Volumetric Criteria and An Automated Assessment Tool Development for Optimizing Building Permeability Design in High-Density Urban Environments

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Abstract

Better urban ventilation can significantly contribute to achieving UN SDGs through better liveability for sustainable cities and communities (SDG 11), better air quality for health and well-being (SDG 3), and more climate-responsive building design for climate action (SDG 13). Aligning with the said goals, a set of guidelines comprising 2-dimensional prescriptive building separation requirements was promulgated by HKSAR's Buildings Department (BD) in 2011 to promote better urban ventilation. However, some practitioners have concerns about applying the guidelines for projects with complex geometries. Projects may adopt alternative assessment methods using wind tunnel or CFD simulations to demonstrate compliance, but the required time and cost are also a concern.

Given the concerns and stakeholders' collective experience using the guidelines, BD commissioned a study in January 2024 to establish an alternative automated assessment tool for cost-effective evaluation of building permeability design using building information modelling (BIM) technologies. A new geometric parametrisation method - Least Cost Path (LCP) was proposed. The method evaluates Friction Cost (FC) and Turning Cost (TC), measuring a building design's airflow resistance and path complexity. These metrics are applied within a 3D assessment grid system for a building project's low, middle and high zones. Normalised CFD and LCP performances were reviewed, showing a strong correlation ($R^2 \sim 0.8$). The study also identified a cost threshold under the LCP method that differentiates "good" from "poor" ventilation designs. An automated BIM-integrated assessment tool using the LCP method will be further developed in Phase B of the Study.

Keyword
Building permeability, sustainable architecture, volumetric design criteria

1 Introduction

Hong Kong, one of the world's high-density cities, is highly efficient in utilising land use and public transport. However, tall and bulky high-rise building blocks with limited open spaces in between, uniform building heights, and large podium structures have reduced urban air ventilation at the pedestrian level (Ng 2009). Poor ventilation caused outdoor urban thermal comfort problems and worsened urban air pollution by restricting dispersion in street canyons (Ng *et al.* 2011).

In 2011, the Buildings Department (BD) of the Hong Kong Special Administrative Region (HKSAR) Government promulgated the Sustainable Building Design (SBD) Guidelines via Practice Notes for Authorized Persons, Registered Structural Engineers and Registered Geotechnical Engineers (PNAP) APP-152 to promote a quality and sustainable built environment in Hong Kong. These Guidelines establish prescriptive requirements for building separation, setback, and site greenery to improve urban ventilation and environmental quality, which significantly align with United Nations Sustainable Development Goals (SDGs) through better liveability for sustainable cities and communities (SDG 11), better air quality for health and well-being (SDG 3), and more climate-responsive building design for climate action (SDG 13).

However, some practitioners have raised concerns about applying the prescriptive building separation requirements for projects with complex geometries, such as sites having irregular shapes, steep topography or abutting different streets with significant level differences. For sites abutting different street levels, determining a consistent "Level Zero" for permeability calculations under the 2-dimensional (2D) prescriptive method is difficult. In addition, urban ventilation blockages within a site, such as heritage, existing structures, or transport terminals, may result in low permeability, especially in the low zone. While projects may adopt a performance-based design alternative using wind tunnel modelling or Computational Fluid Dynamics (CFD) simulations to demonstrate compliance with building separation requirements, the building industry finds this method time-consuming and costly.

Meanwhile, given the increasing uptake of using building information modelling (BIM) technologies by the building industry in Hong Kong and recent successful experiences in developing BIM automated checking tools for various BD's requirements in general building plan (GBP) submissions, BD sees the opportunity to make use of the 3-dimensional (3D) capacity of the BIM and has commissioned a consultant team led by Ronald Lu and Partners (RLP) in January 2024 to carry out a study to develop volumetric criteria and an automated assessment tool in respect of the building separation requirements under the SBD Guidelines for GBP Submission in BIM Format in Hong Kong.

The scope of the study includes the development of volumetric criteria, as an alternative to the current prescriptive method stipulated under the SBD Guidelines for evaluating building permeability, especially for projects with complex geometries. The proposed criteria shall integrate with BIM to provide an automated, efficient and quicker performance-based assessment to facilitate early design evaluation and streamline building approval process for building separation requirements under the SBD Guidelines for GBP Submission.

The study comprises two phases. Phase A included a literature review of assessment methodologies for the evaluation of building permeability, a review of numerous project cases undertaking the prescriptive building separation assessment under the SBD Guidelines, and formulation of volumetric criteria. This paper summarised the research and recommendations for Phase A of the study that contributes to urban planning and building design by offering a new, scalable approach to optimising building ventilation, particularly in high-density areas where prescriptive methods struggle.

The research will move into Phase B, focusing on designing, developing, and deploying a 3D automated assessment tool using OpenBIM as an alternative method to assist design development and checking compliance with building separation requirements under the SBD Guidelines. The ultimate goal is to provide an effective method to facilitate sustainable building design for better urban ventilation in high-density cities like Hong Kong.

2 Literature Review

2.1 Parametric methods for building permeability assessment

Frontal Area Density (FAD), Building Volume Density (BVD) and Plan Area Density (λp) have been proposed to assess the blockage (Juan *et al.* 2023, Bedra *et al.* 2023, Palusci *et al.* 2022, Ma and Chen 2022, Feng *et al.* 2022, Feng *et al.* 2021, Li *et al.* 2020, Wang and Ng 2018a, Wang and Ng 2018b, Gronemeier *et al.* 2017, Yoshie *et al.* 2008, Kubota *et al.* 2008, Yin *et al.* 2014, Ng *et al.* 2011). FAD measures how the building's elevation blocks the incoming wind, adopted as the scientific basis for formulating the extant 2-dimensional prescriptive assessment requirements of the SBD Guidelines. BVD measures volumetrically how buildings occupy the site and thus reduces air space for urban air ventilation. λp is plan area density; it measures how the building occupies the ground on the plan.

These geometric parametrisation methods are simple and suitable for urban planning studies while do not consider the impact of building configurations on airflow dynamics, which can significantly affect ventilation patterns within the site. To leverage 3D building geometry data for GBP submission and checking in BIM format, the volumetric criteria for automated assessment of building separation necessitates new thinking to tackle the complexity from the first principles.

From our literature review, two volumetric parametric methods – "Mean Age of Air" (MAA) and "Least Cost Path" (LCP), were also found. The idea of MAA has been proposed (Peng *et al.* 2019, Antoniou *et al.* 2017, Hamg *et al.* 2009) to measure how quickly the air mass of the city is moved. Its computation is too complicated and may not be easily applied for practical use on a building scale. For LCP, it finds the most cost-effective path from a start point to a destination. The idea of LCP may be further developed to assess air space connectivity.

By applying the LCP method, a geometric representation of these performance metrics can be hypothesised, potentially improving ventilation evaluation. Several studies have demonstrated the feasibility of using statistical methods for permeability assessment by identifying connected pathways through the pores with the least "cost," where blocked pores results in poor permeability and well-connected pores improves permeability. Therefore, a 3D LCP method is proposed to develop a new geometric parametrisation method for Hong Kong's urban environments.

2.2 3D LCP Method

The 3D LCP method is an advanced approach for evaluating building permeability by identifying the most cost-effective path for airflow between two points in a 3D space. Mathematically, the LCP method identifies the most efficient path through the grids that accumulates the least cost. Building on the 2D LCP framework, a calculation method for 3D LCP has been proposed by Seemiller and Shirabe (2021) for urban air ventilation. The 3D LCP method seeks to find a "corridor" of voxels, which are small 3D units, that connects two points while minimising the accumulated cost (*Figure 1* and *Figure 2*). This approach extends the traditional LCP concept into three-dimensional space, offering a more accurate representation of airflow in urban environments, where buildings and other obstacles affect airflow in all directions.

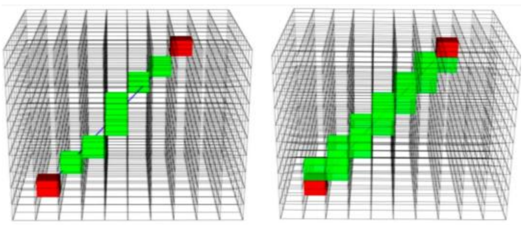

Figure 2. Voxelizing the line (blue) between the initial and target voxels (red) **(Seemiller and Shirabe 2021)**

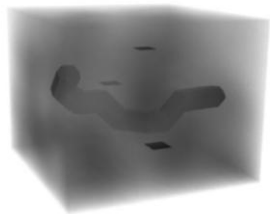

Figure 1. A corridor (tubular region) in a 3D cost grid **(Seemiller and Shirabe 2021)**

The 3D LCP approach integrates well with BIM by constructing 3D assessment grid in BIM model. By defining inlet and outlet sides within the model, the 3D LCP path can be calculated from the inlet to the outlet, providing a precise evaluation of building permeability. This method enables more accurate assessments of how well air flows through a built environment, particularly in complex urban layouts. Further investigation and refinement of this methodology are recommended to fully understand its potential for optimising urban air ventilation and enhancing environmental quality.

3 Research Methodology

3.1 Scientific Investigation of the new LCP method

A new LCP method is proposed. It is inspired by the wind protection effect observed in wind tunnel studies of tree windbreaks and is suitable for tackling porosity assessment on a building scale. In these wind protection studies, the drag coefficient, calculated as the pressure difference ratio between the windward and leeward sides to the dynamic force, measures windbreak effectiveness. Two key factors influencing windbreak efficiency are trees' porosity and configuration (Raine and Stevenson 1977, Bitog *et al.* 2011, Bitog *et al.* 2012). Porosity, the ratio of open space to tree mass, affects wind speed reduction and the sheltered area behind windbreaks. While the relationship between porosity and drag coefficient is complex, low-porosity windbreaks generally offer more significant wind reduction.

By treating a building as a porous medium, two cost-based metrics - Friction Cost (FC), representing airflow resistance, and Turning Cost (TC), reflecting path configuration complexities, are proposed for the new LCP method. FC and TC are treated as relative or notional costs in the method. In other words, the method does not offer a definitive benchmark to determine acceptable or unacceptable air ventilation impacts. However, it enables the comparative evaluation of design options in building ventilation and highlights potential areas for design improvement.

The calculation of FC and TC is conducted on a grid system. To align with the extant prescriptive requirements of SBD Guidelines, we propose a threshold cost of 1 for grid cells with a building opening not smaller than 3m for FC and a turning angle of not greater than 15 degrees for TC. The following equation represents their relationship:

$$FC_{cell3m} = TC_{cell15^{\circ}} = C_{threshold} = 1$$

where FC_{cell3m} and $TC_{cell15^{\circ}}$ represent friction and turning costs at these thresholds, respectively.

Based on this assumption, the equations for FC can be developed as follows:

$$FC = C_{threshold} \text{ (If a cell is bounded by building wall(s))}$$
$$FC = C_{non-bounded} \text{ (If no building wall bounds a cell)}$$

where $C_{non\text{-}bounded}$ is the friction cost in an unbounded cell, determined through CFD sensitivity tests.

The equations for TC are as follows:

$$TC = a * Deg + b \text{ (If Deg < 15°)}$$
$$TC = C_{threshold} \text{ (If Deg = 15°)}$$
$$TC = \left(C_{threshold} + c * e^{\frac{Deg}{d}}\right) * N \text{ (If Deg} \in [15°, 90°))$$

where TC is the turning cost; "a" and "b" are coefficients derived from $C_{threshold}$; N is the grid step within the current path segment; and "c" and "d" are scaling factors used to adjust TC.

3.2 Assessment Methodology Considerations

3.2.1 Point-to-point approach

The LCP starts from a point on the inlet side and ends at the corresponding point on the outlet side, remaining within the same vertical layers (no vertical turning costs) and lateral layers (no lateral turning costs). The point-to-point correspondence (*Figure 3*) ensures that air pathways navigate through porous spaces, if any, within or between buildings to detect porosity, especially for sites with irregular configurations.

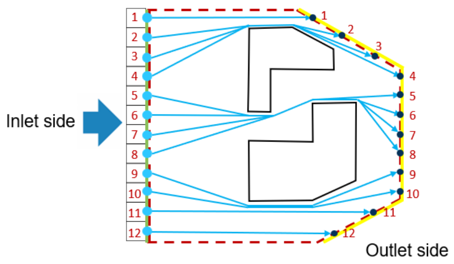

Figure 3. Point-to-point correspondence

3.2.2 Assign assessment grid

The LCP assessment begins with structuring the building project in BIM format into three-dimensional grids. These assessment grids cover the entire project site's air space and building(s), including streets on the inlet side and, if applicable, extending to the centrelines of adjacent streets on the left and right. For sites abutting curvilinear streets or with more than one street along the inlet side, the x-axis aligns with the street's centreline or its most extended tangent. For sites not abutting streets, the x-axis aligns with the longer side of the site boundary.

3.2.3 *Assessment zones*

The LCP assessment is to be evaluated separately for the low (from street to 20m above ground), middle (between 20 to 60m above ground, which is about the mean building height of the majority of existing buildings in the dense urban areas of Hong Kong), and high (between 60m above ground to the roof level of the subject building under assessment) zones (*Figure 4*). The building permeability of the low and middle zones is critical to for pedestrian ventilation comfort, while the high zone influences the overall urban ventilation of the surrounding neighbourhood. Building height variation mainly at the upper zone will be addressed accordingly.

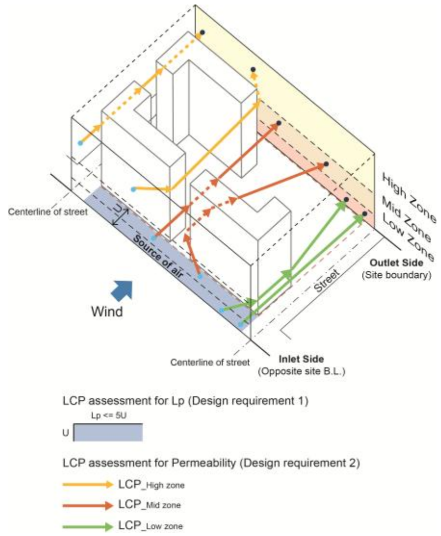

Figure 4. Assessment Zones

For irregularly shaped sites or cases where the site partially abuts streets, the inlet side may include the opposite site boundary, street centreline, or segment of the site boundary, depending on connectivity to form LCP paths follow the geometry of the site boundary. For cul-de-sac sites, the inlet side aligns with the site boundary adjacent to the cul-de-sac.

3.3 Parametric study using randomly generated building block configurations

To determine the optimal ratio between Friction Cost (FC) and Turning Cost (TC) and validate the LCP method, we conducted CFD simulations on 24 randomly generated building block configurations. These scenarios were generated using a custom MATLAB script with the following parameters, varied in building coverage ratio (0.2–0.6), building width (15–200m), building length (15–100m), number of buildings (0–8), building gap (0–200m), test area dimensions (200m x 100m) with a constant height of 120m.The 24 randomly generated building blocks have been reviewed and marked for compliance or non-compliance with the prescriptive requirements of the SBD Guidelines (*Figure 5*).

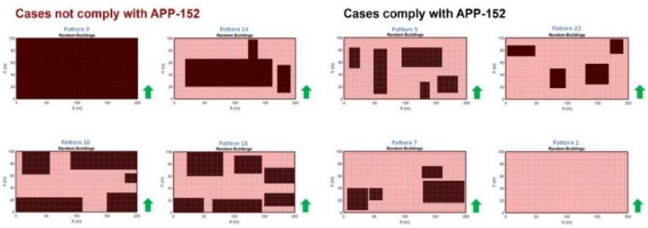

Figure 5. Plan view of examples of 24 random building block configurations evaluated using CFD simulations and the LCP model

Because in practical building design evaluations, designers are not required to consider uncontrollable surrounding buildings, our LCP method is developed without data on surrounding structures, extending the evaluation area by 7.5 meters in each direction. To ensure a fair comparison between LCP and CFD results, the CFD domain is similarly arranged with no upwind or downwind buildings to avoid interference with the flow patterns. Symmetric boundary conditions are applied laterally to emulate the impact of dense urban environments.

The CFD simulations employed Reynolds-averaged Navier–Stokes (RANS) equations with a realisable k-epsilon turbulence model. The computational domain extended 215 m (x), 2500 m (y), and 500 m (z), providing ample buffer distance upwind (negative y-direction) and downwind (positive y-direction). A 7.5-meter buffer between the building blocks and the lateral boundaries, reflecting half of the average street width in central Hong Kong (He *et al.* 2022). Inflow wind profiles, oriented along the y-axis, follow log law equations, with a roughness length of 1 m and a reference wind speed of 8.2 m/s at a 500 m height from Waglan Island weather station.

3.4 Parametric study using metrics from the SBD Guidelines

After establishing a promising correlation through the preliminary parametric design, further parametric studies are conducted to determine compliance thresholds based on real projects' three-dimnsional data ranges. The studies focus on four major combined metrics derived from the SBD Guidelines: the percentage of permeable elements (PE), changes in wind path direction, continuous projected façade length (Lp), and overall building permeability (P).

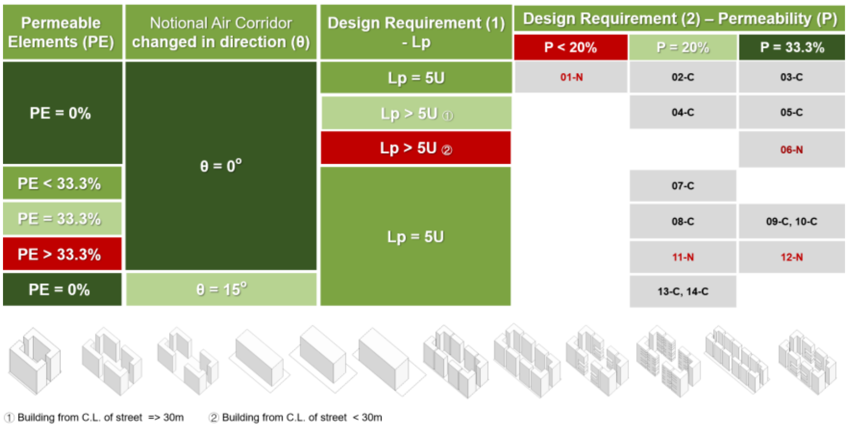

Figure 6. Parametric model matrix with PNAP APP-152 building design parameters

The parametric study matrix examines scenarios with overall permeability set at 20% and 33.3%, varied in percentages of PE, wind path direction changes, and continuous projected façades lengths. Additionally, several non-compliance cases have been included to delineate the "threshold" for the LCP. This comprehensive analysis enhances our understanding of building permeability compliance and informs future design iterations to meet the requirements under the SBD Guidelines (*Figure 6*).

The study has taken account of scenarios based on building design parameters of real projects' three-dimensional data ranges for building blocks, building separation, continuous façade lengths, and permeable elements/ void spaces within or between buildings. 8 nos. of scenarios are being carried out at the time of writing to include scenarios of completed real-world projects and other projects proposed by stakeholders. Various parametric models are assigned to meet the building permeability standards stipulated in PNAP APP152 to establish the equivalent performance standards under the LCP method.

The computational efficiency advantage of the LCP is demonstrated in our parametric study, comparing the time required for a single run of LCP versus CFD. The average simulation time for CFD takes around one whole week, while LCP calculation time requires less than 1 hour. With our latest algorithm development, this can be reduced to under 10 minutes. This highlights the time-saving benefits of using LCP, which favours rapid design optimization and verification.

4 Findings and Discussion

4.1 Correlation between LCP and CFD

The parametric study outlined in Para. 3.3, conducted using linear, exponential models and power fit model, showed strong agreement between LCP and CFD results, with R-squared values around 0.8 (*Figure 7*). Additionally, designs compliant with PNAP APP-152 requirements generally demonstrated higher normalised CFD performance, indicating that the LCP method aligns well with the geometric parametrisation approach mandated in the guideline.

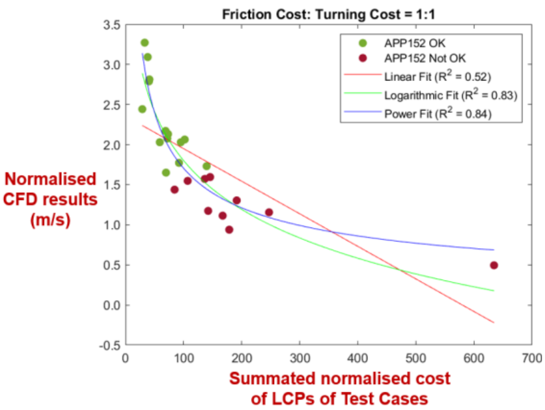

Figure 7. Relationships between spatially-averaged CFD and LCP results for 24 random building plot scenarios. Both logarithmic and power-law fits demonstrate strong agreement (R2 > 0.8) between LCP and CFD results, highlighting the robust performance of the LCP model.

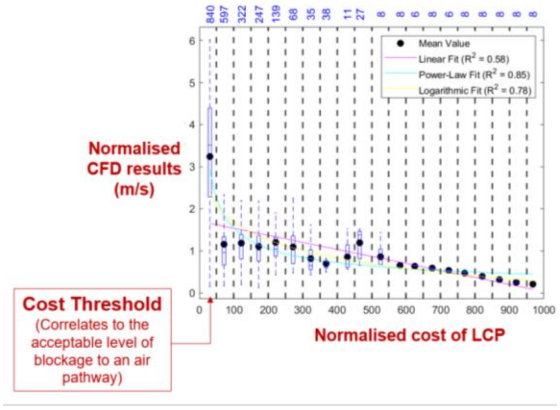

Figure 8. Relationships between path-specific CFD and LCP results for 2400 paths grouped into 20 bins. The results reveal a distinct marginal decreasing trend in mean CFD-simulated wind speeds as the mean LCP cost increases, with a clear turning point in normalized LCP cost emerging between bin 1 and the subsequent bins.

4.2 Cost threshold of the LCP method

To consider a threshold total cost for individual LCP paths for building permeability evaluation, LCP path costs from 24 randomly generated building block with 2200 paths were analysed. These total costs were sorted into bins with intervals of 50 cost units. Box plots were generated to display and compare each bin's maximum, minimum, mean, and median values.

The cost threshold for the LCP model results presented in this study was determined through a sensitivity analysis of the data distribution pattern of path-specific normalized LCP costs against CFD results. Bin widths of 25, 50, 100, and 200 were tested. As shown in *Figure 8*, the analysis indicates that the turning point of the normalized LCP cost becomes more pronounced when the bin width is reduced from 200 to 100. However, no significant difference is observed when further narrowing the bin width from 50 to 25. Furthermore, the normalized LCP cost range of 50 to 100 corresponds to the values that distinguish scenarios meeting the APP152 criteria from those that do not.

The normalised CFD performance and cost of the LCP from the PNAP APP-152 parametric model from the parametric studies described in Para. 3.3 and Para. 3.4 will be further compared to establish the LCP threshold.

4.3 Formulation of LCP Performance Standards

To evaluate building permeability, the LCP method introduces the concept of LCP%. An open site with no building blockage is taken as the baseline. The total cost of all airpaths within an assessment zone, as discussed in Para. 3.2.3 will be zero for the baseline. The LCP% of such a baseline is defined as 100%. For a project with building blockage, its building permeability is measured

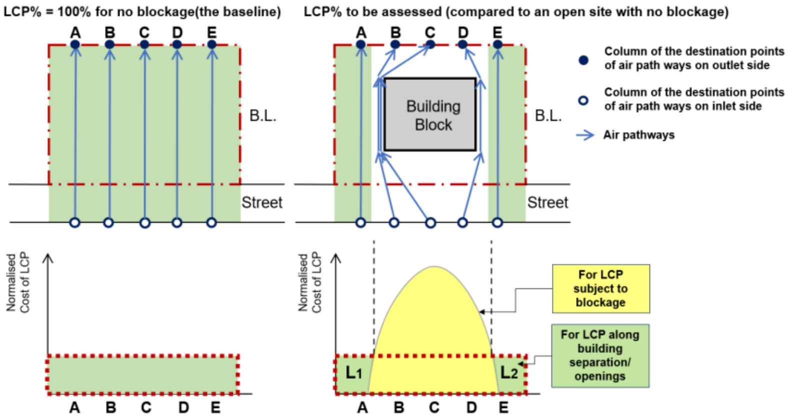

Figure 9. LCP% of a proposed building scheme

by the summation of the values between the cost threshold (as discussed in Para. 4.2) and the LCP costs of airpaths that fall below the threshold. The LCP% of the project will be expressed as a percentage compared to the baseline (*Figure 9*).

LCP% for cases having permeability of 20%, 25% and 33.3% in compliance with the prescriptive requirements of the SBD Guidelines that were tested in the parametric study mentioned in Para. 3.4 will be evaluated to establish LCP benchmarks equivalent to the performance standards required under the extant SBD Guidelines.

4.4 LCP application for special cases

The 2D prescriptive approach for compliance checking has limitations, particularly in six generic typologies for special circumstances where its application is challenging (*Figure 10*). Five of these relate to geometry or blockage and can be effectively addressed using the LCP method.

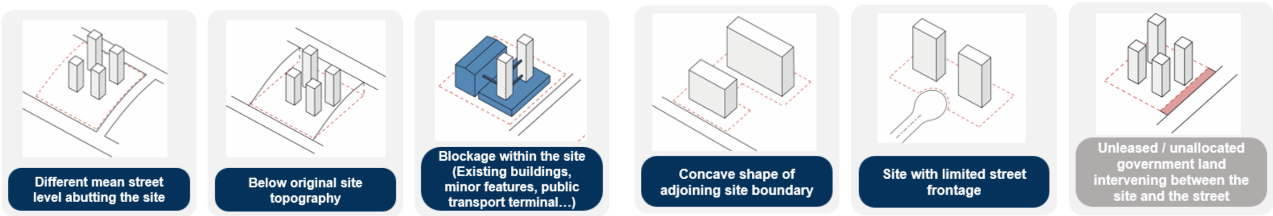

Figure 10. Six generic typologies for special circumstances

For sites with topographical features abutting different mean street levels or part of buildings below the original site topography, the tool will adopt a “Ground-Follow” principle. The tool will establish a “notional ground” and automatically adjust the grid size on the outlet side to ensure point-to-point consistency. For irregular boundaries or limited street frontage, the tool evaluates individual “notional” sites separately.

Additionally, this tool distinguishes between heritage / existing buildings and new buildings within the site and assesses new developments only. The heritage / existing buildings for adaptive reuse (with no additional building bulk) will be exempt from LCP assessments. Permeability requirements for the “notional site” shall be compiled while the Lp requirement shall be exempted. For certain special buildings with functional constraints that prevent stacking or make compliance with P in the low zone difficult, an exemption for P is proposed. In contrast, Lp compliance is recommended to maintain adequate airflow in the area. For sites with limited street frontage, the LCP assessment focuses solely on P, with the inlet side aligned along the site boundary at the cul-de-sac.

The basic principles for the specific cases have been established and will be translated into an algorithm in Phase B, as they require additional parameter setups before conducting the LCP assessment. In early Phase B, we will conduct pilot testing on several real-world examples to ensure that the results are not inferior to the existing PNAP APP152 prescriptive approach. These findings demonstrate the LCP methodology’s flexibility in accommodating various urban contexts, from standard rectangular plots to complex sites with unusual topographies or heritage buildings. Its adaptability makes it a valuable tool for addressing multiple urban planning and design challenges.

4.5 Stakeholder Engagement

The stakeholder consultation forum, which included representatives from the government, planners, engineers, architects, designers, and industry stakeholders, was held to discuss the research findings and the proposed LCP methodology of Phase A. Stakeholders' feedback from the questionnaire after the Forum indicated strong industry support for the LCP method and its integration with BIM systems as an alternative to the existing prescriptive approach. Stakeholders also recognised the value of the tool in enabling informed decision-making early in the design process, minimising costly revisions while adhering to design requirements.

However, concerns were raised about the performance of the LCP method compared to the current prescriptive method. Simulations of 24 test cases showed a strong correlation between the LCP method and CFD results. While designs compliant with PNAP APP-152 generally performed better, the LCP method proved more effective in capturing airflow dynamics for complex geometries. A few non-compliant designs yielded similar results with some compliant cases, and further refinement of cost thresholds will be reviewed in Phase B.

5 Conclusions and Further Research

This study explores the integration of the new LCP methodology with BIM to assess building permeability in high-density urban areas, providing a cost-effective alternative methodology to the in-use prescriptive method. By leveraging LCP's computational efficiency and ability to account for 3D airflow dynamics, this study offers a more flexible and scalable approach to evaluating building permeability during the early design phases where planners and designers can quickly assess the permeability of various building configurations and make design adjustments as needed. This could significantly help achieve UN SDGs through better liveability for sustainable cities and communities (SDG 11), better air quality for health and well-being (SDG 3), and more climate-responsive building design for climate action (SDG 13).

The proposed LCP method was validated against CFD simulations, showing a strong correlation between the two methods ($R^2 \sim 0.8$), confirming its reliablity and efficiency. Additionally, the LCP method demonstrated adaptability in complex building configurations, irregular site boundaries, and particular special cases raised by the stakeholders when using the prescriptive approach to calculate permeability for their projects. Future research will focus on refining the LCP model, notably by considering granular grid resolution for more detailed analyses and determining the LCP threshold, which is not inferior to current prescriptive approach requirements.

Looking ahead, the study will transition into Phase B, where the focus will be on the design, development, and delivery of a 3D automated assessment tool with BIM tools based on the proposed LCP methodology. BIM models usually contain complex geometric and semantic details that need to be simplified into grid formats without losing critical information, which can be time-consuming and prone to errors, traditional BIM APIs also lack support for parallel computing. The LCP algorithm addresses these inefficiencies by incorporating multi-processing capabilities which enhance data exchange, processing speed, and design accuracy. The project will undergo user acceptance testing to ensure its functionality and ease of use in actual project applications. Training materials and guidelines will be developed to ensure that industry professionals can fully utilise the tool to assess compliance with building separation and ventilation requirements under the SBD Guidelines.

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