

Review of Strategies for the Geometric Creation and Population of Urban Microclimate Models

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Abstract: Heightened demand for larger and more accurate microclimate models for heat transfer, pollution accumulation, and wind level prediction has posed new challenges for researchers working in wind tunnels, as well as those employing computational fluid dynamics modeling. Namely, the problem is how to generate geometrically accurate and up to date models inexpensively and quickly without compromising potentially critical details. The problem is an important and growing one, as there is an increased tendency to use such models as the basis for planning permission and long-term policy decisions in urban areas. This review paper traces the recent evolution in the size and detail-level of microclimate models (both physical and numerical) and explains the difficulties of applying the existing technology traditionally adopted in virtual city model creation. Finally, the paper provides an overview of recent innovations in the geometric creation and population of microclimate models to overcome existing documented deficiencies in an absence of architectural detailing in the investigated models through use of aerial laser scanning data.

Keywords: Air quality, wind environment, urban heat island; microclimate, laser scanning, LiDAR.

INTRODUCTION

Several environmental factors have increased the need for an interest in urban-scale and micro-urban-scale modeling. These include increasing levels of air pollution, global warming, urban wind flow, and the need to limit energy consumption [1, 2]. In each case, there are a variety of factors related to aspects of the built environment of interest to researchers, planners, and engineers. For example, these include the percentage of paved surfaces, the amount of reflective surfaces, the street and building configurations, the level of natural ventilation, and the characteristics of the building façades [3].

To attempt to address some of these factors, a variety of strategies have been developed for computational modeling, laboratory testing, and field measurement. However, increasingly there is pressure to incorporate additional factors and to derive more accurate predictions [4, 5]. As such, the approaches used to undertake these activities are changing. To better comprehend traditional and evolving strategies to populate computational and physical models and to monitor field sites, this paper provides a survey of recent models for studying urban heat islands, air pollution dispersion, and wind environment and introduces up and coming technologies that may provide a new and highly cost-efficient means to populate both computational and physical models for microclimate modeling.

To understand new and emerging trends in environmental modeling of urban areas and to identify continuing impediments to more accurate and cost-effective modeling,

this paper examines a sampling of newly published research covering the years 2005-2010, with a concentration on the years 2008 to 2010. The main topics included are air quality, wind environment, and urban heat islands. A total of 40 papers are included conveying the efforts of 120 authors from 22 countries.

Air quality modeling has included a variety of concerns. Prominent amongst these are ventilation, contaminant transport, and wind flow; inter-vehicle spacing and vehicle emissions; and pollutant concentration, dispersion, and removal. Wind environment modeling has involved wind direction, urban wind flow, natural indoor ventilation, thermal comfort, and post-occupancy evaluation. The factors of preeminent concern in urban heat island modeling are optimized air flow, urban heat island effect, heat extraction rate, climate change analysis, natural ventilation, draught cooling, heat storage characteristics, outdoor cooling in a hot-arid region, atmospheric heat balance, wind speed, and air temperatures. So although there are a few topics of direct overlap, between the three topics, each area of investigation has a large number of other concerns. What closely unites these three topics is the need to portray aspects of the built environment. This paper investigates how this is currently done with respect to the size, characteristics, and level of detail in a wide range of urban, microclimate models. The aim is to better define the current state-of-the-art as to how the geometries of these urban environmental models are generated and to what extent various elements of the built and natural environment are actually included.

RESEARCH APPROACH

Across the three areas of study, a number of different modeling approaches have been adopted. In air quality and urban heat island investigations, numerical modeling is the predominant approach with this adopted in 92% of the air

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quality papers examined and 85% of the urban heat island ones. For wind environment modeling, 76% concentrated on numerical, and 24% on physical modeling.

Despite the apparently three-dimensional (3D) nature of each of these 3 problems, of the 40 articles reviewed in this study, 12 relied strictly on a two-dimensional (2D) domain, while 27 worked in the 3D domain, and 1 author compared 3 different methods for modeling wind driven rain without providing domain information. The distribution of articles is shown in Fig. (1).

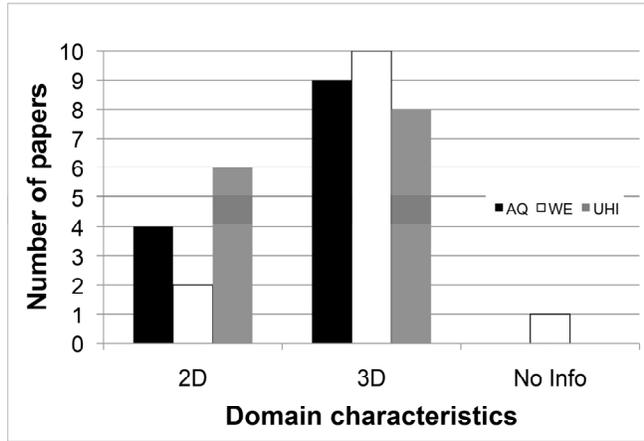


Fig. (1). Distribution of articles reviewed.

The nature of the study areas varied greatly. A total of 24 of them represented a real location(s), while 16 were based on a hypothetical or theoretical locale(s). Within the 40 models, the aspect ratio (height of the building to the width of the street) used by the authors ranged from 0.4 to 8. Six researchers used an aspect ratio of 1. The study area size also greatly varied ranging from 0.014 m² to 1,270 km² in plan and 0.192 m³ to 1,843,200km³ in 3D models (Fig. 2).

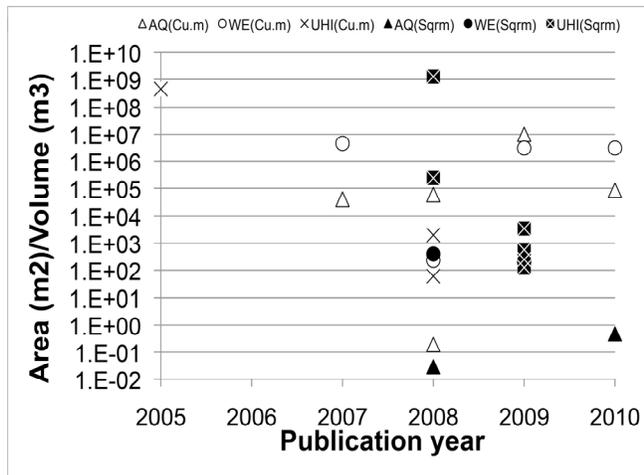


Fig. (2). Area covered in study (2D cases in black and 3D cases in white).

The models ranged greatly in configuration from being comprised of only a single building (e.g. a stadium, a library), to groups of buildings (e.g. an enclosed-arcade market), or selected street canyons (simple ones and those with plantings) and vehicular intersections, up to entire city sections. Of the 40 papers, only 30% specified the number of

buildings in the model. In those, the number of buildings specified ranged from 1 to 35 (Fig. 3).

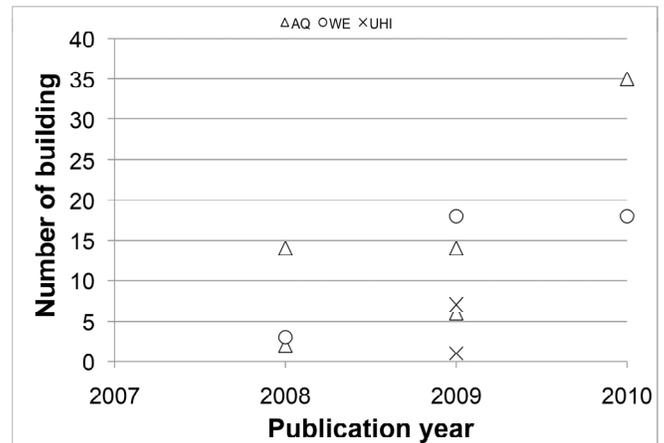


Fig. (3). Number of buildings around focused area.

The scale used in modeling ranged from 1:20 to 1:1000 (Fig. 4). Four researchers used a wind tunnel and four others employed physical modeling, along with numerical modeling or used previous physical modelled results from published literature to validate their Computational Fluid Dynamics (CFD) results.

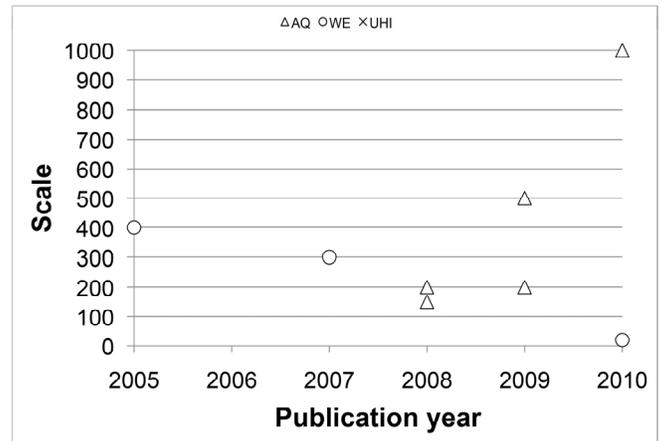


Fig. (4). Modeling scale.

The models used in different studies are shown in Table 1. In 14 the standard k-ε model was used, in 6 cases the renormalized group k-ε model was applied, and in 4 the cases modified k-ε model was employed. Another ten models were used either once or twice.

Different software packages used in simulation are shown in Table 2 below. Fluent was used in 14 cases, and 11 other packages were used only once or twice.

In Fig. (5), computational domains are plotted against publication year. The logarithmic scale has been used for the Y-axis. The trends show that most of the values are ranging from very small 0.288 to 20E09. In Fig. (6) the number of cells/grids is plotted ranging from 65,908 to 500,000,000.

Most of researchers used either a triangular or hexahedral type of grid in modeling (Table 3). Use of hexahedral elements for discretization is most popular and was used in 4 cases. In three cases, triangular elements were used. Other types of elements were reported only once or twice.

Table 1. Type of Model Used

| Model Type | Times Appearing in Articles |
|---------------------------------------|-----------------------------|
| Standard k-ε model | 14 |
| Renormalized group k-ε model | 6 |
| Modified k-ε models | 4 |
| Realizable k-ε model | 2 |
| Reynolds Stress Model | 1 |
| CFD-Urban-model | 1 |
| Modified RNG turbulence | 1 |
| Large eddy simulation model | 1 |
| Direct simulation method | 1 |
| Implicit Crank–Nicolson | 1 |
| STAR model | 1 |
| Algebraic second-moment closure model | 1 |
| Advection diffusion | 1 |

Table 2. Software Used in Studies

| Software | Used in Articles |
|------------|------------------|
| Fluent | 14 |
| CFX | 2 |
| Phoenics | 2 |
| Star CD | 2 |
| CFD-Urban | 1 |
| STAR | 1 |
| WinAir4 | 1 |
| EnergyPlus | 1 |
| TEACH | 1 |
| ADREA-HF | 1 |
| 3-D CFD | 1 |
| CFD-ACE+ | 1 |

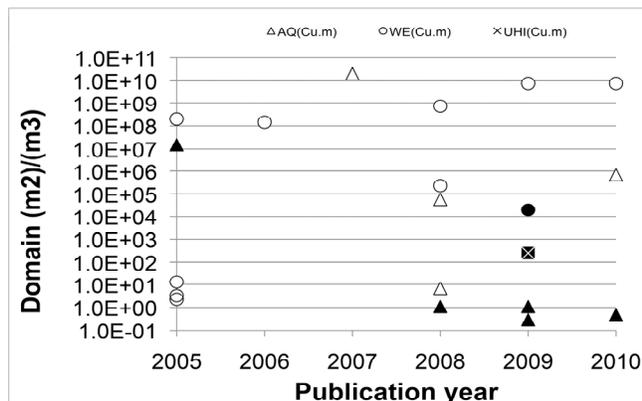


Fig. (5). Computational domains.

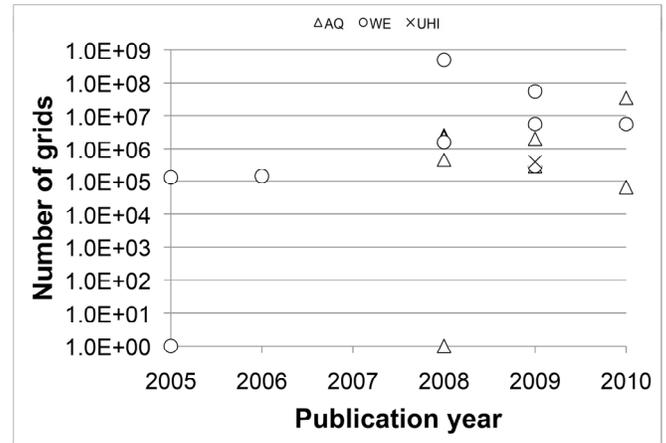


Fig. (6). Number of grids.

Table 3. Type of Grid

| Element Type | Used in Articles |
|---------------------------|------------------|
| Hexaahedral | 4 |
| Triangular | 3 |
| Irregular Grid | 2 |
| Quadtree-Prismatic/Octree | 1 |
| Quadrilateral | 1 |
| Unstructured Tetrahedral | 2 |
| Structured Rectangular | 1 |

The convergence criteria used in different studies varied from 1E-2 to 1E-7, with 37% of the authors using 1E-5 and 25% using 1E-4. Two used the number of time steps as a convergence criterion (Fig. 7).

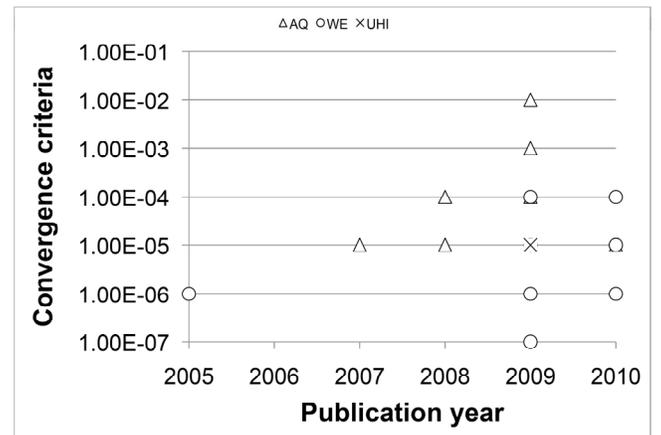


Fig. (7). Convergence criteria used in studies.

The validation of numerical modeling was done using wind tunnel results either by performing experiments or by comparing with previous studies. There are eight cases in which results of full-scale field measurements were used to validate, and in one case, water channel results were used for validation purposes [6]. In most of the cases, the authors claimed that the results were found in close agreement, but quantification of this claim was rarely provided.

In physical modeling of the wind environment, Kim *et al.* [7] used 20 points and 2 wind directions; Szucs *et al.* [8] used 52 points and 3 wind directions, while Yoshie *et al.* [9] used 78 points and 3 wind directions to take the readings. All of these readings were taken in wind tunnel experiments. Agarwal and Tandon [10] used field measurements for modeling of the urban heat island.

The models were examined for the inclusion of footpaths, curbs, street furniture, vegetation, windows, and architectural elements, as well as material texture, signage, and building setbacks and steps. In general, these features were not modelled, and when they were, only a few attributes were included (Table 4). The notable exceptions were McNabola *et al.* [11] including footpaths, Priyadarsini *et al.* [12] modeling the footpaths and setbacks, Gromke *et al.* [13] incorporating trees, and McNabola *et al.* [14] modeling the vehicles. Alexandri *et al.* [15] and Huang *et al.* [16], (2009) modelled the vegetation and texture, while He *et al.* [17] modelled vegetation, windows, and building texture.

VIRTUAL CITIES AND OTHER VISUALIZATION-BASED URBAN-SCALE MODELS

What the above survey shows is that the vast majority of environmental models currently being used are extremely idealized. The absence of realistic urban models raises three questions: (1) do highly idealized models compromise the reliability of the outputs; (2) why are more realistic models not being used; and (3) how does one overcome current bottlenecks for rapidly generating accurate, cost-effective models.

Assuming that with every step towards idealization some accuracy is lost, then the goal should be to generate more realistic models. The main obstacle to more realistic modeling is cost. Given the plethora of highly realistic virtual city models, this may be a surprising conclusion, but a further investigation into the nature, content, and structure of virtual models will show their severe limitations as the basis for in-depth engineering-based modeling.

Originally, Google Earth and other visualization systems for virtual cities, gaming, and the film industry were mostly inhabited with geo-posters [47], where photo-like images were fitted over generic cubes to give the impression of three-dimensionality, but they were simply immutable images. A more selected group of actual 3D models (e.g. Salzburg, Austria and Westport, Ireland) [48] rely on more sophisticated schemes. The most primitive ones (often used in the far-field portion of gaming programs) are instantiated with randomly generated pre-formed structures or other rule grammar- or L-system based solutions [49, 50]. More sophisticated ones use growing techniques. A common one extrudes a building from its plan view outline to the maximum elevation of the points within the data set [51]. Beyond this, some virtual cities (e.g. those for tourism) have striven to reflect actual structures. This latest generation relies on more sophisticated processing and rendering. These models are commonly referred to as various Level of Detail (LOD) models, where the most basic ones of LOD1 depict only block models comprised of prismatic building with flat roofs. The more sophisticated ones of LOD2 incorporate differentiated roof structures and thematically differentiated

surfaces. The further defined LOD3 models include detailed wall and roof structures, balconies, bay and projections, while LOD4 models focus on interior representations.

Attempts to automatically populate virtual cities efforts incorporate a long history of manual, procedural, and direct methods [52]. Some combine simple 3D models with detailed, real-world texture maps. Jepson *et al.* [53] overlaid a GIS-based terrain and aerial photographs to position the final models with respect to road networks. A sophisticated version of this is used in the Virtual Dublin project, where 3DS Max is used to model building surface features with digital photographs mapped atop to improve realism [54]. This is one of many approaches as sampled below.

An early attempt employed photogrammetry to reconstruct scene geometry from photographs. The reconstructed models were then textured in a view-dependent fashion, with textures manually selected from the original photographs. Texture warping relied upon computed depth information [55]. Similarly, the MIT City Scanning Project extensively researched automated data capture for urban simulation [56]. Façade structure and texture were auto-extracted from calibrated pose imagery [57]. This method used sets of images from known positions, which were then correlated to extract vertical façade features. Wang and associates [58] extended this technique with the recovery of microstructure features (e.g. recessed windows) by incorporating multiple images of the same structure from different angles. These techniques relied on calibrated cameras being used from known GPS positions [59]. Similarly, Lee *et al.* [60] automatically textured building model facades by combining aerial photographs (estimating the camera pose data) and ground-based photographs.

Other techniques have concentrated modeling resources on well-known areas and central landmarks and then relied on procedural generation to artificially produce data to complete more distant geographic areas. In the case of virtual Manhattan, building generation was guided by user input related to building type creation and supplemented by manual building insertion based on six buildings [61]. Alternatively, shape grammars can be exploited to generate building models, allowing rapid development of detailed but varied building models, according to rules derived from the real world [62]. In contrast, building footprints from GIS Landline map data and aerial LiDAR can be combined to extrude buildings, as previously mentioned. Sampling the many available virtual cities shows a wide variety of technological orientations, from strictly manual constructions to grammar-based modeling, and visual, auditory, and haptic response feedback [63]. A unifying characteristic, however, is the immutability of the underlying data set.

In virtual projects, the fact that those systems are static remains a major obstacle for their potential to be developed further as a part of an engineering-oriented, modeling tool. This is because intelligently populating a GIS-based or similar system for high-level engineering analysis requires three things: (1) collecting data in a manner that is timely, cost-efficient, and inherently compatible with the existing underlying system, (2) obtaining data of sufficient accuracy and detail that the resulting information is meaningful to the

end user, and (3) manipulating, coding, and archiving the data in a format that critical information can be extracted as relevant input parameters to conduct engineering analyses. The advent of new remote sensing capabilities opens the door to meeting these challenges.

NEW OPPORTUNITIES IN REMOTE SENSING DATA CAPTURE

Light Detection and Ranging (LiDAR) is an active remote sensing technology used to collect topographical data [64]. For the aerial version, the data are collected with aircraft-mounted lasers capable of recording elevation measurements at a rate of 5,000-50,000 pulses/sec. The difference in time is measured from when a laser pulse is emitted from a sensor to when the target objects in the path of the laser reflect back the pulse. Using the speed of light, these time measurements can be converted into distance or range [65]. The LiDAR instruments collect elevation data. To make these data spatially relevant, the points' positions must be known. Thus, a high-precision global positioning system (GPS) antenna, mounted on the aircraft, is used to determine the spatial position of each data point. The end product is accurate, geographically registered positions for every data point with respect to longitude, latitude, and elevation from mean sea level (x, y, z) and is typically presented in a plane co-ordinate system [66]. The terrestrial version of LiDAR uses essentially the same technology but is acquired from the ground with either a stationary or truck-mounted unit.

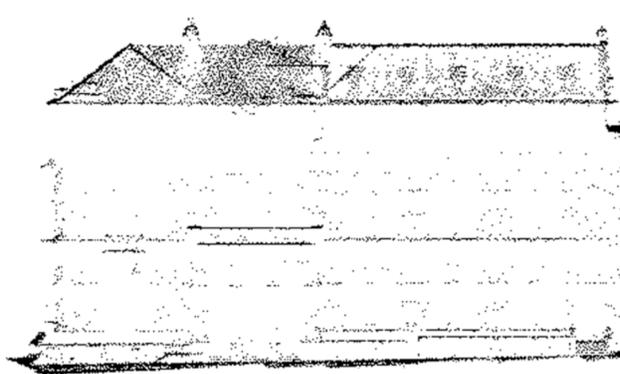
LiDAR is capable of providing both horizontal and vertical information at high spatial resolutions and vertical accuracies. In general, airborne-based LiDAR data can be within centimetre accuracy and the terrestrial of sub-millimetre accuracy depending upon the distance, scanning period, and hardware. The extent of aerial LiDAR point density depends on flying height and system dependent factors such as platform velocity, sampling frequency, and field of view [67-69]. LiDAR has been used in many applications such as (a) mapping, (b) forestry, (c) coastal engineering, (d) flood plain mapping, (e) disaster damage assessment and response, and (f) urban modeling. A current limitation of LiDAR is that it does not store any topological, shape, or size information of the geographical features

scanned. A LiDAR dataset is simply a collection of somewhat randomly distributed 3D points. As feature information is not provided, clever and efficient algorithms are required for element identification depending upon the desired application. Furthermore, attributes must be assigned to groups of points to enable analysis. Recent advances in flight path planning and hardware have radically improved the resolution, as shown in Fig. (8) [70].

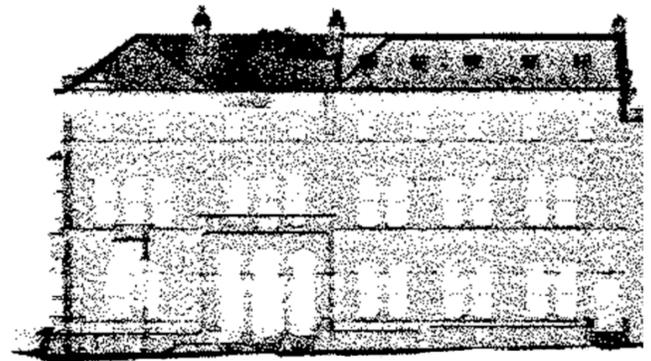
DIVERGENCE

To properly envision the population, construction, and ultimate usage of a large-scale computational urban model, there must first be an understanding of the comparative needs of this type of system vs the previously described virtual cities and visualization-based, urban-scale models. In a visual model, there may be a great emphasis on architectural details, colour, shading, and texture. Even the surface degradations caused by pollution, rust-staining, efflorescence, plant decay, and wind erosion may be of great importance to be captured to adequately convey the feel of an environment (Table 4). Additionally, building signage, window trimmings in the form of curtains and shades, and other non-structural façade elements may play a crucial role to make an environment appear realistically inhabited. But in the same way that street furniture (i.e. benches, trash bins, and railings), rarely influence engineering assessments and decisions, their absence would leave a visual rendition of an urban environment less convincing. Thus, in the context of a visual model, their importance must be respected, but their absence in an engineering context should not be confused as a deficit in that model. In fact, the converse is most likely true as computational models must in part be considered in terms of processing speed and memory requirements. In current applications, it is not unusual for the single run-time for one large structure to require more than 24 hours. As such, when considering city-scale computational modeling and the requisite computing power, it would appear to be absolutely crucial that extraneous (or at least non-critical) items be excluded.

Of the 14 items listed in Table 5 as possible characteristics or feature content for urban-scale models, nearly two-thirds of them have no commonality between visual and engineering models. Of the other 5 topics, 3 have



(a) LiDAR from a conventional, single path flyover in Dublin study area



(b) LiDAR from a multi-path swath flyover in Dublin study area

Fig. (8). Comparison of conventional flight path resolution vs employing techniques developed in Hinks *et al.* [70].

Table 5. Comparison of the Needs of Visualisation-Based and Computationally-Based Urban Models

| Consideration | Visualisation-Based | Computationally-Based | Commonality |
|-----------------------------------|---------------------|--|-------------|
| Attractiveness | High priority | Not applicable | None |
| Shading | High priority | Not applicable | None |
| Window identification | High priority | High priority | High |
| Colour | Medium priority | Not applicable | None |
| Texture | Medium priority | Not applicable | None |
| Architectural details | Medium priority | Low priority | Medium |
| Building signage | Medium priority | Not applicable | None |
| Vegetation | Medium priority | Not applicable | None |
| Street furniture | Medium priority | Low priority* | Low |
| Vehicles | Low priority | Not applicable | None |
| Spatial accuracy | Low priority | High priority | Low |
| Material identification | Low priority | High priority | Low |
| Structural feature identification | Not applicable | High priority (somewhat application dependent) | None |
| Mutability | Not applicable | High priority | None |

*Of some significance during high explosives based blast modelling as these object may become projectiles.

a low commonality, 1 a medium commonality, and only window detection is of high mutual importance.

What may be difficult to understand at a visceral level is that an urban model may have great functionality without being visually compelling and that the converse is also true. Namely that although an image may have great visual appeal and be highly realistic in all of its aspects, it may have limited, if any, capabilities from an engineering perspective. Presently, the functionality of most virtual or visualization models is limited to ray tracing activities, which may be useful for such circumscribed topics as determining cell phone reception. This is not to say that eventually the two concepts may not be completely aligned, but that for the present there is a major disconnect that needs to be acknowledged.

BOTTLENECKS

Current bottlenecks to generating urban-scale computational models are in large part related to the cost of populating such systems with relevant, geo-spatially accurate data. A major challenge is in the automatic identification of individual structures without any a priori knowledge. Although readily identifiable to the human eye, the required data segregation by building, without using known building, outlines or other a priori means, has proven problematic. Recent efforts by Hinks *et al.* [70] indicate the strong potential to do this in the near future with a high level of reliability through LiDAR data (Fig. 9).

The LiDAR data outlined in the previous section is not a panacea. It cannot capture the interior of structures, nor identify the sizing and exact positioning of structural members, nor categorize the construction materials.

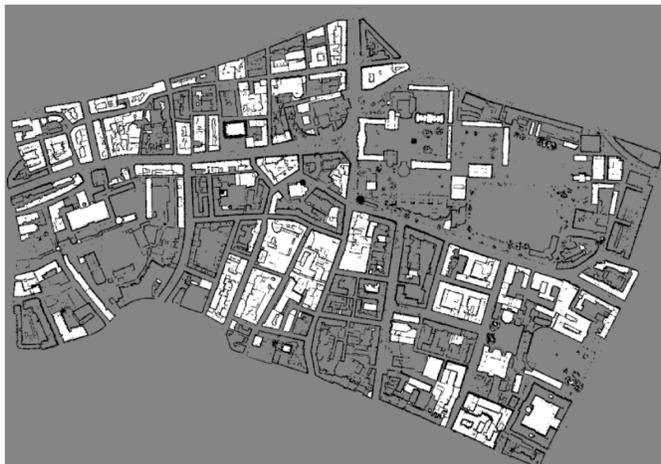


Fig. (9). Comparison of the results of traditional techniques vs work in progress techniques by Hinks *et al.* [70] for automatic building identification, with results evident by the flood-filled structures.

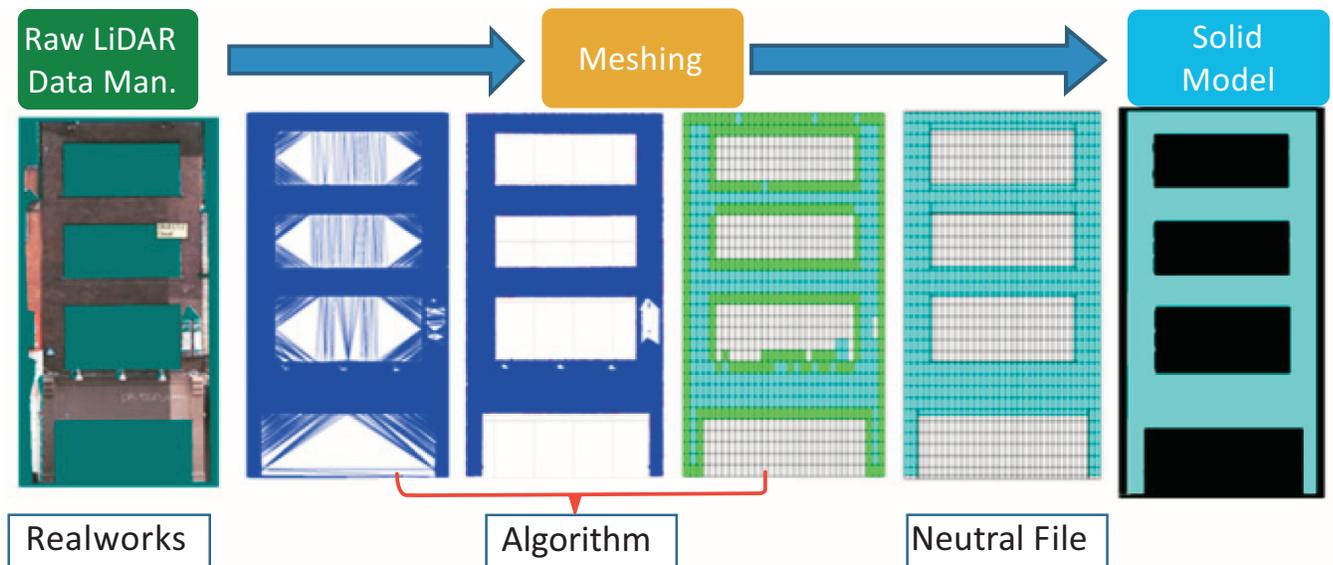


Fig. (10). LiDAR processing from terrestrial point cloud data into a commercial programme's solid model [71].

However the existing technology could provide a major cost-savings in terms of identifying the position, outline, and major features of the buildings, and in those respects is no different than the role of the traditional survey team sent to document existing structures in-situ.

DISCUSSION

What is envisioned is a pipeline using remote sensing to automatically and seamlessly to generate neutral files that can be read by commercial computational modeling programmes to generate solid models that converge without any further intervention and generate reasonable results on a city-scale. The fundamentals of such a pipeline are depicted in Fig. (10). These encompass only the items listed as high priority for computational modeling in Table 5. The technology is likely to prove most readily transferable in city-scale modeling of air pollution. For instance, in the European Union funded project Population Exposure to Air Pollutants in Europe (PEOPLE) simultaneous diffusive measurements of outdoor, indoor and human exposure benzene concentrations were made in 6 European cities. In that study, a linear relationship was evident between ambient levels and human exposure [72]. Similarly real-time concentrations of PM10 were monitored to examine the influence of daily activities and locations on the personal exposure of city centre office workers to air pollution to compare various filter separation and frequency analysis techniques in success of segregating background concentration from real-time personal exposure data [73]. These studies raise the question of how the built environment can be geometrically modified to lower ambient levels. More realistic 3D computational modeling would support such investigation.

CONCLUSIONS

In this study, recently published strategies for the creation and population of urban microclimate models have been reviewed in the context of physical and numerical modeling for air quality, wind environments, and urban heat

islands. The trends showed predominance for numerical modeling with the study area covered by different authors varying from single buildings to entire city sections. The scale used in modeling ranged from 1:20 to 1:1000. The standard k-e model was most widely used model, and Fluent was the most commonly applied commercial code. In numerical modeling researchers used a wide range of computational domains, number of grids, element types, and convergence criteria. In physical modeling different wind directions and number of point for readings were variously selected. This paper outlines the fundamental incompatibility between existing urban-scale models developed for visualization and those that will be increasingly needed for computational modeling in the twenty-first century. The critical characteristics required for these future systems are introduced and a portion of the required pipeline to achieve this in an entirely automated manner is introduced using aerial LiDAR as the main component of its input data.

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CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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