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URBAN MORPHOLOGY AND AIR QUALITY IN DENSE RESIDENTIAL ENVIRONMENTS: CORRELATIONS BETWEEN MORPHOLOGICAL PARAMETERS AND AIR POLLUTION AT STREET-LEVEL

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Abstract

This study is the second part of the series that identifies whether site-specific urban morphological parameters are correlated with air quality. This study aims to identify the most important urban morphological parameters that affects air quality at street level that affect air quality in metropolis like Hong Kong through field measurements and statistical analyses. The study considers 20 urban residential areas in five major districts of Hong Kong and real-time street level air pollutant and microclimatic data are collected from these areas. 21 morphological variables are identified and calculated based on the geometry of the urban fabric. Using principal component analyses, it is shown that out of the many urban morphological factors, only five morphological variables (plan area density, occlusivity, aerodynamic roughness height, mean built volume, compactness factor) and four land development factors (aspect ratio, distance between building, mean building height and standard deviation of building height) correlate with particulate matter. Besides mineralisation factor, contiguity and canyon ratio marginally correlate with particulate matter. On the other hand, nine variables (plan area density, compactness factor, occlusivity, aerodynamic roughness height, average size of building volume, aspect ratio, distance between buildings, mean building height and standard deviations of building heights) correlate with NOx. All others play insignificant roles in street-level pollution effect. Moreover statistical analyses show little correlation between CO and ozone with urban morphological parameters. It is also established that the key microclimatic variables that connects PM and NOx with the urban morphological factors are northerly wind, relative humidity and temperature, which in turn translates to affecting the street-level air pollution.

Keywords: Urban morphology, Urban morphological parameters, Meteorological factors, Principal component analyses, Urban environment.

1. Introduction

Street level air pollution is one of the main concerns in megacities in the world [1], as mentioned in Part I of the study (Edussuriya et al. [2]; hereafter referred to as Part I). Laymen usually associate air pollution with the density of the urban environment and the pollution generated therein. As a matter of fact street level air pollution deals with many facets in urbanism: urban microclimate, urban morphology, physical setting and geometry, human and industrial activities, man-made structures, etc. Hence street-level air pollution deals with a large number of complex variables other than its sources, which are not yet properly identified and understood. It had been suggested that the physical geometric configuration of the urban environment significantly affects the physics of urban air pollution [3-5]. The problem, however, is that there is no general consensus on what are the true underlying factors behind the problems. Different researchers look at the problem from a different angle, and it is difficult to conclude which particular factors or parameters would be more important in determining the air pollution scenario within an urban context.

In Part I of this work we have limited our discussion to morphological factors, we have realised that the geometries of urban structures alter the flow field within the urban street canyon in a variety of ways [6, 7]. Oke [4] and Golany [8] explained that certain street geometries, orientation, street width and city layout affect the wind field and air movement in the city. It can be easily established that urban forms affect the micrometeorology within an urban canopy which in turns affect the air pollution scenario [4, 8, 9]. Amongst them, urban winds carry pollutants from the one place to another, with the trajectories determined by various urban morphological factors [10]. However most studies of urban wind are limited to specific aspects of cuboids and do not reflect the urban reality [11].

Aside from the above issues, different works use different approaches and point to different parameters with no general consensus on which parameters is most important. For instance, Givoni [3] identified the following parameters as important in controlling urban climate: overall urban area density, height of individual buildings, street orientations, availability of open spaces and green shutter belts. Similarly Oke [4] and Chan et al. [11] pointed to dimension parameters of urban geometry as the factors in determining the microclimate inside a city. There is no indication on how these factors could contribute to air pollution. An urban morphological database was developed by Cionco and Ellefsen [10] while Newton [12] analysis of archetype urban systems identified the influence of land-use on air quality of a region in the macroscale.

The only consensus the above research is that there is a relationship between urban fabrics and street-level air quality. The question is actually, what kind of urban fabric and how it physically affects it. The objective of this series of work is thus to identify the factors available to investigate which ones are more important. In Part I of this study, we have shown that in spite of the large number of in-district variations in morphological variables, air pollution variations at sizeable district levels of typically 2 to 5 km radius township are insignificant for most of the variables. It means that air quality in Hong Kong are distinguishable not by district-level variable but rather in-site fabrics. In Part II of this study, we shall look into the variation within the site and attempt to identify the key parameters that affect air quality and urban microclimate at site level. It is anticipated that these information would become useful in future development of megacities.

In specific terms, it is postulated that urban morphology alters the urban microclimate through physical intervention, which in turns affect air quality. It is presumed, a priori, that the urban fabric practically controls the ventilation pathways and thus affects the microclimatic behaviour within the site. In turn, these ventilation pathways control the dispersion of air pollutants and thus alter its concentration. The objective is to identify what sorts of ventilation pathways are the most important in a cityscape like Hong Kong. Field measurements of air pollution and micro-climatic data were taken at multiple sites in various residential areas of Hong Kong. The urban fabric is studied and analysed through digital maps and their urban morphological factors are calculated. The urban morphological factors and air pollution concentration data are then analysed using principal component analysis and Kruskal-Wallis and Spearman R tests to identify the correlations, if any, and to single out the most important factors during the process.

2. Key Urban Morphological Attributes and Variables

Table 1 explains the importance of these urban morphological variables in different contexts, especially in the dense settings of Hong Kong. These parameters are classified to conceptualise the variables and to distinguish which are the ones most pertinent to the urban fabrics of Hong Kong. Details of these parameters and their calculations can be referred to Part I.

Table 1. Urban Morphological Indicators Used in this Study [2].

Affect Variables	Independent Variables	
	Development Factors	**Built Form Factors**
1. Regional factors - topography / urban terrain - altitude - distance from water body	1. Land coverage / utilisation - plot ratio, packing ratio - mineralisation factor / percentage of impervious surface	1. Street and building dimensions - canyon aspect ratio - street aspect ratio - canopy breadth ratio - street block ratio - mean building height - mean canyon width
2. City-level factors - urban layout: layout, development, street form, open spaces, roof - city size / quotient - proximity to pollution sources and sinks	2. Land use intensity - compacity factor - complete aspect ratio - mean contiguity factor - frontal area density	2. Canyon / building orientation - wind angle to longer-street axis of buildings
3. Site composition / locality factors - population density quotient - urban land use - traffic load - location	3. Roughness related intensity - urban density, rugocity or floor area ratio - roughness height - zero-plane displacement height - mean built volume - urban porosity - sinuosity - occlusivity	

3. Methodology

Considering the large number of variables, statistical methods based on field survey data have been adopted for this work. Since this study is a spatial analysis, we have adopted Karatasou et al. [9] spatial field regime for the study as in Part I.

Twenty sites (Fig. 1) are selected and measurements of pollutant concentrations and urban geometries are taken. Predominantly residential sites with marked differences in urban layouts and building geometries have been selected as they maximise the representation of spatial variations of the urban morphologies with similar pollution characteristics in terms of pollutant types. References are based on the previous study in Part I for selection criteria, focusing on similarity in traffic, terrain and activities. Samples of selected study areas are presented in Part I. Due to high density situation, large contrasting variations of building geometries can be observed within the urban fabric in Hong Kong. For this reason various simplifications must be applied as in Part I of this paper. The computations of the morphological indicators, based on methods by Ratti et al. [13] and Part I, involve calculations of the dimensions of all the buildings and structures of the sample sites based on the high-precision digital maps and data supplied by the Lands Department of Hong Kong. Morphological and surface data are calculated based on the Grimmond and Souch [14] and MacDonald et al. [15]. Upon simplifications, the morphological indicators as listed in Table 1 are calculated for all sites.

Dustscan Sentinel Model 3030 Aerosol Monitor and Casella ETL2000 Multi-component Air Quality Monitor are used to monitor the real-time particulate matters, gaseous pollutants and local meteorological data. A four-hour measurement is taken at least three times for each site over the two-year measurement campaign except weekends. Suspended particulate matter PM2.5, nitrogen dioxide, ozone and carbon monoxide have been collected for this study as they are major air pollutants. Site specific microclimatic conditions such as temperature, relative humidity, wind speed and direction have also been measured. To ensure proper comparison, data collected that fell into days of extreme meteorological conditions and unusual conditions (like traffic conditions) were discarded. The details of the measurement can be referred to Part I.

Fig. 1. Location of Sampling Sites.

4. Understanding the Nature of Primary and Derived Data

The first stage of the statistical work is to identify what are the key correlation factors that have effects on urban air pollutant concentration. To this end, we employ the Principal Components Analysis (PCA, Walpole et al. [16]), which reduces the number and dimensionality of factors and co-variants by identifying similarities among intervene and affect variables and co-variants (independent variables) in groups. In our context, the affect variables are the regional factors, city-level factors and site composition factors, the independent variables are the morphological factors and the intervene variables are the meteorological factors (Table 1). PCA identifies mutually inter-correlated variables and ranks them in order to eliminate insignificant variables. If the correlation amongst co-variants is high or if there are clusters of co-variants with high inter-correlation amongst them, this process can represent them through a smaller number of representative co-variants, and thus eliminate the less important independent variables in the correlation.

5. Testing Hypothesis

Upon removing the irrelevant variables using PCA, we would like to know which pollutant is associated with which respective relevant morphological variables and how one affects the other. The process of finding this association will be performed in two stages. The first step would be to examine whether the predictors (urban morphology and other variables) have any effects on responses (street level air pollutant concentration). The second step would be to measure these effects: the strength of relationships between predictors and responses by correlation analysis. These two steps will establish any links between predictors and responses to satisfy the hypothesis testing.

This hypothesis will be tested using test statistics and inferential statistics. Associations will be tested by conducting Kruskal-Wallis test and Spearman R correlation analysis. Kruskal-Wallis test is a test statistics similar to ANOVA (analysis of variance) test to explore differences that exist between variables in order to detect any relationships. This test will be followed by Spearman R correlation analysis to examine strength of the effects between variables. The latter will quantify the association and describe magnitude of the relationship [17].

Kruskal-Wallis test: Kruskal-Wallis Test uses the H chi-square distribution to test whether there are any significant differences between group means. The degree of freedom is considered as ‘DF = (sample groups – 1)’ to test whether the result is significant. We have considered three groups/clusters (less, moderate and polluted) and thus DF (n-1) is 2. Spearman *R* correlation analysis: Spearman R correlation analysis is a common non-parametric inferential statistical method to find the strength of associations through correlation analysis. Correlation of coefficients is a measure to strengthen of the relationship and it enables us to identify the strength of correlation between the street level air pollutant concentration and factors and co-variants of this study.

Poissant et al. [18] adopted Spearman R correlation techniques for a similar set of microclimatic data analysis and has inspired this study. We use Spearman’s rank correlation co-efficient in our study as it considers rank data and is suitable for analysing nonlinear relationships. Spearman’s rank correlation considers significant relationship by correlation coefficient value denoted by r_s. Calculated

r_s value is compared with critical values for the *n*-1 situations. The degree of freedom is considered as 'DF = (sample size – 1)' to test whether correlation is significant. After removing the two sites with outlying data points, we consider sample size as 18 urban residential areas and thus DF (*n*-1) is 17.

Accordingly, Spearman's rank correlation analysis is performed to test the second step of the hypothesis. This will be performed in multivariate analysis platform in JMP using rank data of responses and predictors. Since there are many factors and co-variants are involved, it is assumed that each pair test is separated and independent to support or reject the null hypothesis assign for this test.

6. Results and Discussion

Preliminary screening of data in this research speculates that relationship between air pollutants and urban morphological variables might be nonlinear and complex. Besides, Part I explains that this study involves multivariate variables and some of these are inter-correlated variables. Hence multivariate analysis and PCA are used to identify the most relevant variables and to reduce the dimensionality of datasets first. After that, correlation analyses are performed in stages and to identify how the three pollutants are related to each factor individually.

Based on the first stage of statistical analyses as summarised in Table 2, the following have been observed immediately:

- Out of the three pollutants (with ozone already discarded in Part I of the Study), CO indicates a moderately significant positive relationship with microclimatic variables (temperature and wind speed) compared with the morphological indicators. NOx indicates a marginally positive relationship with temperature while PM indicates a negative relationship with relative humidity at a moderately significant level. Associations of the morphological variables are higher with relative humidity than other meteorological factors.
- Location effects register a moderately significant positive relationship with CO.
- Mixed associations between morphological variables and air pollutants are reported at either moderate or low significant levels. CO does not correlate to any morphological variables.
- Six variables: frontal area density, porosity, sinuosity, zero plane displacement height, aspect ratio and street block ratio indicate a very poor correlation with the three air pollutants. This suggests they have little connexions with air pollutants or that their characteristics are already being considered by other factors.
- Correlations amongst the same categories of morphological variables are also very high in aerodynamic roughness height, mean building volume, mean building height and distance between buildings.

PCA is then used to reduce the number of dimensionality of similar variables, which enables us to identify the key variables for describing the relationship between air pollution and urban morphology. PCA is performed on the previously identified eight categories of variables that include traffic, locations, and urban morphologies as in Table 2. We summarise here about the response of each urban morphological parameters on PCA (Tables 3).

Table 2. Selection of the Most Explanatory Variables from PCA and Multivariate Analysis.

	Analyses	**Outcomes of PCA decision** (variables to be removed marked as X)				**Multivariate analysis results:**	**Selected variables**
	Variables	Approach 1 Multivariate Analysis	Approach 2 PCs Variance	Approach 3 PCs Loadings	Variables to remove	with significant relationship	
	Factors						
	Traffic						
1	# cars on road	X	?	X	X	X	-
2	VKT (200 grid)	-	-	-	-	PM, NOx	Yes
3	AADT (1000 grid)	-	-	-	-	PM	Yes
	Factors						
	Location						
1	Latitude	X	-	X	X	-	Yes -?
2	Longitude	X	X	X	X	CO	Yes -?
3	(Latitude)2	-	-	-	-	CO	-
4	(Longitude) 2	X	X	-	-	CO	-
5	Latitude x Longitude	X	X	-	-	PM	-
	Co-variants						
	Land utilization Indi.						
1	Plan area density (λp)	?	-	-	-	NOx & PM	Yes
2	Mineralization factor	X	X	-	?	PM	Yes -?
	Compactness effects						
1	Compactness factor	?	-	-	-	NOx & PM	Yes
2	Complete aspect ratio	X	-	X	X	-	-
3	Mean contiguity factor	-	-	-	-	NOx & PM	Yes
4	Frontal area density (λf)	X	-	X	X	-	-
	Pores effects						
1	Porosity (Po)	-	-	-	-	PM	Yes
2	Sinousity (So)	X	-	X	X	-	-
2	Occlusivity (Oc)	X	-	-	-	NOx & PM	Yes
	Roughness effects						
1	Rugosity or FAR	-	-	-	-	PM	Yes
2	Zo	-	-	-	-	NOx & PM	Yes
3	Zd	X	-	-	X	NOx	-
4	Σ Vblg. /no. of blg	?	-	-	-	PM	Yes
	Canyon indicators						
1	Canyon ratio (H / Wst)	-	-	-	-	PM	Yes
2	Aspect ratio (Lst / H)	X	-	-	-	-	Yes
3	Breadth ratio	X	-	X	X	NOx & PM	-
4	Block ratio (street)	-	-	X	X - ?	CO	-
	Bldg & Street Geometry						
1	Distance between bldg	X	-	-	-	NOx & PM	Yes
2	Mean bldg. height	X	-	-	-	NOx & PM	Yes
3	Std. dev. of bldg. ht.	-	X	-	-	NOx & PM	Yes

Notes:

'Yes' denotes selected variables that given significant results from PCA and 'Yes-?' denotes the variables that given marginal significant results from PCA, but selected for further analysis

Land utilisation: Initial multivariate results, Table 3(a), report a moderately high level association between the plan area and air pollutant concentration of PM and NOx but not with CO. However PCA for plan area density and mineralisation factor shows an exceptionally strong association on the principal axis.

Table 3(a). Scores of Land Utilisation Variables against Principal Axes of Variations Using PCA.

Variable	Axis 1	Axis 2
Plan area density (λp)	0.950045	0.155596
Mineralization factor	0.861074	-0.022139

Compactness: Initial multivariate analyses of this group of variables indicate compactness factor and mean contiguity factor with moderately significant relation with air pollution concentration. Very low association has been found with frontal area index and complete aspect ratio. PCA shows that compactness and contiguity factor have a strong association with axis 2 as in Table 3(b).

Table 3(b). Scores of Compactness Variables against Principal Axes of Variations.

Variable	Axis 1	Axis 2
Compactness factor – C_f	0.389479	-0.717278
Complete aspect ratio	-0.045834	-0.180839
Mean contiguity factor (m^{-1})	0.020864	-0.944146
Frontal area density (ρ_f)	0.096882	0.093286

Urban pores: PCA: Table 3(c) shows that trends of relationship for porosity and occlusivity. Although the scores of occlusivity are not significantly high, it is still important to include them in consideration as previous analyses in Part I have identified occlusivity as a key factor at district-level.

Table 3(c). Scores of Urban Pores Variables against Principal Axes of Variations.

Variable	Axis 1	Axis 2
Porosity (Po) - parallel roads	-0.049398	0.986747
Sinuosity (So)	-0.14207	0.022855
Occlusivity (Oc)	0.504334	-0.027774

Urban roughness: Initial multivariate results report high level of associations by all roughness indicators, Table 3(d). However, PCA results show orthogonality trends in data in two principal axes. Zero plane displacement height (Z_d) can be omitted from the analysis, as it has given the lowest loading on higher principal components and it is also embedded in calculation of roughness height.

Table 3(d). Scores of Urban Roughness Variables against Principal Axes of Variations.

Variable	Axis 1	Axis 2
Rugosity (m)	0.114996	-0.972244
Zo	0.950985	0.189386
Zd	0.339208	0.88706
Volume/ no of bldgs (m^3)	0.870117	0.307544

Urban canyon geometry: Analyses of the four variables with PCA demonstrate that only canyon ratio and aspect ratio are associated with the principal axis, Table 3(e). Block and breadth ratio shows only very moderate correlation and thus will be omitted from future studies.

Table 3(e). Scores of Street Canyon Variables against Principal Axes of Variations.

Variable	Axis 1	Axis 2
Canyon ratio	0.362131	0.866877
Aspect ratio - Lst. / H	-0.911254	-0.105221
Breadth ratio	-0.191212	0.726656
Block ratio (street)	0.767251	-0.11076

Street and buildings: PCA shows that all three variables have strong correlations, Table 3(f).

Table 3(f). Scores of Street and Building Geometrical Variables against Principal Axes of Variations.

Variable	Axis 1	Axis 2
D - distance between bldgs. (m)	0.832141	0.29075
Mean bldg.height (m)	0.906032	0.160549
Std# deviation of bldg# height	0.816188	0.021371

In summary (Table 4), the most relevant variables have been identified to represent the study out of the myriads of indicators. It has been found, with certain surprises, that CO shows insignificant correlation to any morphological factors compared with the other two pollutants. This is probably attributed to the low level of CO measured and therefore a correlation cannot be established. To this end CO will not be included in future analyses.

Having established the assumptions we made and identified those important parameters in the context, we now proceed to test the hypothesis: ‘There is an association between street-level air pollution and urban morphologies’ and in so doing identify the roles of the parameters in the relationship.

As in typical statistical hypothesis testing, we establish the following null hypothesis H0 and alternative hypothesis H1:

Null hypothesis H0: Urban morphological variable and other explanatory variables have no effects on street-level air pollutant concentration.

Alternate hypothesis H1: Urban morphological variable and other explanatory variables have effects on street-level air pollutant concentration.

There are four possible scenarios of which the associations can be established:

- How urban traffic variables affect street level air pollutant concentration?
- How urban micro-meteorology variables affect street level air pollutant concentration?
- How are urban morphological variables associated with street level air pollutant concentration?
- How do urban morphological variables intervene with urban microclimate and affect street-level air pollutant concentration?

The hypotheses are tested in two stages by Kruskal-Wallis test and Spearman R correlation analysis to examine the effects and the strengths of the correlation. Kruskal-Wallis test examines whether the predictor (in this case the urban morphological variables) have an effect on the dependent variable (air pollution level), while Spearman R test measures the strength of the relationship. These two tests are conducted in conjunction to measure the triangulated relationships.

Table 4. The Selected Most Relevant Variables for Representing Residential Areas of Hong Kong.

	Family	Variables / indicators	Keys
A	Air quality, micro-meteorological conditions		
A1	Air quality	Level of PM 2.5	AQ1
		Level of Nox	AQ2
A2	Microclimate	Level of Temperature	MC1
		Level of RH	MC2
		Level of wind effect – W x cos θ (E-W direction)	MC3
		Level of wind effect – W x sine θ (N-S direction)	MC4
A3	Traffic	Traffic load: near filed regime VKT	TF2
		Traffic load: intermediate field regime VKT	TF3
A4	Location	Latitude	LO1
		Longitude	LO2
B	Morphological characteristics		
B1	Land utilization indicators	Plan area density (λp)	LU1
		Mineralisation factor	LU2
B2	Land use intensity Indicators	Compactness factor	LI1
		Mean contiguity factor (m-1)	LI3
		Porosity (Po)	LI5
		Occlusivity (Oc)	LI7
		Rugosity and or FAR	LI8
		Roughness length (Zo)	LI9
		Volume per building (Σ Vblg. /no. of blg)	LI11
B3	Building & Street Geometry	Canyon ratio (H / Wst)	BG1
		Aspect ratio (Lst / H)	BG2
		Distance between building (m)	BG5
		Mean bldg. height (m)	BG6
		Std. deviation of bldg. height	BG7
B4	Building & Street Orientation	Wind angle to longer building axis –in degrees	BO1

Table 5 and 6 summarise the results of the Kruskal-Wallis tests for $PM_{2.5}$ and NOx as independent pairs of morphological variables and microclimates under the associations mentioned above. These results will indicate acceptance or rejection of the null hypothesis for each pair of variables and their significances will be analysed.

Significant factors and co-variants that have an effect on street-level air quality under each relationship have been identified from Kruskal-Wallis test. Accordingly, significant variables have been identified comparing calculated H (similar to χ^2) values with critical table values for each test. Critical values are considered at confidence level ranging from 0.05 to 0.1.

Results from the Kruskal-Wallis test strongly affirm the alternative hypothesis that there is a correlation between urban morphology and air pollution concentration. Moreover the analyses also indicate the followings:

- Traffic variations at both near and intermediate field show significant differences amongst groups with both PM and NOx concentrations.

- Results of location effects are insignificant, which further confirms our findings in Part I that district level and location variations are insignificant.
- Urban microclimates play a major role on street-level air pollution concentration. Only NOx with relative humidity reports marginally significant differences amongst groups.
- Out of the 15 urban morphological variables considered that effect on street-level air pollutant concentrations, only five land development (plan area density, occlusivity, aerodynamic roughness height, mean built volume, mean contiguity factor) and four street geometrical variables (aspect ratio, distance between buildings, mean building height and standard deviation of building height) report significant differences amongst groups with both PM and NOx concentrations.

Table 5. Results of Kruskal-Wallis Test and Dunn's Multiple Comparison Test: $PM_{2.5}$ with Factors and Co-Variants.

	Test statistics	Kruskal-Wallis Test			Dunn's test	Reject / accept *Ho*
		H - chi-sq	DF	Prob>H		
	Factors					
I	*Traffic*					
	Near field traffic	7.632	2	0.0220	means of 1 < 2/3 & 2 # 3	Reject Ho
	Intermediate field traffic	6.615	2	0.0366	means of 1 < 2 & 2 # 3	Reject Ho
II	*Location*					
	Latitude	0.883	2	0.6428	-	Accept Ho
	Longitude	0.239	2	0.8874	-	Accept Ho
III	*Microclimate*					
	Level of Temperature	1.551	2	0.4605	-	Accept Ho
	Level of RH	3.923	2	0.1406	-	Accept Ho?
	Level of wind effect (E-W)	0.283	2	0.8679	-	Accept Ho
	Level of wind effect (N-S)	2.753	2	0.2524	means of 1 < 3 & 2 # 1	Accept Ho?
	Co-variants					
IV	*Land utilization indicators*					
	Plan area density (λp)	9.964	2	0.0069	means of 1 < 2 & 3	Reject Ho
	Mineralisation factor	4.833	2	0.0892	-	Accept Ho?
	Land use intensity indicators					
	Compactness factor	5.027	2	0.0810	means of 1 < 3 & 2 # 3	Accept Ho?
	Mean contiguity factor	4.393	2	0.1114	-	Accept Ho?
	Porosity (Po)	1.185	2	0.5529	-	Accept Ho
	Occlusivity (Oc)	9.172	2	0.0102	means of 1 < 3 & 2 # 3	Reject Ho
	Rugosity or FAR	4.587	2	0.1009	-	Accept Ho?
	Zo	9.063	2	0.010	means of 1 < 2/3 & 2 # 3	Reject Ho
	Σ Vblg. /no. of blg	9.550	2	0.0084	means of 1 < 2 & 2 # 3	Reject Ho
	Building & Street Geometry					
	Canyon ratio (H / Wst)	2.203	2	0.2233	-	Accept Ho?
	Aspect ratio (Lst / H)	6.458	2	0.0396	means of 1 < 2 & 2 # 3	Reject Ho
	Distance between building	7.067	2	0.0292	means of 1 < 2/3 & 2 # 3	Reject Ho
	Mean building height	8.338	2	0.0155	means of 1 < 2/3 & 2 # 3	Reject Ho
	Std. dev. of bldg. height	7.370	2	0.0251	means of 1 < 3 & 2 # 3	Reject Ho
	Building & Street Orientation					
	Wind angle to longer axis	5.40 (G^2)	10	0.858	n/a	Accept Ho?

Notes: H significance level were referred to table value as critical values, df = 2 at P<0.05 to 0.10 levels in three regions n= 4, n=5, n=5 sample categories.

Dunn's multiple comparison results denotes here shows that mean rank of region 'x' lower than the means of 'y' as; 'x' < 'y' and region 'y' did not differ significantly from other region 'z' as; 'y '# 'z', which x, y & z refers to region 1, 2 & 3 in this study.

Marginally significant variables are marked as 'Accept Ho-?', which will be further analysed before eliminate them

Table 6. Results of Kruskal-Wallis Test and Dunn's Multiple Comparison Test: NOx with Factors and Co-Variants.

	Test statistics	**Kruskal-Wallis Test**			**Dunn's test**	**Reject /accept *Ho***
		H - chi-sq	DF	Prob>H		
Factors						
I	*Traffic*					
	Near field traffic	6.830	2	0.032	means of 1 < 2 & 2 # 3	Reject Ho
	Intermediate field traffic	6.852	2	0.032	means of 1 < 2 & 2 # 3	Reject Ho
II	*Location*					
	Latitude	0.002	2	0.998	-	Accept Ho
	Longitude	0.500	2	0.778	-	Accept Ho
III	*Microclimate*					
	Level of Temperature	0.417	2	0.811	-	Accept Ho
	Level of RH	5.221	2	0.073	means of 2 < 3 & 2 # 1	Reject Ho
	Level of wind effect (E-W)	0.536	2	0.764	-	Accept Ho
	Level of wind effect (N-S)	3.263	2	0.195	-	Accept Ho?
Co-variants						
IV	*Land utilization indicators*					
	Plan area density (λp)	9.231	2	0.009	means of 1 < 3 & 2 # 3	Reject Ho
	Mineralisation factor	4.139	2	0.126	-	Accept Ho?
	Land use intensity indicators					
	Compactness factor	4.331	2	0.114	means of 1 < 3 & 2 # 3	Accept Ho?
	Mean contiguity factor	5.829	2	0.054	means of 1 < 2/3 & 2 # 3	Reject Ho
	Porosity (Po)	0.662	2	0.718	-	Accept Ho
	Occlusivity (Oc)	11.27	2	0.003	means of 1 < 2 & 2 # 3	Reject Ho
	Rugosity or FAR	3.651	2	0.161	-	Accept Ho
	Zo	10.263	2	0.005	means of 1 < 2/3 & 2 # 3	Reject Ho
	Σ Vblg. /no. of blg	10.35	2	0.005	means of 1 < 2/3 & 2 # 3	Reject Ho
	Building & Street Geometry					
	Canyon ratio (H / Wst)	1.045	2	0.593	-	Accept Ho
	Aspect ratio (Lst / H)	8.540	2	0.014	means of 1 < 2 & 2 # 3	Reject Ho
	Distance between building	8.559	2	0.013	means of 1 < 2/3 & 2 # 3	Reject Ho
	Mean building height	11.30	2	0.003	means of 1 < 2/3 & 2 # 3	Reject Ho
	Std. dev. of bldg. height	11.27	2	0.003	means of 1 < 2 & 2 # 3	Reject Ho
	Building & Street Orientation					
	Wind angle to longer axis	8.38 (G^2)	10	0.596	n/a	Accept Ho?

Notes: H significance level were referred to table value as critical values, df = 2 at $P<0.05$ to 0.10 level in three regions n= 2, n=5, n=5 sample categories.

Dunn's multiple comparison results denotes here shows that mean rank of region 'x' lower than the means of 'y' as; 'x' < 'y' and region 'y' did not differ significantly from other region 'z' as; 'y '# 'z', which x, y & z refers to region 1, 2 & 3 in this study.

Marginally significant variables are marked as 'Accept Ho-?', which will be further analysed before eliminate them

Results therefore show clearly that there is a link between street-level air pollution and urban morphologies, and the key factors have been identified. The strengths of these relationships are then studied through Spearman R analysis. Similar to the previous test and using the same hypotheses, we assume that the relationships between air pollutant concentration and factors and co-variants are independent. Tables 7 and 8 summarise the Spearman's rank results.

Significant correlations between predictors and responses under each relationship category are identified from Spearman R correlation analysis. Accordingly, crucial variables are identified comparing calculated r_s values with critical table values for each test. Spearman R correlation analysis results support the assigned alternative hypothesis that street-level air pollution has a correlation with urban morphological factors identified through Kruskal-Wallis rank-sum analysis. According to these results, the relationships between street level air pollutant concentration and urban morphology can be summarised for each air pollutant. Results indicate the following findings in terms of four ways of associations for the groups considered:

Table 7. Results of Spearman's Rank Correlation Analysis - Correlation between $PM_{2.5}$ and Factors and Co-Variants.

	Test statistics	Spearman's rank analysis results			Reject /accept ***Ho***
		Spearman's Rho = r_s	DF	Prob> Rho	
	Factors				
I	*Traffic*				
	Near field traffic	0.470	17	0.048	Reject Ho
	Intermediate field traffic	0.318	17	0.197	Accept Ho
II	*Microclimate*				
	Level of Temperature	0.108	17	0.667	Accept Ho
	Level of RH	-0.244	17	0.327	Accept Ho-?
	Level of wind effect (E-W)	-0.034	17	0.893	Accept Ho
	Level of wind effect (N-S)	0.341	17	0.165	Accept Ho-?
	Co-variants				
III	*Land utilization indicators*				
	Plan area density (λp)	0.739	17	0.0005	Reject Ho
	Mineralisation factor	0.443	17	0.065	Accept Ho-?
	Land use intensity indicators				
	Compactness factor	0.633	17	0.005	Reject Ho
	Mean contiguity factor	0.429	17	0.075	Accept Ho-?
	Porosity (Po)	-0.134	17	0.595	Accept Ho
	Occlusivity (Oc)	0.363	17	0.132	Accept Ho
	Rugosity or FAR	0.500	17	0.034	Reject Ho
	Zo	-0.581	17	0.011	Reject Ho
	Σ Vblg. /no. of blg	-0.401	17	0.099	Accept Ho-?
	Building & Street Geometry				
	Canyon ratio (H / Wst)	0.435	17	0.070	Accept Ho-?
	Aspect ratio (Lst / H)	0.180	17	0.473	Accept Ho
	Distance between building	-0.494	17	0.036	Reject Ho
	Mean building height	-0.336	17	0.102	Accept Ho-?
	Std. dev. of bldg. height	-0.215	17	0.390	Accept Ho
	Building & Street Orientation				
	Wind angle to longer axis	-0.192	17	0.445	Accept Ho

Notes: Above r_s significance level were referred to a 'cap' adopted from table value of 4.72 as critical value, at Prob>Chi-Sq = 0.05 level in sample size of N = 18 (Siegel and Castellan, 1985).

Marginally significant variables area marked as 'Accept Ho-?', which will be further discussed and explained before eliminate them

Table 8. Results of Spearman's Rank Correlation Analysis - Correlation between NOx and Factors and Co-Variants.

	Test statistics	Spearman's rank analysis results			Reject /accept ***Ho***
		Spearman's Rho = r_s	DF	Prob> Rho	
	Factors				
I	*Traffic*				
	Near field traffic	0.380	17	0.11	Accept Ho
	Intermediate field traffic	0.589	17	0.010	Reject Ho
II	*Microclimate*				
	Level of Temperature	0.353	17	0.110	Accept Ho-?
	Level of RH	-0.015	17	0.951	Accept Ho
	Level of wind effect (E-W)	0.133	17	0.598	Accept Ho
	Level of wind effect (N-S)	0.153	17	0.542	Accept Ho
	Co-variants				
III	*Land utilization indicators*				
	Plan area density (λp)	0.662	17	0.002	Reject Ho
	Mineralisation factor	0.369	17	0.131	Accept Ho
	Land use intensity indicators				
	Compactness factor	0.585	17	0.011	Reject Ho
	Mean contiguity factor	0.453	17	0.058	Reject Ho
	Porosity (Po)	0.063	17	0.804	Accept Ho
	Occlusivity (Oc)	0.632	17	0.005	Reject Ho
	Rugosity or FAR	0.063	17	0.804	Accept Ho
	Zo	-0.653	17	0.003	Reject Ho
	Σ Vblg. /no. of blg	-0.661	17	0.002	Reject Ho
	Building & Street Geometry				
	Canyon ratio (H / Wst)	-0.058	17	0.816	Accept Ho
	Aspect ratio (Lst / H)	0.387	17	0.112	Accept Ho
	Distance between building	-0.434	17	0.072	Accept Ho-?
	Mean building height	-0.585	17	0.011	Reject Ho
	Std. dev. of bldg. height	-0.484	17	0.041	Reject Ho
	Building & Street Orientation				
	Wind angle to longer axis	-0.404	17	0.096	Accept Ho-?

Notes: Above r_s significance level were referred to a 'cap' adopted from table value of 4.72 as critical value, at Prob>Chi-Sq = 0.05 level in sample size of N = 18(Siegel and Castellan, 1985).

Marginally significant variables area marked as 'Accept Ho-?', which will be further discussed and explained before eliminate them

Near field traffic report a significant correlation only with PM; while intermediate traffic conditions and NOx concentrations report strong correlation. It might be attributed that NOx, being gaseous, is more dispersive and thus the range of effect is larger. In terms of urban microclimate, only marginally significant correlations are found between PM and northerly wind; while the same is valid for NOx and temperature. Although Kruskal-Wallis test indicates an effect with microclimatic variables, it is not apparent in r_s values in the Spearman R test. Some of these findings contradict to previous test findings and therefore, these correlations will be further verified.

Five morphological variables (plan area density, occlusivity, aerodynamic roughness height, mean built volume, compactness factor) and four land development factors (aspect ratio, distance between building, mean building height and standard deviation of building height) correlate with PM. Moreover mineralisation factor, contiguity and canyon ratio marginally correlate with PM.

Nine variables (plan area density, compactness factor, occlusivity, aerodynamic roughness height, average size of building volume, mean building height and standard deviations of buildings, aspect ratio, distance between buildings) correlate with NOx. Contiguity and orientation of buildings marginally correlate with NOx. All marginal relationships will have to be further verified in the interpretation of results subsequently.

Only two morphological variables correlate with microclimate; plan area density with northerly-wind and relative humidity and mean contiguity with northerly wind. Besides plan area density with wind; and standard deviation of building height, occlusivity, aerodynamic roughness height and aspect ratio with relative humidity marginally correlate. None of the morphological variables correlates with temperature although Kruskal-Wallis test reports significant results and hence marginal correlation between canyon ratio and temperature might be promising.

Figures 2 and 3 summarises graphically the results of Kruskal-Wallis Test and Spearman R correlation analysis and report the intermediate relationships between street level air pollutant concentration and urban morphological variables. Based on these results, we can conclude that there is a correlation between urban morphology, urban microclimate and air pollution. Findings of Spearman R correlation have reported the strength of associations of urban morphological variables and explanatory variables individually with street level air pollution.

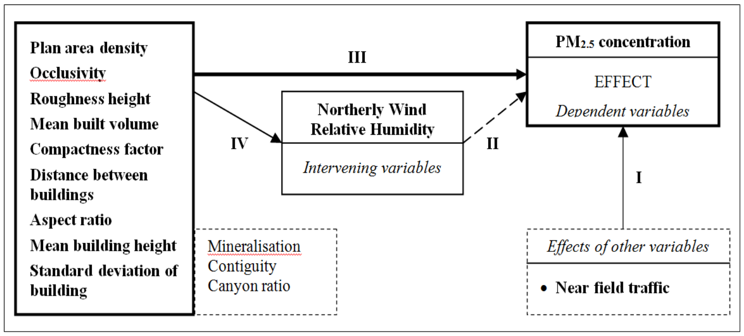

Fig. 2. Intermediate Relationship between Urban Morphology and PM$_{2.5}$ Concentration.

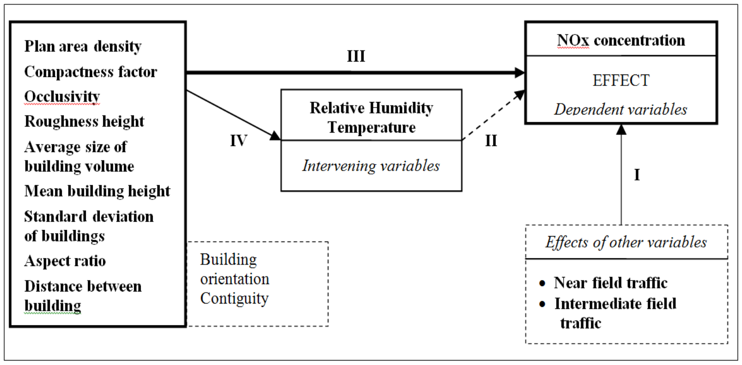

Fig. 3. Intermediate Relationship between Urban Morphology and NOx Concentration.

It is important to obtain a physical interpretation of the correlation. The relationship between PM2.5 and the various morphological factors are relatively easy to understand. All the morphological factors that are deemed related are certain kind of urban blockages and porosities. Obviously the more open space available, the more easily the dispersion and hence that has an effect on the PM2.5 concentration. This relates to factors like plan area density, occlusivity, compactness, distance between buildings and mean building height. Moreover from the analyses it is important to realise that can many of factors are mere duplicates or overlaps of each other (for instance mean building height against individual building heights or plan area density against open space) and thus many morphological factors are absorbed by one another.

It also turns out that the aspect ratio and the standard deviation of buildings have a significant correlation with dispersion of PM2.5. This has been discussed in Chan et al. [11], suggesting that heterogeneities in urban systems actually enhance dispersion. The dependence of PM2.5 with wind and humidity is unsurprising, due to Gaussian arguments and washout alone. The correlation with the northerly wind probably stems from the fact that the pre-dominant passageway (for traffic and wind) is along the north-south axis (Fig. 1).

The arguments for NOx are similar with that of PM2.5. All the morphological factors are identical to that of PM2.5 with the same dispersion arguments applied. In way similar to PM2.5, the main reason for the dependence is the amount of urban porosity and open space for ventilation and dispersion. The dependence on temperature relates nitrogen oxides to a photochemical pollutant which in turn depends on the amount of solar irradiation.

The next step is to identify which factors relate to which effects. If we interpret this according to Davis [19], we will identify an association but we cannot see causal flow empirically in reality of how a four way of associations work together. Therefore, in order to understand these relationships in detail, these variables are further interpreted using pair-wise ‘bivariate analysis’ and ‘effects analysis’. Patterns of correlations between street level air pollutant concentration and urban morphological variables for each pair will be interpreted according to the four ways of associations we have identified. This will be covered in Part III of the work.

7. Conclusions

The association between urban morphology and air quality in various dense residential environments of Hong Kong are investigated through field measurements and statistical analysis. With regard to the myriads of parameters available in the literature, this study aims to identify the most important urban morphological parameters in the street level and district levels that affect air quality in Hong Kong. The study postulates that there is an association between urban morphology and urban air quality and a statistical model is developed to explain the relationship amongst urban air quality, micro-meteorology and urban morphological dimension. The study considers 20 urban residential areas in five major districts of Hong Kong and real-time street level air pollutant and microclimatic data are collected from them. 21 morphological variables are identified and calculated based on the geometry of the urban fabric.

This study is the second part of a series which focuses to identify whether district demarcation is correlated with air quality. From the statistical analyses, it is shown that out of the many urban morphological factors, only five land development factors, namely plan area density, occlusivity, roughness height, mean built volume, mean contiguity factor and four street geometrical variable namely aspect ratio, distance between building, mean building height and standard deviation of building height report significant differences amongst groups with both PM and NOx concentrations. All others play insignificant roles in street-level pollution effect. It is also established that the key microclimatic variables that connects PM and NOx with the urban morphological factors are northerly wind, relative humidity and temperature, meaning that the certain urban morphologies affect the urban micro-climate, which in turn translates to affecting the street-level air pollution.

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