact with each other during the simulation. For instance, Household Formation will lead to migration in many cases. Due to the statistical nature of the MSM, it is inflexible to accommodate distinctively different behaviours of individuals, especially where microdata are unavailable. ABM elements are implemented to provide the flexibility of behaviour modeling. Individuals are modeled as "agents" that can stop following the "external rules" from the MSM probability-based simulations and start to act and react according to their unique built-in "internal rules" according to individual characteristics. For instance, individuals aged 19 to 30 in full-time education are modeled as "university student agents". In the Migration process, they only stay in a city for a certain period of time according to their higher education programs, then leave upon graduation. They prefer living close to their fellow students and the universities, subject to accommodation availability. More details of the agent elements of the hybrid model are described in section 3.

The population and its dynamics are described through the application of the model to the urban area of Leeds, a city of 730,000 people in the north of England. The Leeds area is used for illustrative purposes throughout this paper, but this model is completely generalizable between local areas across the country. As population is at the center of any public planning and policy, this model can be used to facilitate a range of policy making and public planning. Three applications in the areas of Land Use, Public Health and Public Transport have been described in the following sections to demonstrate some of the potential applications of the model.

3. RESIDENTIAL LAND USE APPLICATION: STUDENT ACCOMMODATIONS

Migration is a complex demographic process where interactions and behaviors play an important role and this is difficult to model. Due to its central geographical location in UK and its reputation for university education, Leeds has been attracting students to get their higher education from all over the UK. Leeds also has an important place in the international market for student recruitment. University student migration is an important component of Leeds migration and student accommodation areas are an important part of the residential land use planning. Therefore the model needs to capture the interactions between the student migration and accommodation demand in small areas. However, it is difficult to model the distinctive behaviors of individual student migrants using MSM, due to its statistical nature. As a result of students joining the general migration process, the MSM results in a considerable number of students reside in suburban areas and many students continue to stay in Leeds after their study and grow old in the central area. This projection is not an accurate reflection of the reality (Wu *et al.,* 2008). Therefore a hybrid approach combining MSM and ABM techniques is adopted to strengthen the modeling of the subtlety of the local migration patterns in our model and the behavior modeling of the student migrants, as this is less well studied and lacks an appropriate theoretical basis in MSM. The main advantage of using ABM here is that it is relatively easy to introduce heterogeneous agents with distinctive behaviors that are not mathematically tractable, as ABM is most useful for problems where ‘‘writing down equations is not a useful activity” (Billari *et al*., 2002).

Assumptions used in this application are similar to the behavior in housing choice that is described in Schelling’s famous model of housing segregation (Schelling, 1971), suggesting that people have the tendency to live where ‘‘similar” types of residents to themselves are. In the Migration process of the hybrid model, “university student agents” do not follow the “non-student” migration probability-driven simulation steps, instead they follow their built-in rules to interact with other agents and the environment to achieve the goal to move to the areas where their fellow students stay. The typical interaction of a “student agent” with another would be “finding my fellow-students in the area they stay” and the typical interaction with the “environment” will be checking if the targeted area has a vacancy for the student to move in. Thus the “student agents” move around and interact with each other and their environment, as well as make decisions and take actions according to their individual rules that developed under simple assumptions described above. The heterogeneous migration behaviors of student migrants therefore can be captured within the projections and annual replenishment of young population has been achieved in small area population projections. In Figure 1, the hybrid model results in 2030 have been compared with the results generated using pure MSM and the observed in 2001.

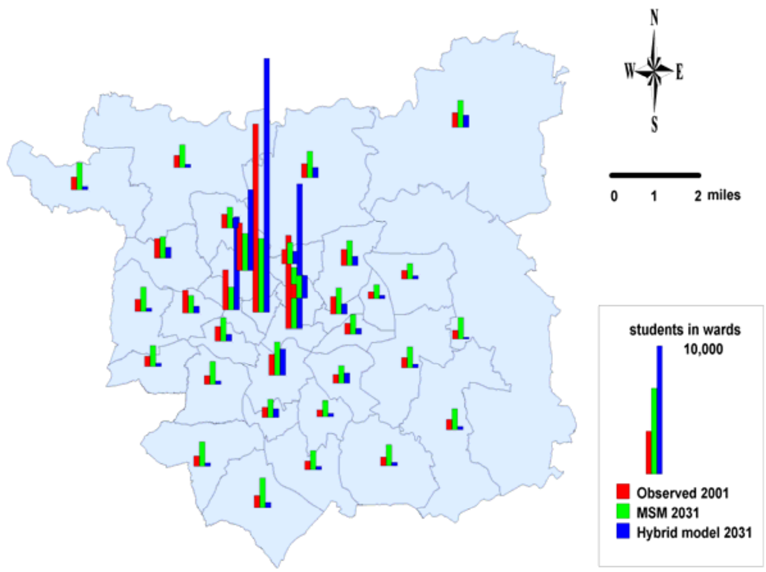

Figure 1. Residential land use application: students in small areas 2001 and 2031
Source: Wu *et al*., 2010. Census data and area boundaries are Crown copyright 2003

As we can see, the map shows that there are both clear concentrations of the student populations in the city centre areas that are close to the university campuses in Leeds. In contrast, the MSM result suggests an even distribution of the student population throughout the whole city, even in the suburban areas.

The hybrid model therefore can provide a better groundwork for the residential land use planning by producing more accurate projections of the sub-population of university students. In terms of the strategic planning of the land use, the concentration of student population in the centre of the city gives a clue to the location choices when planning the residential land use for student accommodations. The projection of the student population in small areas in the future can also provide an indication in terms of the volume of land use demand and the number of housing units in the small areas in the future. This application has been developed with deliberate simplifications, but it demonstrates the potentials of the hybrid model. With minor modifications according to the specific residential land use purposes, this model can be used to explore various residential land use purposes, for either the whole population within the studied system or with a focus on certain sub-populations. As the model produces annual projections and previous impact is captured in the next year's simulation, the model results can be used not only to facilitate short-term planning purpose, but also for longer-term decision making.

4. PUBLIC HEALTH APPLICATION: MORTALITY SCENARIOS

One of the advantages with simulating geographically identified populations is that the local context can influence the individual characteristics to a degree. Such information is important for public health planning. However, sometimes it is not only the current small area that influences behavior, but the places that individuals originally came from or used to live in often also play an important role. In some demographic processes such history can have a great impact. One simple example can be: the mortality/morbidity risks of the miners should not suddenly change a great deal once they retired to a pleasant residential area. In order to model such impacts, we need to assess individuals' behaviors using information from their personal histories. An ABM can meet such requirements with much more ease than a MSM, as agents can simply have a function to retrieve specified information from their own history that they carried along. Based on the hypothesis that mortality/morbidity probabilities depend on not only their current personal and environmental conditions, but also on their personal histories, we explored 3 scenarios of mortality projections in the Moses hybrid model that are based on current destination location, original residence location in the system/birth places and personal migration histories specifically. Take a simple example of an individual migrant that can be called A here. If his origin is ward 1 and in the last 5 years his migration destinations are: ward 2 in year 1, ward 2 in year 2, ward 2 in year 3, ward 3 in year 4, ward 4 in year 5. Then in the 1st scenario, migrant A will check his current location and his mortality probability in year 6 will be determined against the age-sex specific probability in ward 4 that corresponds to his age-sex group; while in the 2nd scenario, his mortality probability will be based on his age-sex specific probability in his origin: ward 1; in the 3rd scenario, his mortality probability will be based on his age-sex specific probability in the area that he stayed the longest, ward 2. Such changes in the individuals, both different types of migrants and non-migrants, can be interesting for various researches and will result in significant changes in local population structure (Wu *et al*., 2010).

Projection results under different assumptions after 30 years have been compared spatially to assess the difference in the mortality distribution of the city in 2031. Although the distribution patterns of the mortality in three scenarios all look similar on the whole, the experiments reveal some interesting variations in small areas. We can see from the map (Figure 2) that there tend to be a higher mortality in the more established suburban wards in the north of the city in scenario 2 than in the current residence based projection. In comparison, scenario 3 indicates a reduction of mortality than in the current residence based projection in the northern suburban areas. It also indicates an increase of mortality in the southwestern belt around the city centre, as well as in a strip in the eastern area of the city. The mortality projection based on individual migration history in scenario 3 seems to differ from scenario 2 by indicating more deaths in traditionally immigrant/more deprived areas in the city. Such findings demonstrate that personal history could have an important impact on mortality (Figure 2).

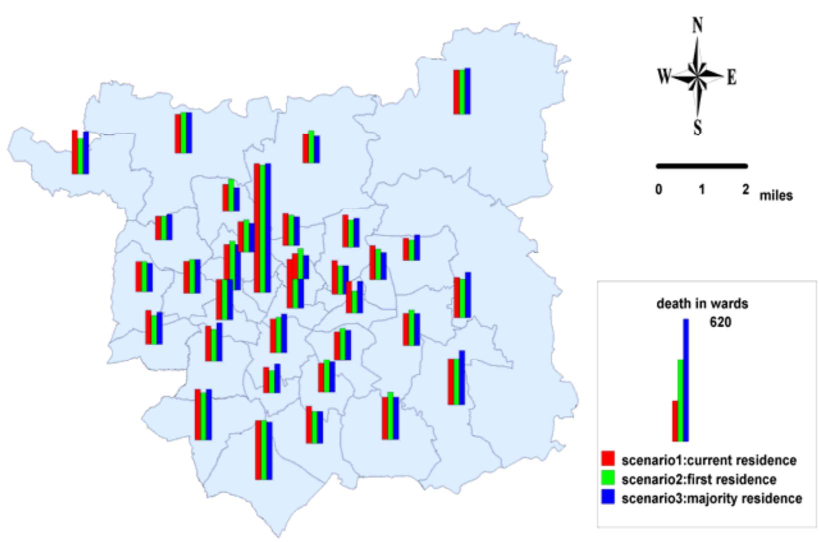

Figure 2. Public health application: mortality scenarios in small areas 2031
Source: Wu *et al*., 2010. Census data and area boundaries are Crown copyright 2003

Empirical research on the relationship between limiting long-term illness and migration established that the illness status of migrants is mid-way between that of their origin and destination locations (Norman *et al*., 2004). If this finding also applies to mortality, then a combination of all three scenarios may be needed to represent the mortality chances of migrant properly. We will continue to improve the mortality projection in the light of such evidence. Although the mortality experiments discussed here are purely based on hypothesis, it demonstrates that there are many more aspects of the population MSM which can be strengthened through the use of ABM techniques. Important elements of the model such as marriage behavior, fertility patterns and change in health status might all benefit in a similar way. Such explorations are not only just interesting experiments, but potentially can play a vital role in facilitating the decision making where the impact of personal history is required to be taken into account.

As it demonstrated in this application, the hybrid model enables us to monitor the changing patterns in individual demographic processes in the studied population in small areas, assess the impact of personal history under different scenarios of personal history circumstances and explore the relationship between the mortality rates and different environments. Such features can provide useful information to assist better grounded and targeted plans for the public health planning. In this application, the results indicated that the projection of mortality may need to take into account the impact from not only the destinations or origins of the modeled individuals, but also the impact from the personal migration histories. Such information can be useful for both strategic and tactical health planning. In terms of strategic planning, it helps planners to assess the impact on mortality in different scenarios and devise appropriate interventions; in terms of tactical planning, the variations in mortality in small areas can provide an indication to the public health service and support provision in the areas that are worse off than others. Again, with minor modifications, this model can applied to any other demographic process or sub-population to facilitate various planning purposes.

5. PUBLIC TRANSPORT APPLICATION: IMPACT OF NEW INFRASTRUCTURE

New public infrastructures are expensive and have great impact on our society. At the same time, population evolution patterns (e.g. ageing trend), must be taken into account during the development of new infrastructure. Therefore careful consideration should be given to the evaluation and assessment of potential impact on small areas and more importantly, the people who live there. Public transport systems can affect many aspects of people's life: while they play an important role in social inclusion by providing the deprived population with access to training, education and employment opportunities, as well as access to various public services, it can, on the other hand, cause problems such as traffic congestion, air pollution and noise. In fact, transport sector significantly contributes to CO_2 emissions growth in many countries and accounts for 23% of global CO_2 emissions according to the statistics of (IEA, 2007). The excess use of private travel means does not provide a sustainable environment for our society and has already had a serious impact on climate changes globally. Therefore in order to reduce the effect of motorization on environment/climate changes, viable planning and policies need to be implemented to encourage a significant modal shift onto public transport (NETCEN, 2003), as well as provide an optimized structure of urban transport modes. Using the hybrid model, the interactions between the population changes and the environmental changes can be simulated. In this application, we developed a scenario where two new supertram lines are being built in Leeds to encourage the people in the city to adopt more sustainable urban transport modes. The tram lines are running from the city centre to the north-east and north-west. Based on the assumption that many people will switch from their current transport modes by private cars to the use of supertram, we then assess the impact of such changes on air pollution in small areas.

We assess the air pollution on the basis of CO_2 emissions in our simplified transport application model. CO_2 emissions are calculated on the basis of the transport average speed that is determined by the urban transport condition. The speed-emission factor coefficients are calculated according to the vehicle speed emission factor database (Waterson *et al*., 2003) in grammes per kilometer to average speed, for different types and engine size of vehicles and in all the categories of European emission standards from pre-Euro I to Euro II (Liu *et al*., 2009). The impact made by the introduction of the new public transport infrastructure can then be assessed in the pollution map of Leeds (Figure 3). The shading shows the impact of the supertram on pollution by different colours: the colour of red means that the change has a high impact in the small area, while yellow means medium and green means low impact. As we can see in Figure 3, the introduction of the tram lines has made a high impact in the city centre and the north. There is a medium level of impact in the areas from city centre towards the north and the southwest areas. The impact is the smallest in southeast areas of the city. In comparison, impact is greatest in the northern corridor where residents can access both tram routes. This may indicate that there will be more demand arising from passengers in the north suburban switch from the privately owned transport means to the public transport, as the new supertrams can provide them with a more efficient way of travel. Although city centre areas also have the access to both lines, the lower level of impact may indicate that many passengers in city centre are already using public transport as their preferred travel means due to the easy access to public transport services. On the other hand, in the south of the city, where there is no direct access to the tram lines, the pollution map indicates a higher impact in the southwest than in the southeast. This may indicate that there are easier accesses to links to tram services in southwest of the city than in the southeast. More work to improve the accessibility of the public transport network may encourage more travel modal shift in the southeast of the city.

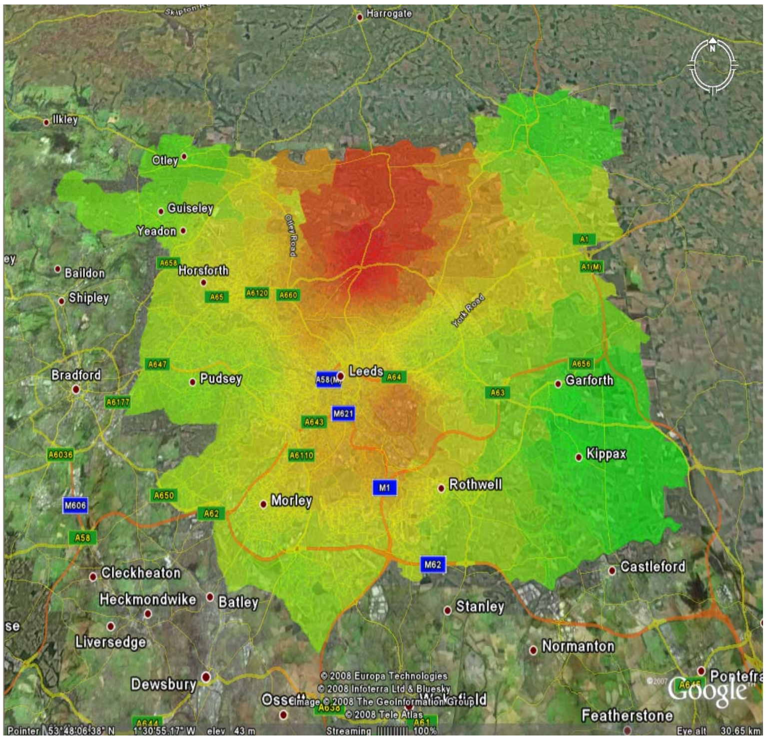

Figure 3. Public transport application: impact of the supertram lines in small areas
Source: Birkin, 20008. Census data are Crown copyright 2003

As demonstrated in the public transport application model, the hybrid model can assist the planners to assess the environmental changes before they implement practical plans in the city. Using the model, various locations can be selected for various transport infrastructure development and different scenarios can be constructed to explore different “what if” situations. The modeling of other aspects of the transport system changes is also possible, for instance, with minor changes, the model can be used to assess traffic congestion and average journey times in the city etc. The results produced by the application model that demonstrate the environment changes can also be used in various studies that can further explore the interactions between the environmental changes and population changes to assist the transport planning through a range of transport simulations and generate indicators of sustainability.

6. CONCLUSION

In this paper, we introduced Moses, an individual based model that simulates the UK population through discrete demographic processes at a fine spatial scale for 30 years from 2001 to 2031. Population changes are simulated at the individual level : Ageing, Mortality, Fertility, Household Formation, Health Change and Migration. The modeling method is grounded in a dynamic spatial MicroSimulation Model (MSM). MSM can model the impact on individual decision units from the changes in strategic planning or government policies (Wu *et al.,* 2008; van Imhoff and Post, 1998), but Moses also brings in the strengths of Agent Based Models (ABM) to enable the modeling of heterogeneous agents to represent individuals with distinctive characteristics within the system (Axtell, 2000). This accommodates the study of sub-populations with distinctive characteristics and behaviors. The ease of introducing unique rules for individual agents in ABM also helps us to provide a better representation of the studied population when there is a knowledge gap or unavailability of data (Wu *et al.,* 2008; Billari *et al.*, 2002).

Experiments carried out to date using this individual-based modeling approach have generated encouraging results. Not only can Moses produce better projections of baseline population for various demographic research purposes, it can be also useful in providing an assessment of multiple scenarios for different planning applications. For instance, using ABM to model the migration process of university students not only provides a better reflection of the unique student migration pattern in our population model and provides a better projection in small areas, it also provides a better groundwork to plan the residential land use for sub-populations with distinctive behaviors, such as university student migrants in small areas. This provides vital information for demographic planning/policy making (especially location based policies). Moses can also benefit other public policy making or public service planning. For instance, the ageing trends in certain suburban areas may promote changes in health service and public transport service provision in order to enable easy access to such services for the old and frail in the area. The rich attributes captured in the system are also very useful in various policy analyses or research purposes, especially in exploring various “what if” situations and testing different hypotheses. This hybrid modeling approach demonstrates great potential in demographic modeling to accommodate the distinctive behaviours of sub-populations and the applications are by no means limited to the examples which have been introduced in this paper. Similar illustrations with relevance to education, policing, land use planning or a wide range of commercial and business problems could equally well have been used. With further development and refinement of the model, we envisage that further model refinements will show its utility across a wide variety of social science domains and policy applications.

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The Effect of Landscaping on the Thermal Performance of Housing

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Key words: Urban heat island, single-family house, thermal performance, landscaping, evapotranspiration

Abstract: The heat island effect influences most of the major cities around the world. This urban phenomenon occurs because air temperatures in densely built urban areas are higher than the temperatures of the surrounding rural countryside. In tropical cities, the exterior environment is already extremely warm due to high air temperatures, especially during dry seasons. However careful planning and development of exterior spaces can reduce the adverse impact of these temperatures. This paper investigates the effect of landscaping on the thermal performance of housing in a hot-humid tropical climate. The climatic parameters, physical characteristics of building construction, and landscape design of three private houses in Shah Alam, Selangor, Malaysia were measured and surveyed. The study focuses on the potential impact of shade trees and different types of foliage on the thermal performance of houses of different ages. Sets of instrument were placed in several outdoor and indoor locations around the houses. Result show that the outdoor air temperatures of the well-landscaped houses were usually lower compared to the minimally-landscaped house. The main findings show that well-designed landscaping around single-family houses could potentially reduce heat build-up by shading, evapotranspiration, and wind channelling by as much as 3°C.

1. INTRODUCTION

The urban heat island effect, an influence in most major cities around the world, is well documented as an urban phenomenon. Buildings and paved surfaces in urban areas encourage the absorption of solar energy into building structures, roads and other hard surfaces. The absorbed heat is subsequently re-radiated, creating an increase in the surface temperature of urban structures of up to 5.5–10°C (Akbari, Davis et al. 1992). As the urban surfaces become hotter, the overall ambient air temperature can increase by as much as 2–8°C. The larger the city, the more intense the summer heat island effect (Oke 1973) and the magnitude of discomfort and associated air conditioning load (Akbari, Taha et al. 1986). Taha et al. (1988) state that residential building are particularly sensitive to high levels of heat since they are envelope-dominated structures. On hot summer days, this urban phenomenon contributes significantly to the urban dweller's discomfort. Appropriate planning and design of residential buildings to take account of these concerns is becoming more important. Well-designed and strategic locations of landscaping around single-family houses could potentially reduce heat build-up by shading, evapotranspiration, and wind channelling by as much as 3°C during peak time of the day.

In tropical cities, the external environment is extremely warm due to the high air temperatures especially during dry seasons. The planning and development of exterior spaces can reduce the energy consumption of buildings by reducing the adverse impact of some climate factors. If the microclimatic condition around the building is very similar to the desired interior condition, little extra energy is required. Conversely, if the microclimate is significantly different from the desired interior conditions, large amounts of energy may be required for cooling (Brown and Gillespie 1995). Solar heat passing through windows and absorbed through the walls and roofs is the major source of heat flow into buildings. Landscaping can have a particularly effective influence on microclimate and associated building thermal performance and is one of the simplest strategies to reduce solar heat gain (McPherson, Herrington et al. 1988). Strategically placed vegetation around a building has been recognised as a means of cooling. It reduces the amount of radiation falling on the building by shading, by moderating temperatures, by the evapotranspiration processes, and by controlling wind direction to assist in keeping the building cool. The appropriate amount, type and placement of vegetation can slow heat build-up on a hot summer day. However the effect of the immediately surrounding vegetation on the thermal performance of single-family houses in a tropical environment has not been widely recognized or quantified.

The study will focus on the potential impact of shade trees and different types of foliage on the thermal performance of houses of different ages in hot-humid tropical climates. It will present propose a methodology, state site selection and climate characteristics, identify house selection and landscape design, and clarify the results and discussion.

2. METHODOLOGY

Research methods in this study were divided into three parts: house selection, observation, and field measurement. The aims of the house selection were to identify and choose similar building constructions and site locations that were sufficiently different in their amount of landscape structures and design. The aim of the field measurement programme was to evaluate and compare the surrounding microclimate which would directly influence the interior thermal performance of the house. The local weather recording was carried out during daytime on 23, 24, and 28 February 2010. Weather on these three days was very similar, where there was sunshine for the whole day, with rain starting softly at night time at 19.30 hours. The study measured climatic parameters and the physical characteristic of the four azimuths of the houses. Each measurement point represents an area of 90m² and an approximate 3–10m radius around the fixed/mobile weather station. The measurements were taken at 30-minute intervals in all locations at a metre above the ground and in the shade. The albedo data for every type of building envelope was also measured during the daytime.

2.1 Outdoor space

The field measurements were carried out on private single-family houses with permission to do surveys during the daytime. The weather measurements were not influenced by shadows or reflected solar radiation. The surface area of the gardens was variously covered by planting including trees, shrubs, groundcover and turf. The basic measuring equipment used for the field measurements included:

i. Two sets of mobile TSI VelociCalc Plus Meters, model 8386, data loggers and sensors. This was to measure surface temperature, wetbulb temperature, drybulb temperature, humidity and wind velocity.
ii. Two sets of portable data acquisition devices, model Babuc A code BSA014, multi-datalogger and sensors to measure air temperature, global temperature, relative humidity and wind velocity.
iii. Two sets of Lux meters PCE-172 to take the albedo measurement.
iv. Two sets of compasses and measuring tapes to ensure and confirm the measurement of the house configurations.
v. A set of drawing equipment to draw and record the house configurations and landscape plans in scale and detail on site.

The same data recorded from two types of equipment at the same time was to validate the data and to ensure all data was accurate.

Figure 1. Babuc A (left), mobile TSI VelociCalc Plus Meters (middle), and Electronic Mini Thermohygrograph (right)

2.2 Indoor space

Four sets of Electronic Mini Thermohygrograph, model testo 175-T2 (Figure 1) were used to measure air temperature, and air humidity data inside the buildings. This equipment was set automatically and placed at a metre above the floor near the windows which faced the four azimuths on the ground floor of the houses.

3. SITE SELECTION AND CLIMATE CHARACTERISTICS

The three houses are located in Shah Alam (3°N Latitude and 101°E Longitude) at an elevation of 27 to 47m in a hot-humid tropical climate. Shah Alam is best known as one of the well-planned cities in Malaysia, the capital of Selangor State, and has actively practised landscaping as part of its sustainable development. The image of Shah Alam as an exclusive ‘city in the garden’ was to emphasize that every development must be balanced with green space. The specific locations for the three single-family houses are at Sections 6, 9 and 11, in the central city. The size of these three sections of low density single-family housing is more than 0.5km^2 each. They represents around 20–30% of the whole residential development with up to 50 houses in each section.

3.1 Site selection

The study was carried out on three single-family residences, one in each of the three sections. The three houses were chosen because of their different ages of construction and hence also different ages of the surrounding landscaping. These were termed 'mature', 'ordinary' and 'new'. The mature landscape house was located in Section 6, and is 30 years old; the house with the ordinary landscape was 10 years old and is situated in Section 11; while new landscape house was located in Section 9 and is 5 years old. The houses in each neighbourhood were surrounded by houses of similar age and landscaping.

3.2 Climatic setting

Two years of climate data (2008-2009) were obtained from the nearby Subang Airport Weather Station. The averages for the dry and rainy season are shown in Table 1. The common characteristics of a hot-humid tropical climate are clearly shown in the study areas where the temperature ranges are from 24–33°C and relative humidity is between 72 and 78%. Precipitation was very heavy throughout the year, with an annual average of about 3100mm with 202 days of rain. The dry season occurs with the south-west monsoon which starts in the latter half of May and ends in September, and the prevailing wind flow is generally south-westerly and light, below 17.6m/s. The north-east monsoon in the rainy season commences in early November and ends in March with steady prevailing north-westerly winds of 14.5m/s. During the two shorter periods of inter-monsoon season in April and October, the winds are generally light and variable.

There is an abundance of solar radiation, with sunshine of about 6–8 hours per day typically between 8.00 and 18.00 hours. The mean daily global radiation is around $18.22 MJ.m^{-2}$ with 7.1 Okta of cloud cover. Hence, these uniformly high average temperatures and humidity levels, with low wind flow and high solar radiation can create an uncomfortable microclimate. Radiant heat gain is significant and a dominant factor as regards human comfort (Baker 1987). One of the most important microclimate modifications, therefore, will be to protect the building envelopes and exterior environment from solar heat gain.

3.3 Environmental condition

The environments around each of the three houses were different, reflecting the age and maturity of their landscaping. The mature landscape house was surrounded by neighbours with similar mature landscaping around their gardens as well as around roadsides and open spaces. The ordinary and new landscaped houses were surrounded by moderate landscaping where most of their shade trees were medium or small. Therefore, the environment of mature landscape house appears to be greener. In addition, the mature landscape house was surrounded by green spaces to its east and south sides, the new landscape house to its south and west sides, while the ordinary landscape house was completely surrounded by other single-family houses without any green space. The open space on the east side of the mature landscape house was fully planted with mature shade trees of up to 10m in height and the open space on the south side had been planted with a few trees, shrubs and turf. Open spaces to the south and west sides of the new landscape house were moderately planted with mature trees, shrubs, grasses and turf. There were no water surfaces in these neighbourhoods.

The three houses received wind from the same direction. In the early morning until mid-noon most of the wind flow direction was from the south-east. Wind directions changed in the early afternoon into a south-westerly direction. Finally from afternoon towards the evening wind flow was from an easterly direction. One advantage of the mature and new landscape houses were that they faced an open space and were located at the end of a lot site, which was more exposed to prevailing wind.

4. HOUSE SELECTION AND LANDSCAPE DESIGN

There were some differences in the architecture of the three case study houses. Each house followed the trends at the time of construction. However, in general their building construction was similar. Measurements taken in this study included house orientation and configuration, size, general construction and materials for floors, walls and roof. The colours of the building envelopes and their areas were also recorded including walls and roof areas, all windows and doors and their shading devices. An interior house setting includes interior spaces, ceiling heights and types.

The tropical landscape design around the gardens was personally inspired by the owners; characteristic of the time each garden was planted and designed. Each had been planted with tropical plants for multiple functions: aesthetic, edible, to provide shade and to produce a pleasant, comfortable and healthy environment. The owners had employed a tropical landscape style by using every type of vegetation structure include trees, palms, bamboos, shrubs, vines, groundcovers and turf. Appropriate choice of vegetation and strategic location will potentially influence their shade, evapotranspiration, and wind channelling characteristics.

4.1 Building construction

These three medium sized single-family houses have employed a conventional tropical style of architecture in the local context of Malaysia. The house configurations were different: the mature landscape house and the ordinary landscape house were oriented in the east-west direction, while the new landscape house was oriented north-south. All three of the two-storey medium size houses had a slightly different size of building footprint and garden area and were built using similar building materials and construction. The main structure had been built on a reinforced concrete pad foundation (R-1.7m².°C/W); all had brick walls (R-1.3m².°C/W) and a pitched timber-framed roof covered by concrete tiles with an insulation layer of aluminium foil paper underneath (R-1.7m².°C/W). Table 2 shows the different amount of building footprint, floor, roof, and garden area, and albedo value in the building envelopes. Solid hardwood material was used for the doors (R-0.34m².°C/W). Ceiling heights for the three houses were around 2.9m and finished with fibrous, cement plaster, and asbestos free fibre cement ceiling sheets. 3mm thick single layer glass with metal window frames (R-0.13m².°C/W) was used for all casement windows, the sliding doors and a few of the doors.

Table 1. The total amounts of building footprint, floor, roof, albedo and garden areas

House type	Building	Floor (m^2)	Roof (m^2)	Wall colour	Wall albedo	Roof colour	Roof albedo	Garden (m^2)
Mature	210	350	225	white	0.30	brown	0.12	500
Ordinary	355	550	375	peach	0.42	Orange	0.33	350
New	285	400	300	creme	0.33	Grey	0.30	250

Table 2. The total area of brick walls and glazed surfaces

Azimuth	House type@Wall (m²)			House type@Glass (m²)		
	Mature	Ordinary	New	Mature	Ordinary	New
North	90	150	90	09.75	21.30	12.30
East	80	120	100	07.70	31.10	25.40
South	90	150	100	23.10	14.90	22.00
West	80	120	120	10.80	20.00	34.80
Total	340	540	410	51.35	87.30	94.50

Shading devices had been built over almost all windows and doors to provide shade during the peak time of the day. At least 0.8m of overhanging gables or hips roof were provided, and a 2–3m width veranda was built facing sliding doors and back windows and doors for the three houses. A porch covering the entrance of the house also provided a shading device for the windows and doors facing this space. Table 2 shows that the total areas for glass and plastered bricks walls are different – where the mature and the ordinary landscape house have 15% and 16% of glass surface respectively, the new house has 24% of glass surface.

5. LANDSCAPE DESIGN

Different configurations of landscaping were investigated for the three houses in four azimuths using different combinations of trees, shrubs, vines, groundcovers and turf. The mature landscape house had a large garden which was planted with a limited amount of vegetation. The majority of the space in the garden was lawn. A total of 22 trees were identified in the garden, 38 individual and groups of shrubs, a planting of vines and 2 groups of groundcover. The ordinary landscape house had a moderate amount of landscaping which was comprised of only 7 trees and 61 individual and groups of shrubs, 5 plantings of vines and 6 groups of groundcovers. The new landscape house has also been planted with a medium amount of landscaping which was still in immature. The 11 trees were planted surrounded by 63 individual and groups of shrubs, a planting of vines and 4 groups of groundcover. The rest of the soil surfaces for the three houses were covered by *Axonopus compressus.*

5.1 Trees

The main function of trees planted around houses is to provide extensive shade to the surrounding garden and house, and reduce heat gain to the building during the day. The 22 trees in the garden of the mature landscape house were planted within a distance of 3–19m from the house. They were planted individually and in groups, which were more concentrated on the north, south and west sides. Their canopies covered approximately 30% of the garden surface. The sizes of the tree canopies varied: most of the trees (50%) were small to moderate size, 41% were small in size, and 9% were medium. The size of canopies was maintained by pruning the branches to keep the trees at an appropriate size and in safe condition. Some of the garden trees were naturally small such as *Juniperus chinensis*. The most common category of tree was edible fruit trees at 36%, followed by garden trees (28%) and a small number of palms and roadside trees (18% each). The majority (60%) of trees were below 4m in height and the balance of 40% of trees was between 5–9m in height with an average trunk height of about 2m. The shape of the trees varied, with round shapes representing 36%, followed by columnar shapes at 23%, and finally spreading and fountain shapes at 18% each. The amount of leaves for every tree has been divided into 3 classes; 50% of trees had a dense canopy of leaves, 36% a medium canopy and 14% trees had a sparse canopy with few leaves. Small sized leaves were dominant in this garden at 59%, and the balance was in medium sized leaves (41%). All trees were from evergreen tropical plant species with an age of approximately 30 years. Proper maintenance could keep all trees at appropriate sizes, forms and heights to survive very well in the dry and rainy seasons every year.

The ordinary landscape house had a minimum amount of trees where the overall amount was less than one-third of those at the mature landscape house. Most of the trees were situated within a distance of 4m from the building. They only covered around 10% of the garden's earth surfaces and were more focused on the left elevation to the north side of the house. Approximately 42% of the tree canopies were of medium size and 29% of them were small to moderate and small sized respectively. 43% of the overall heights were more than 10m with 6m trunk heights; while the rest (57%) were 4m in height with 1-2m trunk height. 70% of the trees were spreading in shape, and 15% were round and fountain shaped respectively. There were generally medium amounts of leaves and medium sized leaves in the tree canopies. Even though all the garden trees and palms were individually placed, they were lush, fertile and could survive very well with shrubbery underneath.

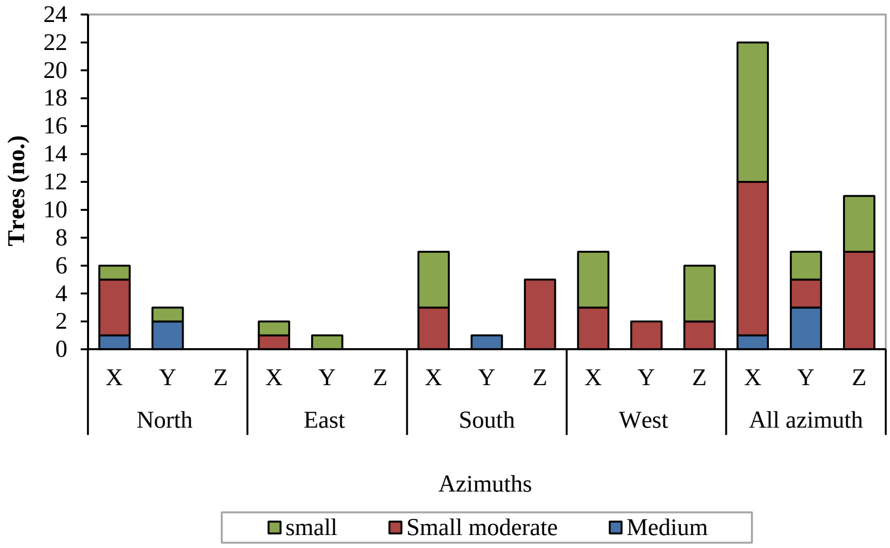

Figure 2. Trees distribution compared over tree sizes and tree azimuth with respect to building for the three landscape houses: mature landscape house (X), ordinary landscape house (Y) and new landscape house (Z)

The amount of planted species at the new landscape house was moderate and the overall amount of trees was around half of that in the mature landscape. Most of the trees were situated at within a distance of 5m from the building. They covered around 20% of garden's earth surface and were more focused on the elevation to the west and south sides of the house. All of the garden tree canopies were small in size with an overall height of between 2 and 4m and a trunk height around 1–2m. There was only one round shaped tree of a small to moderate size planted as a roadside tree with an overall height of 6m and a 3.5m trunk height at the south side. This tree produced a sparse amount of medium sized leaves. 50% of the garden trees were of spreading shape and 50% of fountain shape. The amount of leaves in each canopy was generally sparse, and the leaf-size was generally medium. All the garden trees and palms were planted in small groups or individually placed and were still in a process of growing up, needing a few years to be mature and produce sufficient shade.

5.2 Shrubs, vines, and groundcover

The shrubs, vines and groundcover planted around the houses were a fundamental element of the landscape design. Furthermore, shrubs and vines planted close to the walls could produce shade and reduce heat gain to the building, especially during the morning and afternoon. The groundcover in the gardens was planted to create a transition between the shrubs and turf surfaces and to create balance, harmony and a lively landscape design.

A total of 38 individual and groups of shrubs, 1 group of vines, and 2 groups of groundcover were identified in the garden of the mature landscape house. The majority of shrub types was from the garden shrub category at 68%; followed by 27% of edible shrubs. Only 13% were palms shrubs. Shrubs were spread on four sides of the house, where 34% of the shrubs were located to the south side, 29% to the east, 21% to the west side and 16% to the north side. 80% of the shrubs were grown at a distance of within 5m from the building; 16% of the shrubs were positioned at 9m and 5% were close to walls and at a distance of 14m respectively. Shrubs located within 9–14m were located underneath shade trees. A planting of vines was located to the south side of the house. *Quisqualis indica* was climbing on a pergola structure close to the building walls in a group of $5m^2$ with a medium amount and size of leaves. Only 2 groups of groundcover were scattered in the garden of the mature landscape house. *Cuphea hyssopifolia* and *Zephyranthes candida* were located to the south and west side respectively within a distance of 5m from the building. The two groups of groundcover had been planted in groups of $5–9m^2$. All of them have a medium amount of small sized leaves. On average all shrubs, vines and groundcover were in moderate size and conditions, but the total amount of them were small compared to the total area of the garden.

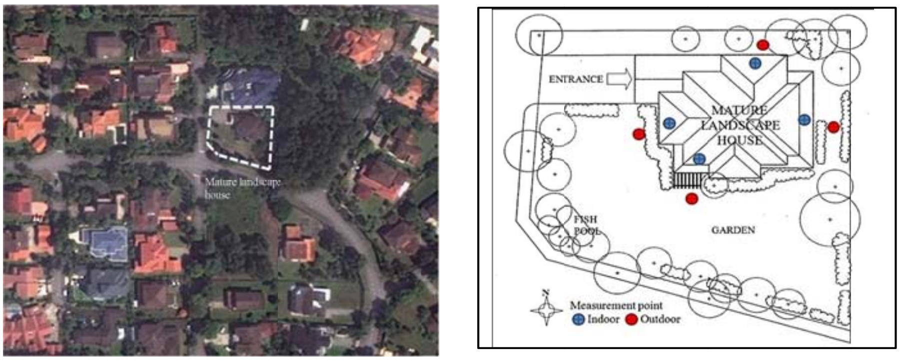

Figure 3. Location plan (left) and landscape plan (right) of the mature landscape house

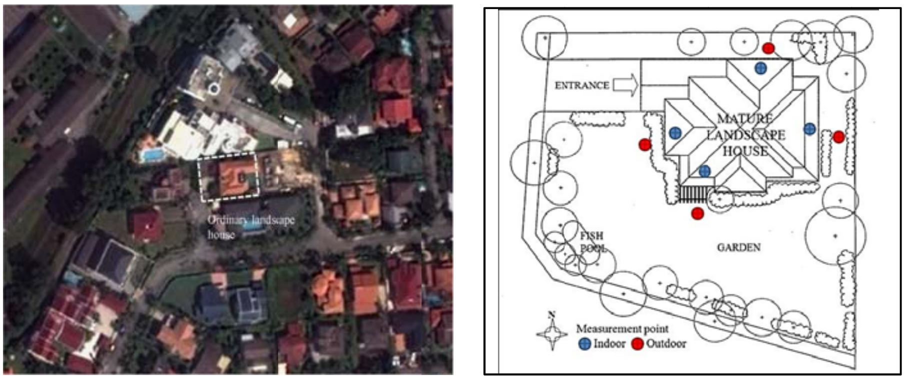

Figure 4. Location plan (left) and landscape plan (right) of the mature landscape house

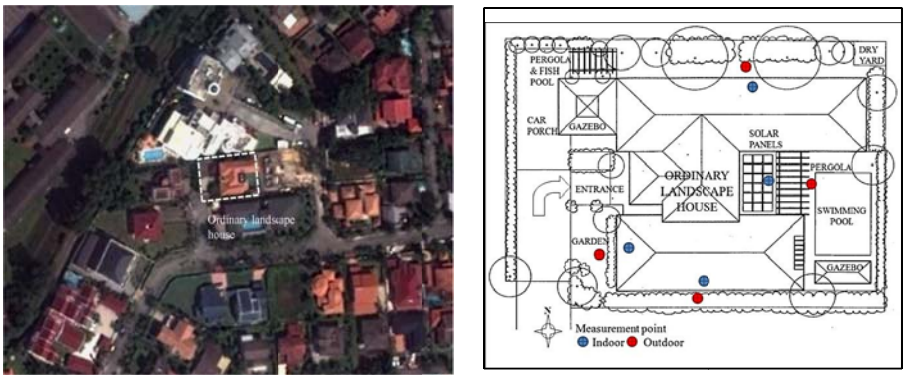

Figure 5. Location plan (right) and landscape plan (right) of the ordinary landscape house

The total amount of shrubs, vines and groundcover around the ordinary landscape house were almost double that of the mature landscape house. There were 61 individual and groups of shrubs, 4 plantings and groups of vines, and 6 groups of groundcover were identified. The majority of shrub types were from the garden shrubs category at 70%, followed by 20% of edible shrubs and finally only 7% and 3% were from bamboo and palms shrubs respectively. 36% of the shrubs were located to the north side, 30% to the east side, 19% and 15% to the east and south sides respectively. 67% of the shrubs were grown at within a distance of 5m distance from the building. 25% of the shrubs were positioned close to walls and windows, and finally 8% of the shrubs was scattered at a distance between 5 and 9m from the building. 5 groups of vines were climbing on the pergolas and in individual garden structures at the ordinary landscape house. Vines situated to the north and east sides were placed within 5m distance from the building. 3 groups of vines had been planted in groups below 5m², and another 2 groups of vines were in groups of 6–10m². All of them had a few leaves. The majority (60%) had medium sized leaves and the rest had small sized leaves. 6 groups of groundcover were scattered in the garden of the ordinary landscape house. Groundcover was only planted to the west side at different distances from the building. 4 groups of groundcover were located in within 5m, 1 group was close to the walls and within 5–9m from the building respectively. All had a medium amount of small sized leaves.

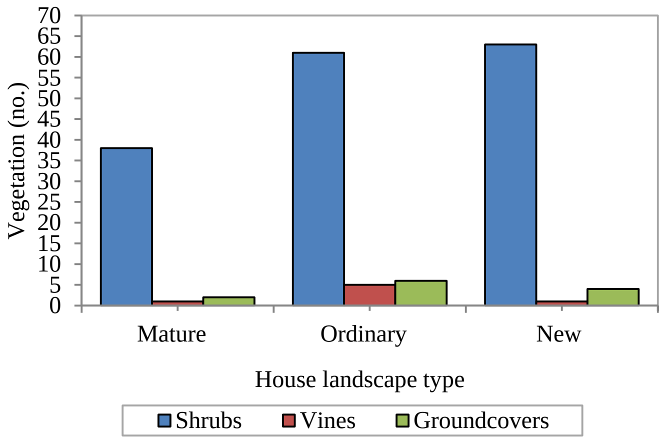

Figure 6. Shrubs, vines and groundcover distributions in the three landscape houses

In comparison, the shrub population in the new landscape house was similar to that of the ordinary landscape house, but different in maturity and size of plant. 63 individual and groups of shrub had been planted around the house. They were categorised into 4 groups: 57% were garden shrubs, 21% edible shrubs, 17% palm shrubs and 5% bamboo shrubs. 35% were located to the south of the garden at a distance of 5m, 24% were close to walls and 19% were in between a 6 and 9m distance from the building. A group of vines with a few small sized leaves was climbing on garden structures.

Tristellateia australasiae was situated to the west side, placed in within a 5m distance from the building in groups of below 5m². 2 groups of groundcover species, *Hemigraphis alternate,* with a medium amount and size of leaves, was located to the south and west side. All groups were within 5m from the building, each approximately $4m^2$ in area.

5.3 Other landscape elements

Every house had different, built, hard landscape structures to suit the soft landscape and the concept of landscape design. The ordinary landscape house has six hard landscape elements around the house including two pergolas, a fish pool, two gazebos and a swimming pool to suit with the tropical landscape design. A pergola with fish pool for *Cyprinus carpio* (Japanese Carp) with a small waterfall underneath was located to the north-west and was partly covered by *Scindapsus aureus* and surrounded by *Phyllostachys sulphurea*. The pool had been built in concrete with an approximate area of 10m², and 0.6m depth. Another pergola, partly covered by *Vallaris glabra* and *Quisqualis indica*, was located to the east side facing the swimming pool. Both of the pergolas were of similar size and constructed in hardwood with an area of 12m² and 2.5m in height. A $20m^2$ area and 2.5m high gazebo was situated at the west elevation, built in hardwood with a double layer pitch roof covered with slate tiles. The second gazebo with an approximate area of $16m^2$ was located to the east side, also built of hardwood with a hip roof covered by sago leave materials. A small sized ($54m^2$ and 1.5m depth) swimming pool was located near the gazebo, built in concrete and finished with light blue mosaic tiles.

The mature landscape house had a pergola to the south side garden which was moderately covered by *Bauhinia kockiana;* and a fish pool for *Cyprinus carpio* (Japanese Carp) situated to the west side of the garden area. The pergola was constructed in hardwood with an area of 10m² and 2.5m in height. The pergola faced an open lawn paved partly with concrete blocks with a grass inlay for the family's activities in the south garden of approximately 50m² in area. The fish pool was constructed in concrete with an approximate area of 5m², and 0.6m depth. It was also decorated with artificial stones and surrounded by palms and garden shrubs. Similarly, the new landscape house had a fish pool and artificial fountain decoration which were located at the south elevation of the house with an approximate area of 10m², and 0.6m depth.

6. RESULTS

The results of this study identified the climate parameters around three houses that had significant effects on the thermal performance of the buildings themselves. These climate data measurements were related to current ambient air conditions including solar radiation and cloud cover, air temperature, relative humidity, and wind speed. All the climate data was influenced by building construction and the distribution of vegetation around the house. The resulting of thermal performance will be affected by human factors to achieve comfort levels such as the operating of air conditioning system which subsequently lead to energy consumption.

6.1 Solar radiation and cloud cover

The current data on solar radiation and cloud cover were obtained from Subang Weather Station. In the case study areas, day length is the interval between sunrise and sunset from around 8.00–20.00 hours (12 hours). The solar radiation starts at 8.00 hours, when the reading was as low as 0.04MJ.m^{-2}. The solar radiation rises within 2 hours to 1.59MJ.m^{-2} at 10.00 hours, and continued until it hits the highest level of 3.69MJ.m^{-2} at 13.00 hours. After 13.00 hours the levels of solar radiation uniformly decreased until they reached the lowest radiation in 0.04MJ.m^{-2} at 20.00 hours. Overall solar radiation in the study area was active between 10.00–18.00 hours in total approximately 8 hours per day with radiation ranges of 1.34–3.69MJ.m^{-2}. The ranges of solar radiation during the peak time of the day were 1.75–3.69MJ.m^{-2}. Cloud cover is relatively extensive in the study area as is typical of a tropical region. The cloud fraction throughout the day at the study areas was 7 Okta.

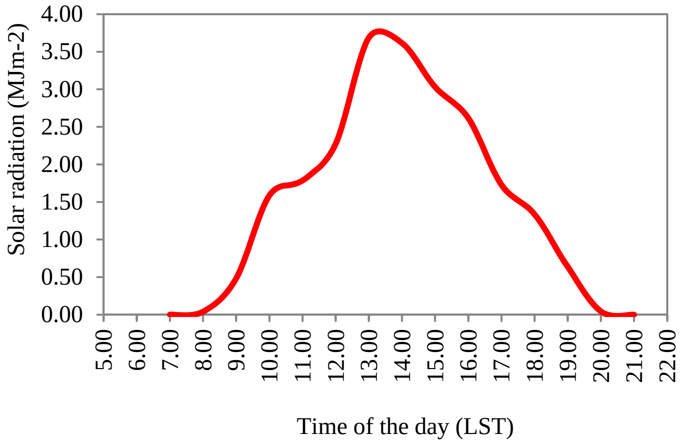

Figure 7. The intensity of surface solar radiation

6.2 Ambient conditions

In order to quantify and characterize the thermal effects of the vegetation in the garden and adjacent to the walls of the residences, a few experimental measurements were made on various combinations of trees, shrubs, vines, groundcover and turf. The procedure used involved the continuing recording of air temperature, humidity and wind speed at all azimuths outside and inside the buildings. According to Parker (1981), wall temperatures are usually obtained since they reflect the summation of the impact of direct and indirect solar radiation as well as the ambient temperature. Therefore, the difference between the exterior and interior wall temperatures determines the rate of heat transfer through the walls and windows.

6.2.1 Air temperature pattern

In order to provide an analytical comparison of air temperature between the three houses, average external and internal temperatures for each house were recorded at various points at regular intervals during the day. The reading of temperatures was at a metre above ground on four azimuths located adjacent to the walls and was recorded between 7.30 and 19.30 hours.

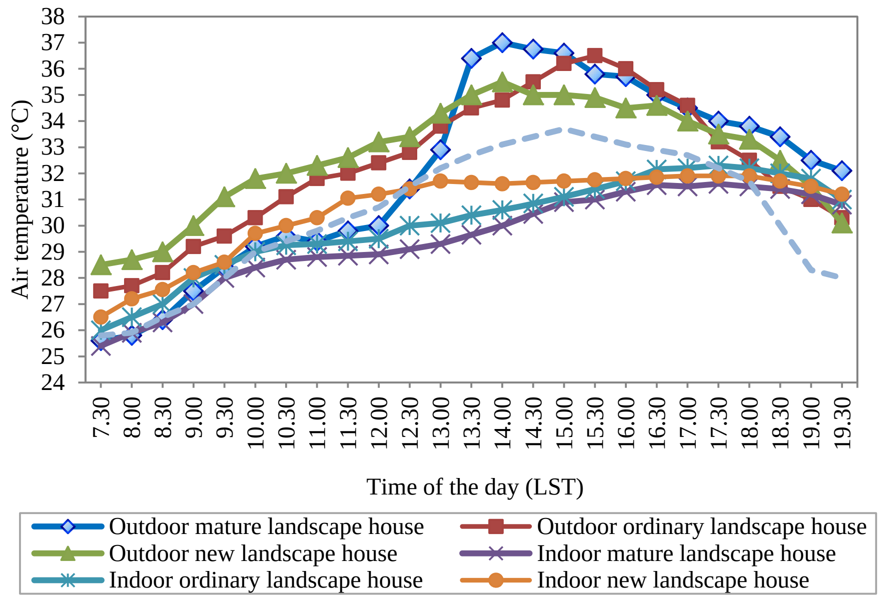

Figure 8. Outdoor and indoor air temperatures at adjacent south walls at the three landscape houses

The maximum cooling effect, of as much as 3.2°C at noon (12.00 hours) was at the exterior of the mature landscape house. The mature landscape house had reached an air temperature of 30°C, compared with 33.2°C at the new landscape house on adjacent south walls, as shown in Fig. 8. Overall the mature landscape house had the minimum outdoor temperature in the morning until noon. The three houses reached similar readings of air temperature during peak time at 14.00 hours, with the highest point being between 36 and 37°C. The air temperature readings declined by the afternoon towards evening, when the readings were about the same. However, the ordinary landscape house appeared to have slightly lower readings compared to the two other houses, with a difference of up to 1.5°C.

Air temperature patterns in interior spaces of the three houses were similar in all four azimuths. Air temperatures gradually increased during the early morning at an average of 0.5ºC per hour until they reached a maximum point in the evening (18.00 hours) which represents a delay of around 3.5 hours compared to outdoor temperature. The gap between the three air temperatures was up to 0.5ºC during the peak time of the day, where the mature landscape house had the lowest level of temperature followed by the ordinary landscape house, with the new landscape house in last place. The mature landscape house had maintained the lowest temperature at the exterior and in the interior of the house with minor differences of temperature reading (up to 1ºC) compared to the other two houses. In comparison, the temperature at the airport area was maintained relatively lower by approximately 1.5–2.0°C compared with the three houses, during the peak time of the day until the evening (13.30–19.30 hours). However in the morning until mid-noon (8.00–13.00 hours), the temperature was much closer to that of the mature landscape house.

6.2.2 Humidity pattern

The relative humidity (RH) measures the partial pressure of water vapour actually in the air at the given temperature compared to the partial pressure of saturation air at the same temperature. The ambient RH pattern at the study areas was typical for the tropical region. The RH levels adjacent to the four exterior walls of each house were very similar. Each house received a stable reading of RH of about 80–98% in the early morning, gradually declined to 55–68% at noon and afternoon and rising to 70–82% in the evening. The three landscaping resulted in only minor differences in humidity levels in the noon and afternoon where the RH levels fluctuated between 55 and 70%. However, the difference of RH between the new landscape house and the two houses were clear at approximately 18–20% higher. The mature landscape house recorded the lowest RH (70%) towards the evening compared to the two houses with differences of up to 10%. Table 5 lists the average RH for the three houses. Overall, the ordinary landscape house recorded the highest RH compared to the other two houses, with slight differences of between 2 and 10%.

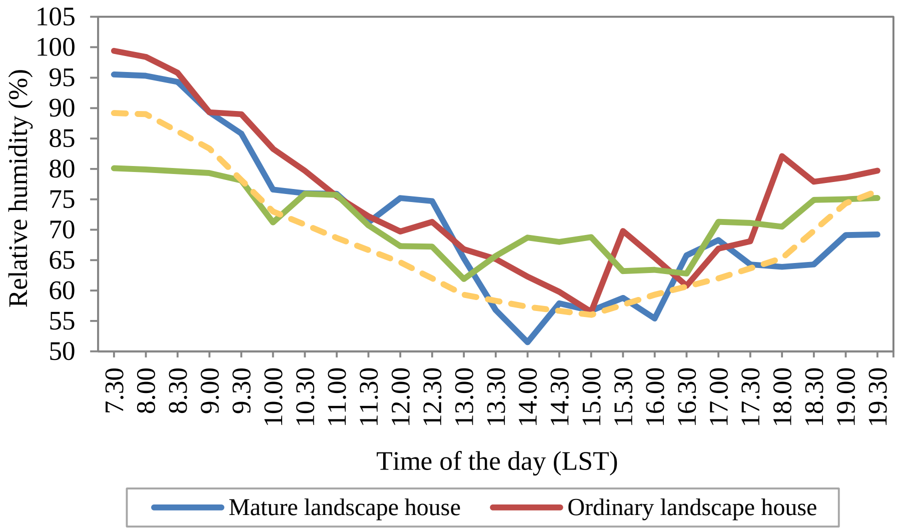

Figure 9. Relative humidity at adjacent south walls of the three landscape houses

RH levels in the interior of each house had uniform and stable reading patterns averaging 70% on all four sides throughout the day. Although there were minor differences of RH level at the exterior of the three houses, these conditions did not affect the interior spaces. The RH in the airport area had a pattern similar to the three houses but it had a smoother form and was slightly lower at approximately 1–8%. However at the peak time of the day and towards the evening the RH of the mature landscape house fluctuated and was slightly lower (5–10%) compared to the RH at the airport, as shown in Figure 9. The absolute humidity is the vapour concentration in the air as grams per kilogram (g/kg). Overall, the results were similar with RH where the ordinary landscape house has higher absolute humidity at 22.94g/kg compared to the new landscape house and the mature landscape house with 22.02 and 21.03g/kg respectively.

6.2.3 Wind speed

The mature landscape house recorded light to moderate wind speeds on each azimuth, where the speeds actively fluctuated in the ranges of 0.04 to 1.2m/s. Wind speed adjacent to the north and east walls was lighter, below 0.5m/s during the afternoon while adjacent to the south walls wind speed was lighter in the morning until noon. For the rest of the time and locations, wind flow was of moderate speed (0.5–1.2m/s). However the highest wind speed of approximately 2.05m/s occurred at 18.30 hours adjacent to the south wall. The ordinary landscape house had different patterns of wind speed, which also fluctuated throughout the day. On the south and west sides the wind blew slowly in the morning until noon, while to the east and north sides a lighter wind speed was recorded in the afternoon, in the speed ranges of 0.04 to 1.75m/s. The winds on the other side were actively fluctuating in the higher ranges until they reached the highest level around the house of approximately 1.85m/s on the north walls at 18.00 hours. Wind in the new landscape house blew at a consistent speed on all sides of the house. Wind speeds were slow (below 1.4m/s) and fluctuated constantly through and around the north and east sides of the house at almost every hour of the day. However to the south and west sides, a lighter wind blew (below 0.5m/s) in the late morning and noon. The highest level of wind speed around the house was 1.38m/s adjacent to the east wall at 13.00 hours.

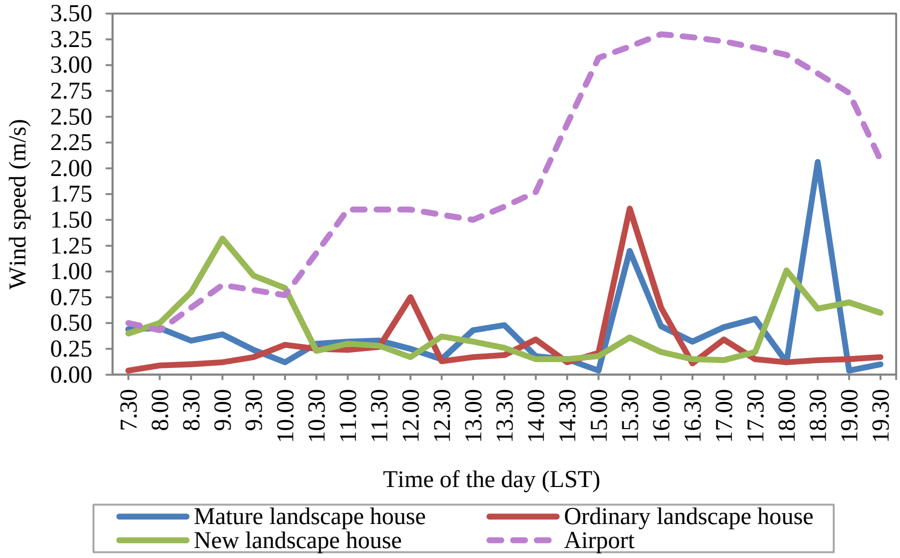

Figure 10. Wind speeds adjacent to the south walls of the three houses

The average wind speeds for the three wind situations around the three houses were very close to each other, where the new landscape house recorded the highest (0.51m/s), followed by the ordinary landscape house, with the mature landscape house in last place. The gap between the three wind situations was up to 0.10m/s. The fluctuating patterns of wind speed in the study areas showed that even where the flow was light and slow, the wind actively kept the ambient air moving and refreshed throughout the day. In comparison, the wind speed at the airport station was definitely higher than at the three houses. During the peak time of the day the wind speed was in the levels above 1.5m/s. The highest wind speed was 3.30m/s at 16.00

hours. Overall the wind blew in a consistent pattern throughout the day in ranges of 0.43–3.30m/s, as shown in Figure 10.

7. Discussion

The results from the three styles of landscaping around three single-family houses clearly illustrated that different ages or eras of landscaping could cause different effects on the surrounding ambient air and the thermal performance of the house. In addition, building construction and design, and living habits also have significant effects that influence the thermal performance of the house. The different levels of air temperature, RH and wind speeds among the three houses were minor because each house represented a modern and moderate style of landscaping. The sizes of shade trees were different, while the other plants such as shrubs, groundcover, and vines were of similar size. The different sizes of garden areas and other landscape elements also brought different effects to the ambient air. This study will discuss the effect of landscaping from different eras and styles on the ambient air and the thermal performance of houses.

7.1 Building construction

Three conventional tropical styles of house design from different eras of construction in the context of the country of Malaysia were identified in this study. The basic style of each house was similar: two storeys of medium size, built in a concrete structure, pitched timber-framed roof, glass windows, and in a square layout. The materials used and construction methods were similar but the design theme was different. The house orientation for the mature landscape house and the ordinary landscape house was east-west, while the new landscape house was north-south. According to Givoni (1994) the main consideration affecting the orientation of the main facades and windows of a building arise from the relative importance of solar and ventilation issues. The strategic location of glass windows could minimize solar penetration and allow natural cross-ventilation during the day and night, reducing air temperatures and relative RH levels. All shading devices for windows provided shade and protected the glass surfaces from direct sunlight at the peak time of the day. Glass windows were located on all facades, however most of the windows or the sliding doors faced the main areas of the garden in all three houses. In the mature landscape house they were mainly on the south side and only received indirect sunlight; in the ordinary landscape house they were on the east side, while in the new landscape house they were on the west side; both received direct sunlight. This resulted in the indoor space temperature in the mature landscape house being slightly lower by approximately 1ºC.

The roof and wall surfaces were the biggest areas exposed to solar radiation, receiving and storing heat gain throughout the day followed by ground floor areas, which were not exposed to direct solar radiation. In a hot-humid region, the building should be compact, with a minimum envelope surface area relative to the occupied space, in order to reduce heat gain and the resultant load on the cooling equipment (Givoni 1994). Table 2 indicates all wall areas in the four cardinal directions for the three landscape houses were in the medium size range. The ordinary landscape house had the biggest envelope with a total of 540m^2 of walls, 375m^2 roof and 355m^2 ground floors areas. This situation also meant that at the peak time of day the temperatures at the adjacent east and west walls, where there was less vegetation, were slightly higher (0.5–1ºC) when compared to the other two houses. Glass surfaces usually allow solar radiation to penetrate directly into the interior spaces. Although every house has been built with a gable or hip roof as a shading device at the windows and doors, which can provide shade on the east and west sides from late morning until the afternoon, the solar radiation still could penetrate, for the walls do not have shrubs covering to a sufficient height during morning and late afternoon. Of the three houses the new landscape house has the highest proportion of glass surfaces (24%) resulting the interior temperatures of the house on the north, south and west sides being slightly higher by approximately 0.1–1.6ºC.

In a tropical region, the solar reflectance ratio at the surface of the walls and roof is very important; which is expressed by the albedo value. The albedo value is affected by the solar radiation reflectance capability on the building envelope. The colour of the external envelope surfaces has a tremendous effect on the impact of the sun on the building and on the indoor temperatures. The albedo values in the houses were in the ranges of 0.12 to 0.42, where all the buildings used light-coloured paint for the walls, and slightly different colours of roof covers. Each house for this study had been well insulated in the roof. All the houses had an application of aluminium foil underneath the roof covers and 2.9m height of proper ceiling construction. The insulation layer and higher albedo value were intended to reflect and reduce heat gain from the walls and roof surfaces. The indoor temperatures of the three houses were similar and lower than outdoor ambient air by approximately 3–6ºC at the peak time of the day.

7.3. Modifying ambient conditions

The results of the ambient conditions of the three study houses included the fact that air temperature, relative humidity, and wind speed were influenced by the surrounding vegetation. Vegetation was planted around each house's garden and also in the surrounding neighbourhood green spaces. In addition, the intensity of the global solar radiation and cloud cover also contributed to a microclimate effect in the case study areas. The surrounding vegetation exerted an influence directly by shading and channelling wind, and indirectly by evapotranspiration.

7.3.1 Shading

One of the primary building envelope components of each house was the roof surface. Roof surfaces need to be properly shaded to reduce heat gain throughout the day. All the shade trees around the three gardens were in the ranges of small to medium sized, failing to provide extensive shading of the roof. Only *Persia americana* and *Eugenia polyantha* located within 5m of the north side of the ordinary landscape house with a height up to 10m, medium size with spreading shape could provide some shade for the roof during mid-day. The other shade trees in individual placements and of small size and located near the walls, could provide shade to the building's lower envelopes. The other shade trees in each house provided shade to the garden areas. However, provision of quality shade would depend on the canopy size, the height and the amount of leaves. Most of the shade trees around the mature landscape house were located along the boundary of the house. The majority of them were of small size and could only provide shade to the garden area. The four shade trees located to the north were close to the house, of medium size and height, had a dense canopy, and would provide shade to the garden and a part of the walls during the morning. In the new landscape house, the majority of shade trees were also small in canopy size, less than 4m in height, and had a sparse amount of leaves; hence they could only provide an insignificant amount of shade to the garden and the building's ground envelope. Too little shade was provided by the trees in the ordinary landscape house and the new landscape house; while trees around the mature landscape house were not in sufficiently strategic locations to provide enough shade to the building.

In the three landscape houses, attention should also be directed to the second largest of building envelope surfaces: the walls. If these surfaces are protected strategically by vegetation, building heat gain will be reduced and lower surface temperatures in the entire adjacent walls will automatically be maintained. Shrubs, vines and groundcover have to be considered as significant types of vegetation to provide shade to the walls and floors of the house. These fast-growing plant species will not harm the foundation of the building because the roots are small and soft. Shrubs, vines and groundcover planted immediately adjacent to the exterior walls can act as a thermal barrier all day long. This type of vegetation can improve insulation properties near the walls and windows, and underneath the house, if strategically planted. Thus, hot air infiltration into the house will be minimized. They also can be effective in all conditions of cooling, whether the house is being mechanically air conditioned or cooled via natural ventilation.

Lush shrubs, vines and groundcover that were planted immediately adjacent to the north-south walls of the ordinary landscape house were on average of sufficient height (1–1.5m) and had medium amounts and size of leaves. Many species planted together created shade for the adjacent walls, windows, and floors. In contrast, there were shrubs and groundcovers planted at the adjacent east-west walls orientation, but the majority of them were of small size and not well-located. The most strategic sides to place lush shrubs would be on the east and west facades, where direct solar radiation hits the building in the morning and late afternoon, compared to the north-south orientation which only receives indirect solar radiation. Shrubs must be plated continuously along the walls to create a natural insulation layer for the walls and floors, and priority should be given to the east-west side. If there is no continuity of shrubs, the high temperatures around the exposed walls will transmit heat to the wall areas, and finally both will have a similar heat gain. There were slightly different outdoor and indoor air temperature readings at the ordinary landscape house compared to the other two houses; even though it had a large amount of lush shrubs adjacent to the walls.

The new landscape house had planted shrubs to the east, south and west sides of the house. The north side of the house was paved with concrete for clothes drying purposes and a part was planted with edible plants. The east side was planted with two layers of shrubs of small size. The orientation of the house was to the south and west, where the garden was located. Shrubs were planted close to the walls and along the fence underneath small shade trees. Shrubs in the size range of small to mature were placed at intervals among the groundcover. Shrubs along the boundary and underneath the shade trees were of medium size. In general, the three sides of the house were planted with mixed sizes of shrubs and the north side was paved in concrete and could not provide continuous shade and insulation along the walls and floors. The mature landscape house had small amounts of shrubs and groundcover located close to its walls focused to the east, south and west sides, and was in small amounts and size and was sparsely planted. This situation would provide less quality of shade to the walls and floors. Shrubs were also planted underneath the shade trees along the fence areas to the east, south, and west directions, and were located very far from the building.

The situation of shade-providing vegetation around the three houses brought slight differences in air temperature readings. In the morning, the differences of air temperature were quite clear, while in the afternoon and towards the evening the air temperature readings were similar, because the positions of the vegetation were not strategically placed. However, the air temperature was also influenced by the evapotranspiration process and wind flow around the garden. The surrounding landscaping at three houses delayed the indoor temperature by 3.5 hours to reach the highest point at 18.00 hours, compare to outdoor at 14.30 hours. On average, the mature landscape house recorded the lowest outdoor and indoor air temperatures 31.8 and 28.9ºC respectively; this was followed by the air temperature readings at the ordinary landscape house and the new landscape house, with progressively higher temperatures of approximately 1ºC.

7.3.2 Channelling wind

In the hot temperatures and high humidities of a tropical climate, winds are needed to increase people's sensation of thermal comfort. An appropriate size and placement of landscape together with appropriate building orientation, will allow wind flow to a building and its surrounding garden. The mature landscape house was located in the centre of Section 6, Shah Alam, surrounded by green spaces to the east and south sides, while the north and west were surrounded by two-storey houses. The mature landscape house had been arranged so that the majority of trees were within 10–19m of the building to the south and west side where the majority of wind comes from throughout the day. A minority of them were located to the north and east sides of the house. The trunk height was up to 1.5m and therefore was suitable for channelling the prevailing wind to the garden area. Some shade trees were planted as individual specimens and the others were in small groups with shrubbery underneath which would divert prevailing winds from the south-east and south-west sides then through to the garden area. The huge lawn in the middle of the garden could allow the wind to move freely to the building. Shrubs located along the walls were small, thus the wind could easily move straight to the building. However on the east side, the prevailing breeze was diverted by a mature small forest in an open space nearby. Therefore, the mature landscape house recorded a fluctuating pattern of wind speed. Moreover, the wind speed moved to the south when it reached the highest speed of approximately 2.05m/s at 18.30 hours. On average, wind speeds around the mature landscape house were approximately 0.32m/s in the four directions. With a minimum of landscaping adjacent to the walls, natural ventilation was moderately effective.

The ordinary landscape house was located in the middle of a housing estate in Section 11, Shah Alam. The house was surrounded by two-storey houses which caused changes of wind direction around the house. For example, the local wind direction should be from the east; but northern areas with shrubs of various sizes in the range of 0.5–2.5m in height and trees with trunk heights up to 5m recorded the highest wind speed of approximately 1.85m/s at 18.00 hours. Each shade tree situated around this house had a sufficient trunk height averaging 2.5m to allow breezes to pass through to the building. Lush shrubs close to the adjacent south walls blocked some breezes, diverting them to the north. Figure 10 reveals that wind speeds in the southern area of the ordinary landscape house were higher, reading approximately 1.62m/s at 15.30 hours. On average, wind speeds around the ordinary landscape house were approximately 0.40m/s in the four directions, with heavily and sparsely shrubs around and natural ventilation was effective.

The new landscape house was situated in the middle of Section 9, facing a huge green open space to the south and west sides. However, on the north and east sides it was surrounded by two-storey houses. In some spaces this house utilised natural ventilation during the day and night. The design of the house with vertical form doors-cum-windows was very practical for allowing wind to pass through the building. The size of all trees and shrubs around the house was small and could not block the wind from passing through to the building. The house was in a strategic location, facing an open space where the southerly wind comes from since morning until afternoon. On the other hand, the trunk height of trees at the new landscape house could channel wind effectively to the garden area and to the buildings, to release hot-humid ambient air especially during the peak time of the day. However the east and northerly direction also worked well where wind speed was actively blowing in fluctuating patterns throughout the day. The fluctuating patterns of wind speed were in the ranges of 0.04–1.38m/s. On average, wind speeds around the new landscape house were approximately 0.50m/s, in the four directions, and with a moderate amount of landscaping, natural ventilation was effective.

7.3.3 Evapotranspiration

The measurements taken in and around the three case study houses reveal that a slight difference of RH levels was due to the slight difference in amount, placement and size of the existing landscaping, and other landscape elements. The general RH pattern reached a higher level during the morning and gradually fell in fluctuating patterns at noon and in the afternoon, and increased towards the evening. The relatively fluctuating patterns between the configurations occurred at the peak time of the day. Fluctuating patterns of RH were caused by the fact that the landscaping around the house was not strategically placed, resulting in different impacts of the amount of water vapour in the ambient air around the four sides of the houses. For example, the ordinary landscape house had lush and green shrubs and shade trees to the north-south side but fewer shrubs in the east-west. This arrangement had also been used in the gardens around the other two houses. If the vegetation around the house was located in strategic places and arranged in an organized way, the RH pattern would move smoothly and in stable readings throughout the day. Thus the shortcomings of the landscaping resulted in higher levels of RH around the house. The ordinary landscape house may have produced a higher of average RH level of approximately 77%. The average RH levels in mature and new landscape house were 71 and 72%

respectively and were influenced by surrounding landscaping and nearby green open spaces.

Each house had a water element in the garden. However the ordinary landscape house had a huge amount of water surfaces in its swimming pool and fish pool, which contributed to evaporation. The transpiration process was also influenced by the amount, placement and size of plants around the garden. This combination made the evapotranspiration process slightly higher than at the other two houses. The higher absolute humidity throughout the day at mature landscape house was because of high levels of evapotranspiration and furthermore the density of the water vapour in the ambient air was increased to reduce air temperatures. The average absolute humidity was hardly approximate 22.94g/kg, which slightly lower 1g/kg than at the other two houses. This suggests that medium size shade trees, lush shrubs, vines, groundcover and turf located close to the house together with water landscape elements will produce higher relative humidity and absolute humidity level.

8. Conclusion

In a hot-humid tropical climate, low vegetative planting around building was one of the main factors increasing daytime temperatures and creating heat island in residential area. Vegetation has a significant influence on the microclimate directly by shading surfaces and channelling wind, and indirectly by evapotranspiration of water. Proper house configuration, high albedo level and strategic locations of surrounding landscaping also can influence the thermal performance of the house by reduce air temperature and create a comfortable environment for buildings. Shading device for windows is very effective to provide shade during the peak time of the day, supported by well insulated in the roof and appropriate albedo value for building envelopes. Moreover, the strategic location of glass windows would minimize the solar penetration and allow natural cross-ventilation.

Vegetation reduces the ambient temperatures not only by shading but also by reducing warm air infiltration and creating cool microclimates around buildings by evapotranspiration. In addition, during the peak time of the day, vegetation in urban housing areas can act as a wind channel and have a substantial impact on a residential building’s thermal performance. By combining of every type of vegetation and strategically placed around residential buildings would produce a more comfortable house. The other structures such as neighbour’s houses and open green space around the houses also influence the quantity of prevailing wind and the quality of evapotranspiration. A greater evapotranspiration combined with sufficient shades from trees, shrubs, vines, groundcovers and turf to cover the building envelopes and garden surfaces, and moderate wind flow might provide cool and comfort ambient air. In addition, proper house configuration, and well insulated and appropriate albedo value for building envelopes resulted in the indoor space temperature being slightly lower by approximately 1°C and can reduce outdoor air temperature as well as urban heat island effects to the surrounding city up to 3°C.

This study clearly demonstrates that the better way to create a favourable microclimate for a tropical residential landscape is by proper selection of amount, size, and arrangement of landscaping. Moreover, the environmental consequences of these designs can extend beyond the residential or development scale to the macroclimate or regional scale.

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Automated quantification of solar photovoltaic potential in cities

Overview: A new method to determine a city's solar electric potential by analysis of a distribution feeder given the solar exposure and orientation of rooftops.

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Abstract: Solar photovoltaic (PV) energy conversion offers a sustainable method of producing electricity to maintain and improve the standard of living within cities. Planning for large-scale adoption of PV in cities, however, provides a challenge to urban planners because of the distributed nature of PV. This paper develops a new methodology to determine a city's PV potential by analysis of solar PV generation potential by distribution feeder given the solar exposure and orientation of rooftops serviced by a specific feeder within the city. The methodology is applied to an example feeder, and then can be scaled to apply to the network of any city. The method comprises the following steps: (i) rooftop extraction from aerial photos; (ii) service parcel and territory matching based on geographical information system (GIS) data; (iii) simulation of the solar exposure of the customers connected to distribution feeders based on local meteorological conditions and the general roof orientation of the customers serviced by the feeder; and (iv) sensitivity analyses of electricity yield as a function of PV module efficiency. Experience from the case study such as trade-offs between time consumption and data quality is discussed to highlight a need for connectivity between demographic information, electrical engineering schematics and GIS. Finally conclusions are developed to provide final methodology with the most and useful information from the highest constrained sources and can be adapted anywhere in the world.

1. INTRODUCTION

Solar photovoltaic (PV) energy conversion offers a sustainable method of producing electricity to provide for contemporary society's needs (Pearce, 2002). The advantages of PV in producing electricity include: i) generating no atmospheric emissions or radioactive waste during use, ii) acting as a distributed electrical generation source, iii) assisting in national energy security and iv) improving long-term economic growth (d'Estaintot, 2000). These advantages are made available for any country that aggressively develops the technology. This has led to international cooperation and technology investment over the past 25 years, which in turn has given rise to fantastic gains in solar PV cell performance and a predicted changing landscape in R&D activities for solar cell technologies (d'Estaintot, 2000; EPIA, 2003; Hoffman, 2006; Green, Emery, et al., 2010). Solar cells made from a variety of materials have demonstrated efficiencies over 10% and are currently manufactured globally. As the technological proficiency of the solar cell industry matured, the total shipments of solar cells increased rapidly. By 2010 about 35 GW have been installed having started out less than 1GW in 2000 with a substantial annual growth rate (IEA, 2011; REN21, 2008; Doty, McCree, et al., 2010). This growth rate, while impressive, must be kept in context of the global energy market. In 2000, the peak electrical generation capacity in the U.S. was 825 GigaWatts (GW = 109W) while the cumulative total global installed solar PV was less than a single GW. In the last four years the market has surged although it is still a tiny fraction of the overall global energy supply.

The increasing technological competitiveness of solar PV, among other kinds of renewable energy technologies, has contributed to a 'new logic of infrastructure provision' (Marvin and Guy, 1997) and a 'paradigm shift in energy policy' (Helm, 2005). However, in the debates on urban and regional development and regional infrastructure policy, the delivery of utility services still seems to be taken for granted and to be left to engineers, network operators and (supra)-national utility regulators. Consequently, there has been little research on the urban and regional impacts of utility restructuring and the changing environment for urban and regional governance (Marvin, Graham, et al. 1999; Monstad, 2007). In particular for the case of solar PV, its use is still dwarfed, by conventional, centralized and largely fossil fuel-based energy production methods. The limiting factor does not lie with resources to deploy solar PV, but with the appearance of prohibitively high levelized costs of electricity in the conventionally highly-subsidized energy market, lack of scale, and market experience, resulting in a low rate of uptake in absolute terms (Neuhoff, 2005, 2008; Sanden, 2005; Pearce, 2008; Branker, Pathak, et al., 2011). To improve the rate of PV deployment by levelling the economic playing field, governments throughout the world have introduced incentives such as feed in tariff (FIT) programs (Branker and Pearce, 2010; REN21, 2008) and there has been several new methods of financing proposed to increase and speed access to the necessary capital (Branker and Pearce, 2011; Branker, Shackles, et al., 20110. To properly and effectively implement a FIT program, or take advantage of PV technology's continued price declines in a city, an understanding the urban local potential (roof space and solar exposure among others) is critical for utility planning, accommodating grid capacity, deploying financing schemes and formulating future adaptive policies (Wiginton, Nguyen, et al., 2010).

This paper develops a methodology to determine a city's PV potential: (i) ranking city-owned buildings by solar resource, facility stock and economic potential for PV generation leading to the economically feasible investments in solar PV for the city itself; (ii) analysis of solar PV generation potential by distribution feeder (e.g. 44 kV, 13.8 kV, and 5 kV feeders) given the solar exposure and orientation of rooftops serviced by city using one example feeder with view of applying it to the rest of the network; (iii) give sensitivity analyses on PV technology and efficiency. The methodology presented here forms the next piece in a pyramidal process of accessing solar PV potential from a regional scale

(Wiginton, Nguyen, et al., 2010; Nguyen and Pearce, 2011) and examines the three most popular methods of roof top extraction for energy planning. This paper then presents a case study as an example of the methodology in Kingston, Ontario. Experience from the case study such as trade-off between time consumption and data quality is discussed to highlights a need for connectivity between demographic information, electrical engineering schemes and geographical information system (GIS) and a typical factor of solar useful roofs extracted per method. Finally conclusions are developed to provide final methodology with the most and useful information from the highest constrained sources and can be adapted anywhere in the world to guide future work.

2. METHODOLGOY

The level, scope and access of municipal GIS data depend on the technical sophistication and the policy of each city. The case study of Kingston, Ontario provides an example of what is typically available, although the challenges presented here serves as a worst case scenario for projects of a similar scope and purpose. The method comprises the following steps: (i) rooftop extraction from aerial photos using ArcGIS version 9.3; (ii) service parcel and territory matching based on Electricity Distribution System (EDS) GIS data; (iii) simulation via PVSyst version 4.37 of the solar exposure of the customers connected to Kingston Hydro's distribution feeders based on local meteorological conditions and the general roof orientation of the customers serviced by the feeder; and (iv) sensitivity analyses of electricity yield as a function of panel efficiency respectively. The inputs necessary for the analysis are aerial photos of the city and a parcel shapefile of the service territory.

To account for shading manual roof outlining is carried out on aerial photos. The assumptions and technical considerations for rooftop PV were: (i) 0 degree in azimuthal angle, (ii) roofs were either flat (0 degree tilt) or sloped (45 degree tilt); (iii) HVAC and other rooftop obstacles were taken into account and (iv) shading by trees and surrounding buildings were also taken into account. In the absence of HVAC, other rooftop equipment and shading factors, the installable ratios for gabled roof, hipped roof and flat roof are recommended by Suzuki et al. (2007) to be 50%, 62.5% and 100%, respectively. The resultant roof space, which was outlined in consideration of its orientation, rooftop obstacles and potential shading and which was the projected value of the true roof, Ap. It should be noted here that the error in the assumptions governing the azimuthal and roof tilt angles can be easily limited by all PV simulation software. Once extracted into a shapefile, roof space was categorized in terms of tilt angle and circuit number provided by the grid operator. Although this approach is much less complex than remote sensing, computerized image processing and boasts least cost and ease for adaptation, it was expected to be time consuming and supervision intensive, thus providing measure for trade-off in terms of automation, data quality, time and adaptability.

3. CASE STUDY ANALYSIS

3.1 Rooftop extraction

The inputs for roof outlines are aerial photos of the city of Kingston, which were taken between February and September 2008. These are of 5cm in resolution, 1km² in coverage and under NAD1983 UTM 18N coordinate system. A roof print shapefile already exists for Kingston and was provided by Queen's University Map Library. In Figure 1, the service area of the case study region of an individual feeder (104) is shaded light grey and overlaid with the aerial photos and Ap (in pale white line).

Figure 1. Service area of an individual feeder (104) shaded light grey and overlaid with the aerial photos and third-level outline scheme (in pale white line).

3.2 Service parcel and territory matching

Categorization of roof space according to primary or secondary line and verification of service territory were done using GIS shapefiles on parcels associated with feeder 104 and a territory markup (paper and digital) for primary and secondary circuits of this feeder. It was recognized that the operating system and available GIS data are not yet perfectly compatible, hence transformer symbols on Kingston Hydro schematics were assumed to be associated with the closest distribution line to the civic address listed for each transformer. Any building that fell out of the parcels identified to be serviced by feeder 104 was accordingly eliminated.

3.3 Photovoltaic energy conversion simulation

The primary input for simulation is area, hence any error in rooftop extraction will affect this step. Another assumption was that panels were closely packed on the roof, i.e. no spacing. This assumption was made to determine an absolute highest case PV power impact on the grid. These numbers were later reduced using more common PV system design layouts and socio-economic analysis of the probability that a PV system would be installed by the utility. PVSyst computed incident insolation as comprising of global, beam, diffuse, albedo components on an hourly basis using the default Hay model, however the user can also specify the Perez et al. model, which is more complex but which gives a more detailed and accurate treatment of diffuse radiation on tilted surfaces (Perez, Stewart, et al. 1987; Perez, Ineichen, et al., 1990).

4. RESULTS

4.1 Roof area calculation

Following the methodology in section 2 and applying it to the case study feeder, the maximum area available for PV (A_{max}) was found to be 133,200 m^2. This is total projected area of all roofs that fall in the service parcels for feeder 104. Wiginton et al. (2010) determined the total absolute error by running Feature Analyst (FA) compared to A_{max} is 15%, giving A_{fa} = 113,220 m^2. Note that from either A_{max} or A_{fa} it is not possible to distinguish between the flat roof areas (A_{flat}) and the tilted roof areas (A_{tilt}). This third method with its attention to detail allowed this, giving A_{flat} = 22,050 m^2 and Atilt = 21,390 m^2. Therefore $A_p = A_{flat} + A_{tilt}$ = 43,440 m^2 or 33% of the total projected area of all roofs that fall in the service parcels for feeder. This value of about a third may be useful for more general estimates in urban centers where only a projected roof area is available.

4.2 Solar PV yield and system size

From the ArcGIS platform, roof outlines were categorized as flat or sloped and exported separately to an Open Office Spreadsheet, where they were to be binned according to four classes: up to 10kW; from 10kW to 250 kW; from 250kW to 500 kW and over 500kW. These size classifications correspond to Ontario Energy Board and Ontario Power Authority connection policy and pricing categories. The capped area for each class and for each type of panel i) monocrystalline silicon (mc-Si), ii) polycrystalline silicon (p-Si) and iii) thin film amorphous silicon (a-Si) was found by selecting the nominal power mode in the preliminary system design menu of PVSyst. The resultant areas for each class are shown in the Table 1.

Table 1. Baseline areas for different system sizes and technologies

System Power [kW]	mc-Si [m^2]	p-Si [m^2]	a-Si [m^2]
<10	83	95	167
10 to 250	2083	2381	4157
250 to 500	4167	4762	8333

For flat roof tops, the majority of potential systems would be built in the 250kW system class, as summarized in Table 2.

Table 2. Total projected area of flat roof by system size and technology

System Power [kW]	mc-Si [m^2]	p-Si [m^2]	a-Si [m^2]
<10	165	266	836
10 to 250	23869	23768	26078
250 to 500	2880	2880	---

There are no tilted roofs that can fit the larger class of 500 kW systems. As shown in Table 3, more roofs still fall into the category of 250kW system size compared to the 10kW system size; however, the trend is reversed for thin film amorphous silicon panels, as expected since a-Si has the lowest efficiency and hence requires the largest area to attain a given nominal power. It should be noted here, however, that a-Si:H PV output is generally under-predicted by conventional techniques developed on mc-Si/p-Si-based PV technology, because of (1) the superior a-Si:H temperature coefficient (Schwabe and Jansson, 2009; Carlson, Lin, et al., 2010) and (2) the use of integrating photometers such as pyranometers can directly introduce errors up to 20% in the prediction of a-Si:H PV system yearly output due to this spectral effect, depending on seasonal and locational effects (Ruther, Kleiss, et al., 2002; Gottschag, Betts, et al, 2004; Hirata and Tani, 1995; Betts, Jardine, et al., 2005).

Table 3. Total projected area of tilted roof by system size and technology

System size [kW]	mc-Si [m^2]	p-Si [m^2]	a-Si [m^2]
<10	10000	11900	18400
10 to 250	16100	14200	7700

4.3 Sensitivity analysis on module efficiency

Using RETScreen, different efficiencies were chosen for three technologies: mc-Si 15-20%, p-Si 10-15% and a-Si 6-10%. The nominal output per m^2 of panels (P_{unit}) was then multiplied with the total area of panels for each type of roof (A_{flat} and A_{tilt}), accounting for optimal tilt (35 degrees) and azimuthal angles (0 degrees) to give the maximum nominal power (P_{flat} and P_{tilt}):

$$P_{flat} = P_{unit} * A_{flat} \qquad (1)$$

$$P_{tilt} = P_{unit} * A_{unit} \qquad (2)$$

Table 4. The summary of the effect of efficiency on MW yield for the individual feeder.

mc-Si efficiency/%	kW per m^2 - Sunpower	E_{flat}/ MW	E_{tilt}/ MW
16.9	0.17	4.6	4.4
17.3	0.173	4.7	4.5
18.1	0.181	4.9	4.7
18.5	0.185	5	4.8
p-Si efficiency/ %	**kW per m^2 - Q Cells**	**E_{flat}/ MW**	**E_{tilt}/ MW**
10.4	0.103	2.8	2.7
11.2	0.111	3	2.9
12.6	0.125	3.4	3.3
13	0.13	3.5	3.4
13.6	0.136	3.7	3.6
14.3	0.142	3.8	3.7
a-Si efficiency/ %	**kW per m^2 - UniSolar**	**E_{flat}/ MW**	**E_{tilt}/ MW**
7	0.07	1.9	1.9
7.2	0.071	1.9	1.9
7.5	0.074	2	1.9
7.7	0.077	2.1	2
8	0.08	2.2	2.1
8.2	0.081	2.2	2.1

Under the most optimistic case (optimal angles for both tilt and azimuth) and of the most efficient technology (mono-Si, 18.5% efficiency), the area serviced by feeder 104 could expect to generate 5.0 MW_p from flat roof and 4.8 MW_p from tilted roof as seen in Table 4. Given the same technology and efficiency, Figure 2 below shows that flat roof yields slightly higher nominal power than do the tilted roof tops and this difference widens with less efficient panels. It should be noted here that this is the largest possible capacity available with current technology. This is also assuming close packing of PV modules. So for example the ratio of MW/acre is larger than in a traditional ground mounted system because every square meter identified on a tilted roof top as usable area is assumed to be covered with PV. This number represents the baseline for applying other filters such as social/cultural and economic that would restrict the actual installed capacity in the short to medium term.

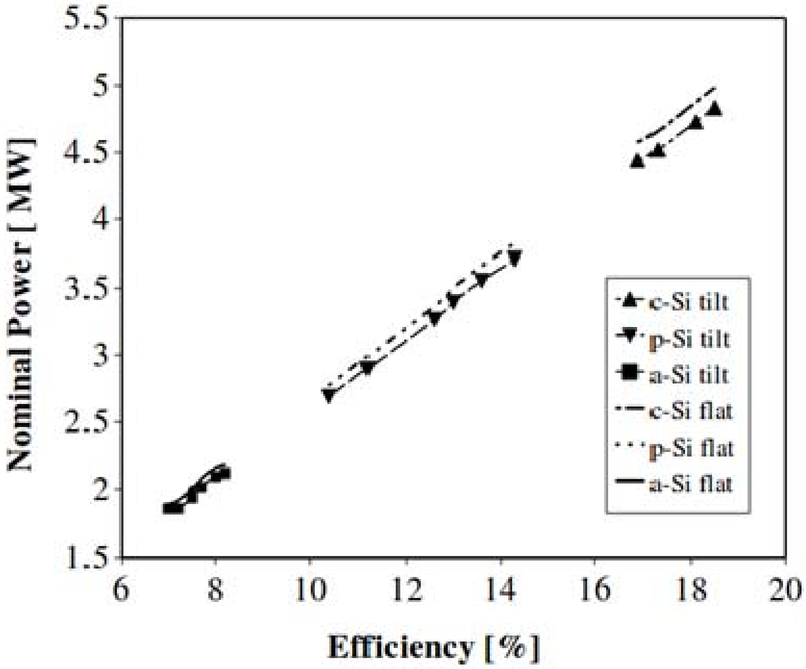

Figure 2. Nominal power in case study for different panel efficiencies and silicon-based PV technologies

5. DISCUSSION AND FUTURE WORK

GIS techniques have been applied by several authors to study PV deployment and/or impervious urban fabric (Gadsden, Rylatt, et al., 2003; Ghosh and Vale, 2006; Izquierdo, Rodrigues, et al., 2008; Kraines, Wallace, et al., 2001; Kraines and Wallace, 2003; Ryatt, Gasden, et al., 2001). Image recognition, both object-based and spectrally-based, supervised and unsupervised, has been used as a means of studying urban fabric and determining roof area (Akbari, Shea Rose, et al., 2003; Guindon, Zhang, et al., 2004; Ratti and Richens, 1999; Richens, 1997; Taubentock, Roth, et al., 1999). Unfortunately, this past research is not directly applicable to determining the rooftop PV potential in Ontario for one of the following reasons: (i) the technique was applied a single building, neighborhood or city, not a large-scale region (Gadsden, Rylatt, et al., 2003; Ghosh and Vale, 2006; Ryatt, Gasden, et al., 2001); (ii) the goal is to classify land use designations rather than extract roof area (Akbari, Shea Rose, et al., 2003; Guindon, Zhang, et al., 2004) or (iii) the input data is different from that which exists for many locations including the case study in Ontario (Izquierdo, Rodrigues, et al., 2008; Kraines, Wallace, et al., 2001; Ratti and Richens, 1999; Richens, 1997; Aramaki, Sugimoto, et al., 2001). In particular, Feature Analyst (FA) has been used in the assessment of buildings and/or land use. Psaltis & Ioannidis (2008) and Ioannidis *et al.* (2009) used FA in detecting building change in

Greece, while Yuan (2008) detects land-use/land-cover change. FA has also been used for quantifying impervious land cover for hydrology studies (Kunapo, Sim, et al., 2006), tsunami vulnerability assessments (Sumaryono, Strunz, et al., 2008) and for studying trends in salamander populations (Miller, 2005). None of the work with FA had studied roof area quantification for PV deployment until Wiginton *et al.* (2010) filled in the gap and discovered a linear relationship between population density and roof area across a region in Ontario. The relationship indicates a total roof area of 70.0 m^2 /capita ± 6.2%. The training of FA and subsequent error analysis was done using the existent building foot prints, indicating uncertainty.

Although the result of the case study speaks only directly for Kingston, the procedure here is typical of what can be done for an urban setting, especially where there is a dis-connectivity between remote sensed data of different kinds (GIS, satellite, aerial photos and radar) and across sectors (electric grid operation, demographic).

Data quality induced several assumptions and constraints, which provide room for improvement of the methodology:

(i) Digitization is inherently flawed as the human eyes can only see to a certain resolution of the photos, which is equivalent to 20cm on true ground;

(ii) Since supervision was required for every individual house concerning roof type, shaded portion, orientation and inclination, it takes about 2 weeks to process 0.5km^2 of urban space.

This does not take into account the distortion and multiple view problems arising through merging hundreds of aerial photos into one large tile which also needs to be corrected. While the resultant solar-useful roofprints eliminate shading, which is unpredictable by time of day, month, variable with urban morphology but become relevant as we go down to the household/ single system level (Carneiro, C., Morello, et al., 2009) and hence often hard coded as a parameter in simulation, in the process they become static (i.e. cannot be broken down into monthly or daily values) and their accuracy cannot be verified. At the same time neither study found in previous literature of similar scale and approach has yet attempted to take care of shading from surrounding trees and architectural structures (Suzuki, Ito, et al., 2007; Beseničara, Trstenjakb, et al., 2008). In many aspects, the method presented diverges from full automation, which is expected from remote sensing data (e.g. airborne laser scanning), but which is still missing in treatments of utilities scale of km^2 of land (Pfeifer, M., Rutzinger, et al., 2007).

In addition to the time and labor consumption, final results are dependent on the user's experience, which becomes another uncontrolled uncertainty and which utilities always attempt to minimize. The availability of an airborne laser scanning (ALS) dataset can give hope to solve the misalignment problem, increase the degree of automation, accuracy, efficiency and adaptability. It has been established that building footprints, if up to date and positioning-accurate, can serve as a 'gauge' to extract cloud points corresponding to buildings, which will then be filtered further by using a height that distinguish the rooftop level from any lower objects from within the cloud points (e.g. Pfeifer, M., Rutzinger, et al., 2007; Dorninger, Pfeifer, et al., 2008; Jochem, Hofle, et al., 2009). Indeed, a systematic combination of aerial photos, building footprints and Light Detection and Ranging (LiDAR) backscatter can process twice the size of urban space involving trees and roof configurations of various levels of complexity in half the time (Nguyen, Pearce, et al., 2012). This approach can then be used to account for shading (Nguyen and Pearce, 2012).

LiDAR for this application is extremely promising. Although historically costly, the prices have also come down with time and many cities already have some limited LiDAR data available. Perhaps, even more promising is the recent improvements in software to analyze digital photographs and generate a three-dimensional model of the photos and a point cloud of a photographed object(s). These programs use some version of pattern recognition to compare portions of images to create points (point cloud), which are then compared to convert the image into a model. This true 3-D model can then be used following the example of Nguyen and Pearce to extract real PV potential including near-obstruction shadow losses (2012). Examples of this software technology include, Adobe 123D Catch and Photosynth developed by the University of Washington and Microsoft Live Labs. Both of these tools have been made available for free to users, although there is also work underway for fully free and open-source software tools that can provide the same or better levels of performance. In addition, in order to actually take the necessary number of photographs there has been substantial developments in the open-source hardware community (specifically see DIYDrones.com, openpilot.org, or code.google.com/p/arducopter). These developments enable extremely low-cost small drone camera platforms to automatically photograph sections of cities. In this way point clouds could be created even for substantial cities for very small investments in time, money and labor. Future work is needed for these developments to be integrated into the methodology described here to provide a completely automated high accuracy process for estimating PV energy generation potential from existing city rooftops.

Future work requires practical evidence from local operating systems for an integration of such design aspects as row on row shading for the flat roofs. However, the methodology provided a means of analysis of solar PV generation potential by distribution feeder (e.g. 44 kV, 13.8 kV, and 5 kV feeders) given the solar exposure and orientation of rooftops serviced by a utility using one example feeder with view of applying it to the rest of the network. In addition it also extended the argument on the interaction between urban structures and energy demand made by Madlener & Sunak (2011). Although the current design of cities is responsible for high urban energy consumption, especially in developing countries, the building stock can still be utilized towards a larger share of renewable energy, solar PV-derived electricity in particular, in urban electricity planning given a certain level of technical advancement, appreciation and experience. For existing cities, the case of Kingston has provided a rule of thumb that a value of about a third may be useful for more general estimates in urban centers where only a projected roof area is available. However for emerging (mega)cities the way trees are going to be planted and houses built can affect the uptake of solar energy and its role in the often heavily pressured electricity grid, hence the city's performance in sustainability, as demonstrated in the breakdown of different roof types for different system sizes and hence potential benefits under the FIT program. This calls for multi-dimensional, participatory and multi-sectoral urban energy planning, whereby a new generation of software and techniques for the purpose of streamlining urban structure extraction for renewable energy assessment can be of great assistance.

6. CONCLUSIONS

The paper has presented a methodology to provide urban solar photovoltaic resource assessments, which is widely applicable throughout the world. The results of the case study presented here indicate that utilities needing to plan for large scale solar electric generation in urban areas can make a rule of thumb estimate. In the absence of advanced computational expertise and high quality remote sensed data, one third of the projected area of roofprints can be used as a first pass estimation of the available area for PV installation. Then simple geometry and potential system specifications can be employed to evaluate the potential solar energy generation. The methodology presented here could be run in a similar case study area in the urban region of interest to reduce error without moving to more complicated, time consuming and costly methods. However only an accurate aggregate assessment can be output in terms of (i) the s imulation of the solar exposure of the customers connected to distribution feeders based on local meteorological conditions and the general roof orientation of the customers serviced by the feeder and (ii) sensitivity analyses of electricity yield as a function of panel efficiency. As the required levels of detail, accuracy and flexibility are raised, roofprints will become secondary to a symbiotic relationship between airborne laser scanning, roof segmentation and shading simulation. Thus such rules of thumb will be phased out as the combination of different disciplines (computer vision, solar energy system engineering, spatial analysis) for PV continues to be a proliferate area of research.

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