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From Cities to Districts: Combined Analysis on Density Variation of Chinese Cities in different Climate Zones

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Abstract: In the analysis of the built environment, holistic analysis and hierarchical assessment of sustainability is strongly needed to avoid the isolation of the component parts and fragmented decision making. This paper presents an ongoing research based on the case study with a combination of quantitative and qualitative analysis methods. The aim for this paper is to validate Holistic Sustainability Evaluation Framework for Asia-Pacific Regions (HSEFA), find out the influencing indicators of urban climate which is one of the sixteen modalities in the framework, and propose recommendations on best practice in urban form. The authors have analysed the density of 85 Chinese cities statistically according to the pre-defined climatic indicators. A close qualitative case study is followed on the districts of five representative Chinese cities located in four different climatic zones. The holistic sustainability evaluation framework established and validated aims to assist the design and decision making in urban design which is suitable for Chinese cities and other cities in the Asia-Pacific Regions.

Keywords: Urban Density, Urban Climate, Sustainable Development, Holistic Sustainability Evaluation Framework for Asia-Pacific Regions (HSEFA)

Background Research

SUSTAINABLE DEVELOPMENT CAN be described as a journey towards the goal of sustainability. The concept of sustainable development was widely accepted in 1987 after the Brundtland Commission definition of sustainability: "to meet the needs of the present without compromising the ability of future generations to meet their own needs" was published (Brundtland and Development. 1987). In 1992 the Earth Summit in Rio de Janeiro presented Agenda21 marking the milestone of sustainable development with 27 principles and the recognition of integrated concerns in decision making about environment and development (UNCED 1992). A complex system to manage ourselves, individually and collectively is required (Peet and Bossel 2000). Traditional reductionist methods of analysis which breakdown and isolate the component parts will bring the risk of fragmented decision making with potential unforeseen consequences. Systemic, holistic goal-directed and hierarchical assessment of sustainability is strongly needed (PCE 2002).

Entering the 21st century and distancing itself from its early planned economy there are now new economic and social imperatives in China. However, in the last twenty years Chinese cities have confronted serious problems of balancing fast, intensive economic and urban development while attempting to achieve sustainability (Xiong 2005). Meanwhile,

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many of the urban theories and sustainability evaluation methods applied to Chinese cities have been appropriated from western models of urban development. Since the concept of sustainability is value-based and values can vary over time and between cultures, (PCE 2002) there has recently been a movement toward indigenous approaches to sustainability supported by local knowledge (George and Dei 1995; Phillips O. and TiTilola O. 1995; Bank 1997; Berkes 1999; Appleton, Fenandez et al. 2005). This has provided motivation for this research to find best practices in sustainable urban development and evaluation methodologies that are based on indigenous philosophies and the urban practice in Chinese cities.

The world consists of human activity and natural phenomenon in mutual interactions which change over time. The framework developed in this research inherits the character of "ordinal loops" of philosophical diagram in Chinese indigenous knowledge that is suitable for the sustainability evaluation framework. In this framework the "ordinal" is represented in "individual-collective axis". "Loop" is represented in cyclical structure (Fig 1).

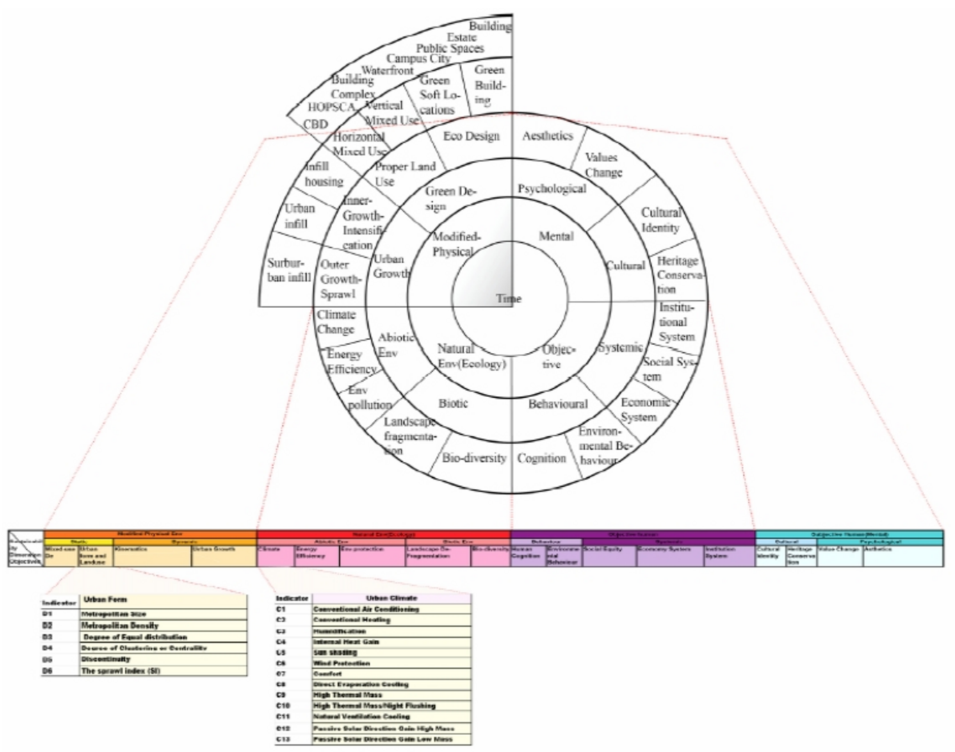


Fig 1: Holistic Sustainability Evaluation Framework for Asia-Pacific Regions (HSEFA) and the Position of the Two Modalities in the Whole Framework

The framework developed in this research comprises hierarchical modalities where the built environment and the natural environment are two of the four main modalities of the sustainability. Urban form is one of the sub-modalities of the built environment, and climate is one of the sub-modalities of the natural environment. Social and economic factors are components of the objective human modality. This paper mainly discusses the relationship between these two modalities where urban density is one of the key indicators of urban form.

China covers a vast area with various climatic zones, and thus great climatic distinctions exist in the cities from Northeast to the South. The urban density of Chinese cities also varies widely. This paper mainly focuses on the city level of density comparison of 85 cities across the nation and the urban form parameters of five large Chinese cities at district level. The five selected cities Harbin, Tianjin, Wuhan Chongqing and Shenzhen are located in four distinct and different climatic zones: very cold zone, cold zone, hot summer-cold winter zone, and hot summer-warm winter zone.

Purpose of Study

The aim for this paper is to validate Holistic Sustainability Evaluation Framework for Asia-Pacific Regions (HSEFA), find out the influencing indicators of urban climate which is one of the sixteen modalities, and propose recommendations on best practice in urban form.

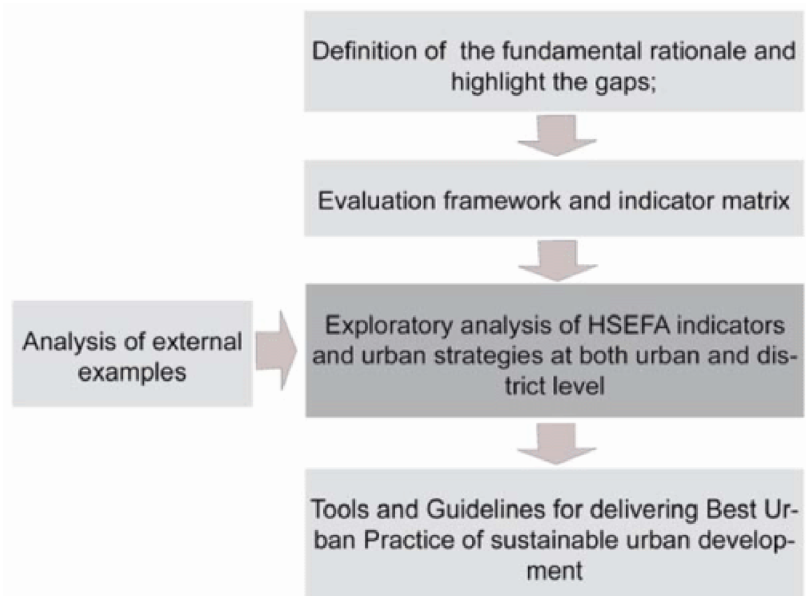


Fig 2: Position of this Paper in the Objectives of Whole Project

This paper forms part of data analysis in the author's higher research degree thesis (Fig 2). In the thesis, six Chinese cities are examined covering a twenty year period of development to explore the currently applied urban form and urban strategies, based on a holistic sustainable evaluation framework. The guidance for best urban practices will be proposed at the end of the research; a holistic sustainability evaluation framework established and validated is suitable for Chinese cities and other cities in the Asia-Pacific Regions.

Literature Review

Recent theories of sustainable urban form have seen prominent development both from qualitative to quantitative, and from the view of developed countries to developing cities (Burton, Jenks et al. 1996) (Williams, Jenks et al. 1999) (Jenks and Burgess 2000) (Jenks and Dempsey 2005) (Jenks, Kozak et al. 2008) (Newman and Kenworthy 1999). Interdisciplinary researches are questioning and reflecting on this concept (Anthony 2004; Holden and Norland 2005; Fincher 2007; Forsyth, Oakes et al. 2007; Selugga 2008; Sintusingha 2008) (Barter 2000). There is also research in recent years agreeing that urban form is determinant for ecological footprint variation and CO_2 emissions (Green 1996; Newton, Tucker et al. 1999; Muñiz and Galindo 2005). Insight beyond the intensification and mixed-use, more urban approaches towards sustainability are raising people's attention (Register 2006) (Castells 2000) (Newman and Kenworthy 1999) (Thompson-Fawcett 1999). All are making the compact city related developments necessary to be tested and properly guided, especially in Chinese cities which usually have higher population densities.

Unfortunately, there is not much work that has been conducted on Chinese compact cities in recent years. With close examination on these works, it is found that the existing discussions on the density and mixed-use are scarcely related to sustainability. Since the density zoning discussions emerged after 2000, more and more authors start to focus on the empirical methods based on GIS technologies (FENG and ZHOU 2002) (LIAO, XU et al. 2008) (LIU and CHEN 2004) (LV, Li et al. 2005) (Liu, Yuan et al. 2008). The common characteristic of these empirical research studies is that they adopt the research techniques in a technocratic way which greatly relies on the GIS and modelling technologies. However the lack of reliable data sources for GIS modelling greatly limits such research. The cities in the case study are confined to Beijing and Shanghai (Tang and Fu 2003; LIAO, XU et al. 2008) (LI and GAO 2008; Liu, Yuan et al. 2008) (FENG and ZHOU 2002) (LIU and CHEN 2004) (LV, Li et al. 2005). More analysis is required in relation to these cities to find out the best practice in the context of China. Therefore, the methodology in this paper will try to avoid analysis of data which is impossible to find.

So far, most of the existing research on urban climate has focused on the impacts of the built environment on the micro climate (Nahas 1996; Givoni 1998; Hyde 2000; Schiller and Evans 2000; Mardaljevic 2005; Smith 2005; XU 2005; Zhang 2006; Zhao 2006; Oxizidis, Dudek et al. 2008; Tablada, Troyera et al. 2009) and strategies against Climate Change (Riedy 2005; Corburn 2009; Hamin and Gurran 2009). There are also studies on the techniques in solar access and sunlight spacing (Fawcett 1983; Knowles 2003; Muneer, Kambezidis et al. 2004; Mardaljevic 2005; Cheung and Chung 2007; Chel, Tiwari et al. 2009). There is no research revealing the certain climate factors that would particularly affect sustainability of the built environment.

Research Design and Methodology

In analysis, both statistical and qualitative methods will be used. Given the two-fold complexity of sustainable issues and urban systems, the strength of one approach is useful for informing the other(Kumar 2006). According to the sustainability evaluation framework in this research, the macro scale strategies correspond to the quantitative indicators. For the statistical analysis PASW Statistics17 will be used. The micro scale strategies correspond to the qualitative criteria. NVIVO 8.0 will be used for qualitative data and coding (Fig3).

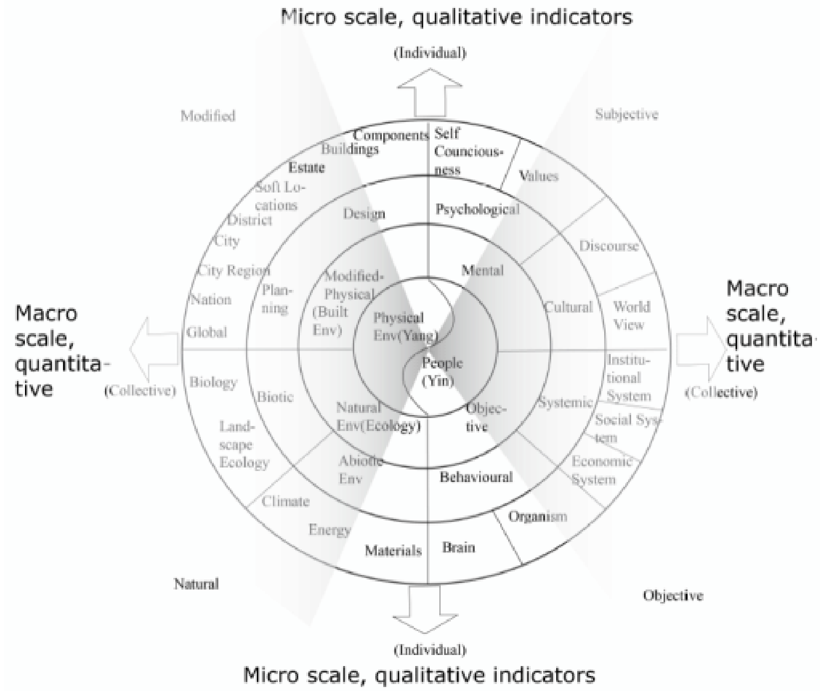


Fig 3: Hierachical Modalities of HSEFA and Quantitative-Qualitative Division Structure

Multivariate analysis and clustering will be used for factor analysis. The result of factor analysis can explain the total covariance of quantitative indicators in terms of smaller number of underlying factors (Hung and Tsou 2006). So here it could evaluate the significance of climatic indicators and make quantifiable comparison between 85 cities.

Cross-Case analysis is the chief method for the purpose of deepening understanding of the generic processes or explanation that occurs across individual cases (Miles and Huberman 1994; Yin 2009). The selection of the five cities aims to ensure variety and opportunities to learn in the search for the best urban practice (Stake 2000).

The estimated details of analysis outputs are: summary of the influencing urban indicators, presented in a correlation table and scatter graph; Recommendations on design strategies and design tools for sustainable development are presented in cross tables. The result of this research will have significant implications, including:

- Providing approaches for best practice in urban development and sustainable evaluation method which is based on the eastern way of thinking and the practice in Chinese cities;
- The investigation of Chinese cities with higher densities offers possible strategies for intensive developments which are pursued by many cities in the world;
- The conceptual process utilizes the eastern thinking model into the organisation of sustainable development evaluation framework;

- Generating systemic recommendations by the systemic framework and combinational analysis method.

The first step in this paper is to identify the climatic indicators from literature review and collect density data of selected cities. The second step is to conduct exploratory data analyses using K-means cluster analyses method and ANOVA analysis method.

In the second part of the research, in order to better analyse the density variation among the districts with similar cultural and physical environments, first it is necessary to identify the variables for the density variation, and to identify the variables of climate that affect built environment. A combinational analysis of quantitative and qualitative methods is presented in the later chapters.

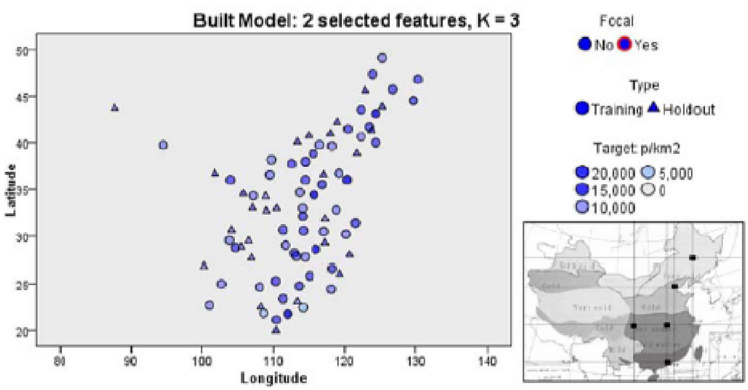


Fig 4: Spatial Distribution of 85 Sample Cities and 5 Case Study Cities in China

85 Chinese Cities which will cover middle and east of China are selected for the first step analysis (Fig4). Convenience sampling method is used during preliminary research. The five Chinese Cities: Harbin, Tianjin, Wuhan, Chongqing and Shenzhen, each located in four zones, will be examined for this study in the second part of the paper (Table1). They are chosen for similar city scale and arithmetical latitudes.

Table 1: The Selected Cities for this Research

	Latitude (N)	**Longitude (E)**	**Population (Thousand)**	**Urban Area (km^2)**	**Population Density (p/km^2)**
Harbin	45°58′	126°43′	3753	318	933.2398
Tianjin	39°06′	117°12′	7468	530	1037.4764
Wuhan	30°37′	114°08′	7542	225	943.4424
Chongqing	29°31′	106°29′	4776	492	1439.835
Shenzhen	22°23′	114°03′	8114	703	932.0184

Data Source

The density data comes from two sources: the demographic figures are sourced from the Fifth National Census database, the information of districts area is from the government website of each districts. The data for this paper also includes the planning scheme, traffic maps as well as street maps.

Urban population in this research refers to non-agricultural population in the built-up urban area. Basically, China's diverse statistical data on urban population is based on both the urban administrative system and the residence registration (hukou) system. The later classifies all the people either as "agricultural population" or "non-agricultural population" and is quite stable; the definitions of the former however, have changed in each of the five national censuses (Liu, Li et al. 2003). This research uses the urban population data of 85 cities sourced from Yearbook 2006 and the fifth national census. For five case study cities, the administrative system uses the 2000 yearbook which was compiled in the same year of fifth national census.

However, population mobility in China has risen dramatically, especially in major cities such as Beijing, Guangzhou, Shanghai where large numbers of "floating population" from the countryside congregate. Nevertheless, the national census includes those in the population who hold Temporary Residence Certificate (TRC). This population accounts for most of the floating population in Chinese cities except the super cities which are not included in the sample.

Climatic zoning in China: The average temperature of January and July is the main index for the division of four different climatic zones in China: very cold zone, cold zone, hot summer-cold winter zone, and hot summer-warm winter zone (Table 2).

Table 2: Climate Zoning Index in Construction Industry in China

Climate Zone	**Zoning Index (Average Temperature)**	
	Coldest Month	**Hottest Month**
Very Cold Zone	≤-10℃	
Cold Zone	0~-10℃	
Hot Summer cold winter zone	≥10℃	25~29℃
Hot summer warm winter zone	≥10℃	18~25℃
Mild Zone	0~13℃	18~25℃
The above is from Zhang, H. (2006). Study on the Thermal Environment of the City Based on the Simulation under Atmospheric Environment Impacts. Architecture of Science and Technology. Wuhan, Huazhong University of Science & Technology. M. Arch: 107.		

Variables Identified: Climate Indicators

In order to analyse the density differentiation in different climatic zones, the climate indicators are indentified from a Climate Consultant to bridge the climate information of each city and their built environment. This software is used to chart the climate data of each city in the EPW format which are sourced from the Weather Data Sources page. The psychometric chart shows the most appropriate time that passive design strategies are required for each city. According to the chart, the six most important climate indicators are identified as main indexes as well as seven subsidiary indexes (Table 3).

Table 3: Climate Indicators (hrs)

Category	Climate indicators	Criteria
Main Index	Conventional Air Conditioning	Hours when none of the other strategies can provide comfort conditions and so some form of cooling is required
	Conventional Heating	Hours when none of the other strategies can provide comfort conditions and so some form of heating is required
	Humidification	Humidification is needed below dew Point Temperature 2.2℃
	Internal Heat Gain	Max. 5.6℃Dry Bulb Temperature Difference below Comfort Low
	Sun shading	Min. 21.1℃ Comfort Dry Bulb Temperature
		Min. 157.7 Wh/sq.wt Global Horiz. Radiation
	Wind Protection	Min. 4.5 m/s Velocity above which Wind protection is desirable
		Max.11.1℃ Dry Bulb Temperature Difference above Comfort High
Subsidiary Index	Comfort	Min. 21.1℃ Comfort Dry Bulb Temperature
		Max. 23.9℃ Comfort Dry Bulb Temperature
		Min. 2.2℃ Dew Point Temperature
		Relative 80%Humidity at Comfort Low Temperature
	Direct Evaporation Cooling	Max. 18.7℃Wet Bulb set by Max. Comfort Zone Wet Bulb
		Min. 11.4℃Wet Bulb set by Min. Comfort Zone Wet Bulb
	High Thermal Mass	Max. 8.3℃Dry Bulb Temperature Difference above Comfort High
		Min. 2.8℃ Nightime Temperature Difference below Comfort High
	High Thermal Mass/Night Flushing	Max. 16.7℃ Dry Bulb Temperature Difference above Comfort High
		Min. 2.8℃ Nightime Temperature Difference below Comfort High

	Natural Ventilation Cooling	2.2℃ Dry Bulb Temperature Increase Above Comfort High
		Min. 1.3 m/s Outdoor Air Velocity for Comfort
		Max. 90% Relative Humidity
		Max. 22.2℃ Wet Bulb Temperature
	Passive Solar Direction Gain High Mass	Min. 157.7 Wh/sq.mt. Beam Radiation for 5.56℃ Temperature Rise
		3 hrs Thermal Time Lag for High Mass Buildings
	Passive Solar Direction Gain Low Mass	Min. 157.7 Wh/sq.mt. Beam Radiation for 5.56℃ Temperature Rise
		12 hrs Thermal Time Lag for High Mass Buildings
The above is from Climate Consultant 3. (http://www.aud.ucla.edu/energy-design-tools)		

Statistical Analysis on 85 Cities

The correlation analysis on 85 cities reveals that natural ventilation cooling is statistically significant (p=0.004). High thermal mass, conventional heating and Conventional Air Conditioning are more related to urban population density than other indicators. But the correlations are not statistically significant (Table4). The graphs below show the scatter points of the four analyses (Fig5).

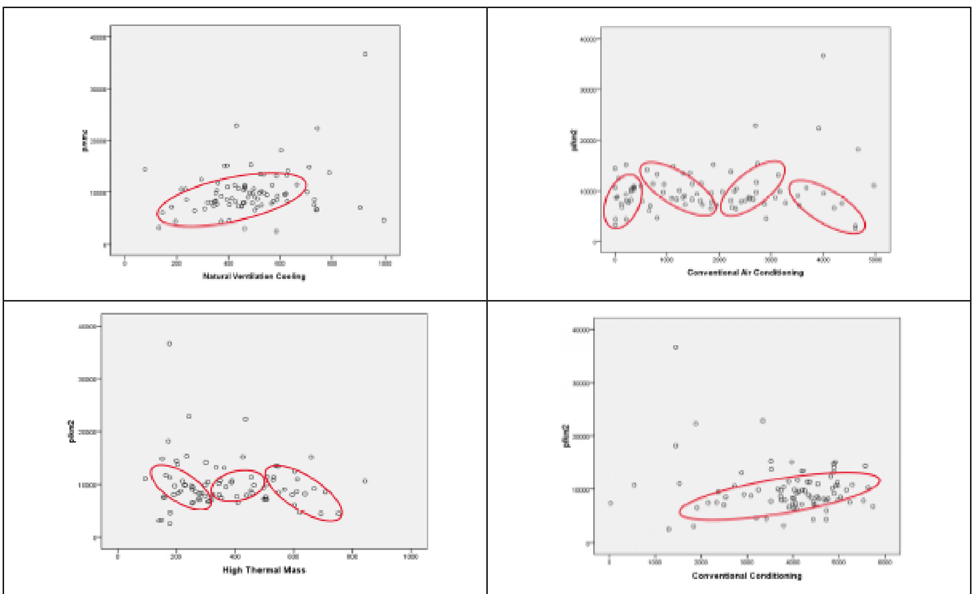


Fig 5: Scatter Plots of Four Significant Density-climate Relationships

Table 4: 85 Cities Correlation Analyses

		p/km2	Comfort	Sun shading	High Thermal Mass	High Thermal Mass/Night Flushing	Direct Evaporation Cooling	Natural Ventilation Cooling
Density (p/km2)	Pearson Correlation	1	-.024	.124	-.147	.025	-.077	.310**
	Sig. (2-tailed)		.825	.257	.181	.819	.485	.004
	N	85	85	85	85	85	85	85
		Internal Heat Gain	Passive Solar Direction Gain Low Mass	Passive Solar Direction Gain High Mass	Humidification	Wind Protection	Conventional Air Conditioning	Conventional heating
Density (p/km2)	Pearson Correlation	.005	-.106	.040	-.080	-.089	.172	-.169
	Sig. (2-tailed)	.966	.336	.719	.464	.416	.115	.123
	N	85	85	85	85	85	85	85

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

Overlay scatter plots show that the combination of two or more climatic factors would affect the urban density much more significantly. For example, the linear regression analysis reveals that sun shading and internal heat gain together affects the density to be more statistically significant (β=-1.133, t (162) =-1.712, p= 0.089(Fig6).

Table 5: Details of Clusters

		Cluster			
		1	**2**	**3**	**4**
Cluster Centres	Sun shading	1726	1303	915	1199
	Humidification	299	1608	5100	3650
Number of Cases in each Cluster		23	18	22	20

For further investigation, cluster analysis is used to find out whether two or more climatic factors would affect the urban density. With the purpose that the cluster may be in accordance to the existing climatic zoning, the number of target clusters is set to be four. The result represents an equal distribution with similar number of cases in each cluster (Table 5).

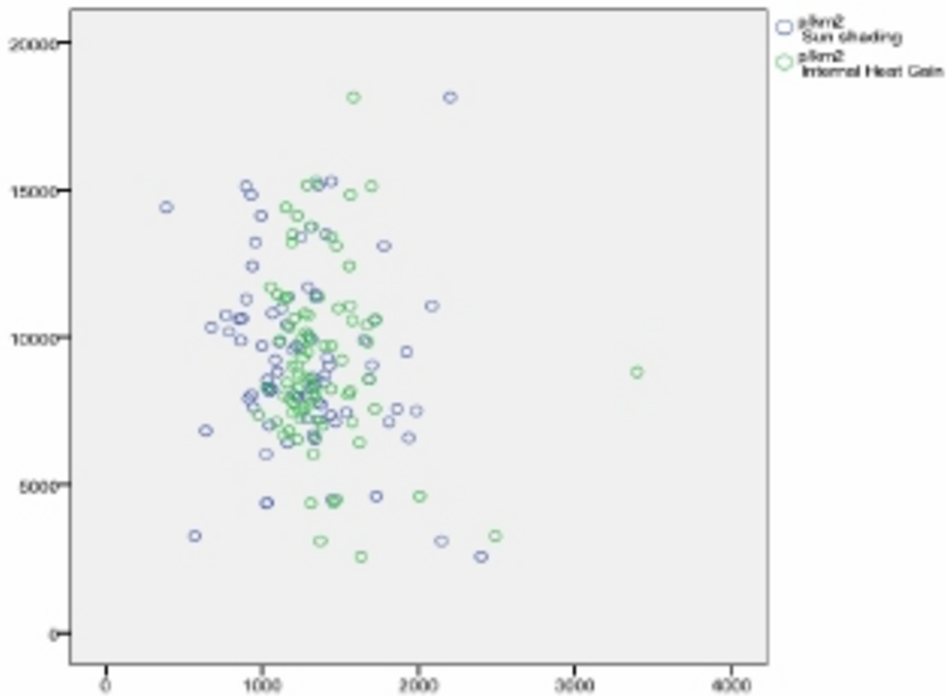


Fig 6: Overlay Scatter Plots of all Density-climate Relationships and Overlay of Sun Shading-internal Heat Gain

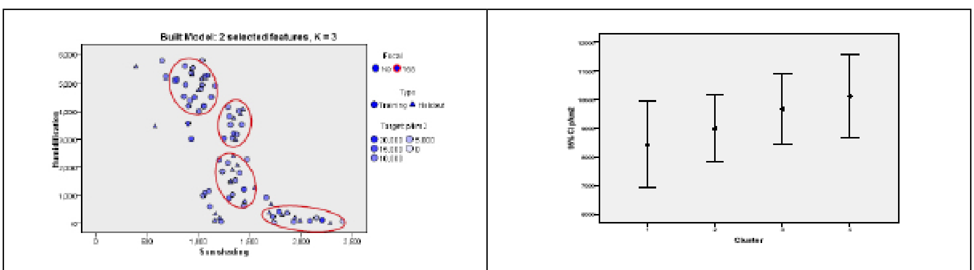


Fig 7: Sun Shading- Humidification Cluster and CI Plots of Densities Variations

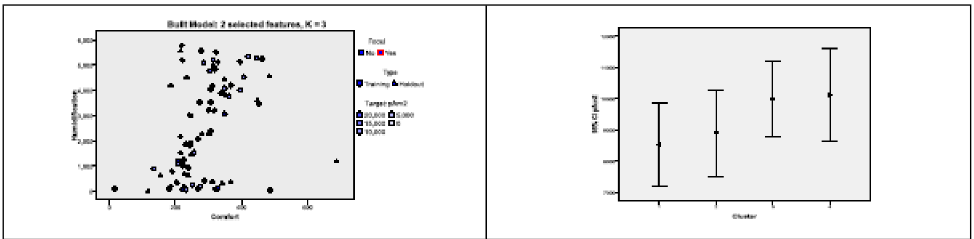


Fig 8: Comfort-Humidification Cluster and CI Plots of Densities Variations

The CI plots shows that the population density varies when sun shading index increases and the humidification index decreases (Fig7). But the ANOVA analysis shows there is no statistically significant difference between the four zones F (3, 81) =1.33, p=0.270.

The four clusters of humidification- comfort include 26, 15, 20, 20 cities in each cluster. But there is also no statistically significant difference between the cities in different humidification-comfort clusters, F (3, 79) =1.51, p=0.219(Fig8).

This is similar to Conventional Conditioning-Humidification clustering. When there are two clusters, there is statistical significance between climate clusters (M=8675.54, SD=2964.790 M=10052.31, SD=2855.682), t (78) =-2.115, p=0.038. But when there are four clusters, there is no statistically significant difference between densities in climate clusters, F (3, 78) =0.854, p=0.469. Even in two climate clusters, the density difference is not significant enough when the entire six main climate indexes are considered (M=8709.38, SD=3019.399 M=9956.13, SD=2838.887), t (78) =-1.903, p=0.061(Fig9).

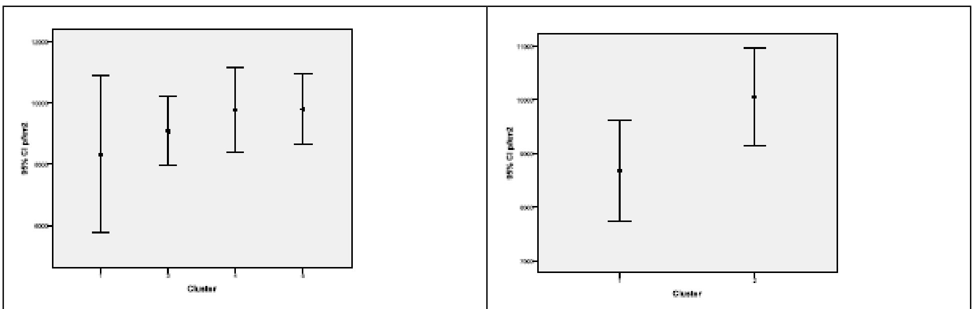


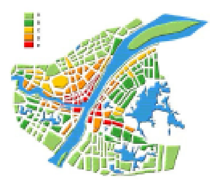
Fig 9: CI plots of Densities Variations in Conventional Conditioning-Humidification Clusters

Case Study on Density Variation of Five Cities: Districts and Variables

A city is a complicated entity. Besides architecture, natural physiognomy like mountains, rivers, lakes and basins also contribute to the spatial distribution of the density. The various physical details of urban space, including the orientation of the streets and the buildings with respect to the sunlight direction are possible to provide a wide range of sunlight conditions in a given level of density(Edwards 1999). So the relationship between the urban density and climate differentiation couldn't be studied solely on the level of the whole city area. Instead, viewing from the micro scale is needed.

Considering the multiplicity of influencing elements, it will be convenient and efficient to integrate the districts of similar characters. So the districts under the administration of boroughs are more appropriate units for analysis. It provides sub-division of the whole city area into different districts according to their different terrain, the orientation of the streets, street grid, transport facility and history. Research on the land grading of Wuhan provides a good example. It shows that building density, FAR, residential density, and green space are correlated to each other (Zhang 2006). Based on these parameters, the districts are graded into five classes from A to E (Table 6). As the level rises from 1 to 5, the building density, FAR (Floor Area Ratio) and residential density (p/ha) rises, while the quality of green space gradually falls.

Table 6: Example on Districts Grading of Wuhan

Level	Building Density	FAR (Fl oor Area Ratio)	Residential Density (p/ha)	Green Space	
A	Below 10%	Below 0.5	Below 200	Very good	
B	10%~20%	0.5-1.0	200-400	Good	
C	20%~30%	1.0-1.5	400-600	Average	
D	30%~40%	1.5-2.0	600-800	Poor	
E	Above 40%	Above 2.0	Above 800	Very Poor	
The above is from Zhang, H. (2006). Study on the Thermal Environment of the City Based on the Simulation under Atmospheric Environment Impacts. Architecture of Science and Technology. Wuhan, Huazhong University of Science&Technology. M. Arch: 107.					

Based on this requisite, 426 sub-districts of Shenzhen (51), Chongqing (99), Wuhan (91), Harbin (106) and Tianjin (79) become the pool of research samples. All of the selected cities have several districts with cultural heritages dated back to the early 20th century. The street grids are all around 1km². The density distributions of the five cities are mapped out in 2D and 3D format for general view in table 7.

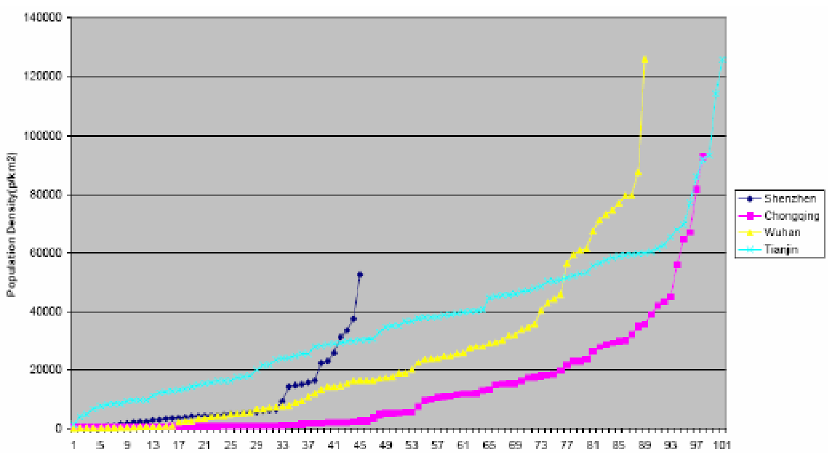
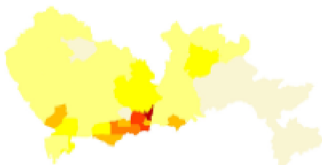
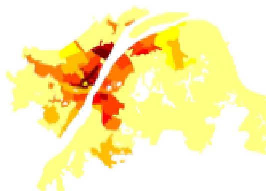
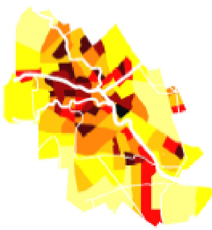
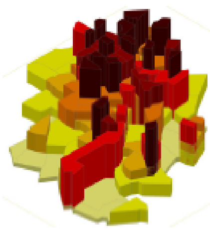
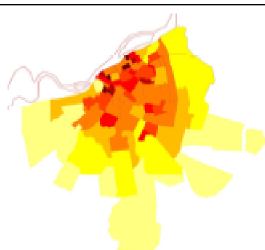
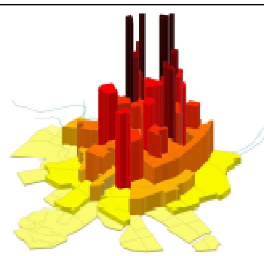
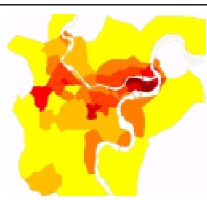
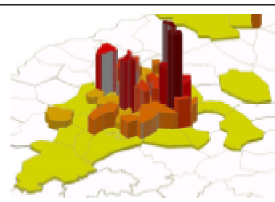


Fig 10: Comparison of Density Distribution of Selected Cities

Table 7: Population Density Map of Selected Cities

City	Density map	3D View of Density
Shenzhen		
Wuhan		
Tianjin		
Harbin		
Chongqing		

From the chart above (Fig 10), we can see that with the similar number of sub-districts, the density of top ten districts rise sharply in both Tianjin and Chongqing, but the slope indicates that Tianjin has a more equal and higher density than Chongqing. In contrast, Shenzhen and Wuhan have a hard city core since the slope begins to rise sharply from the twentieth densest district. The indicators of urban form are also calculated in order to better understand other dimensions of density distribution (Tsai 2005) (Table8).

Table 8: Results of the Urban form Indicators

Dimension	Urban form indicator	Tianjin	Wuhan	Shenzhen	Harbin
D1: Metro-politan Size	Administrative Area(km2)	7418	8494	1952	4275
	Built-up Area(km2)	530	220	713	302
D2: Metro-politan Density	Overall activity intensity in a metropolitan area	1037.476	943.4424	932.0184	933.2397661
D3: Degree of Equal distribution	Gini coefficient (Population- or Employment-based)	0.312095914	0.635187	0.31377	0.552893
D4:The sprawl index (SI)	To measure residential sprawl for metropolitan areas	49.58138368	49.74002	50.26842	50.04837

Unfortunately, there is still no substantial evidence from the calculations above. So an in-depth investigation into the variation among the districts with similar cultural and physical environments is strongly needed. The urban form parameters are indentified as categorical variables: green space, lake, history, rail, river, street grid-mix and free, street grid-radial, street grid-South, street grid-SE, street grid-SW.

All the districts that meet any two variables from each variable category are calculated for their mean population density. For example, there are 49 central urban districts that have rivers and are sourced from three cities with significant humidification index. They are composed of 4 districts from Harbin, 23 from Tianjin, and 22 from Wuhan. The average population density of the 49 districts is 32519.4p/km2.

The CI plot (Fig11) shows that there is statistically significant differences between the mean densities of different climate indexes, $F\ (12, 106) = 6.68$, $p<0.001$.

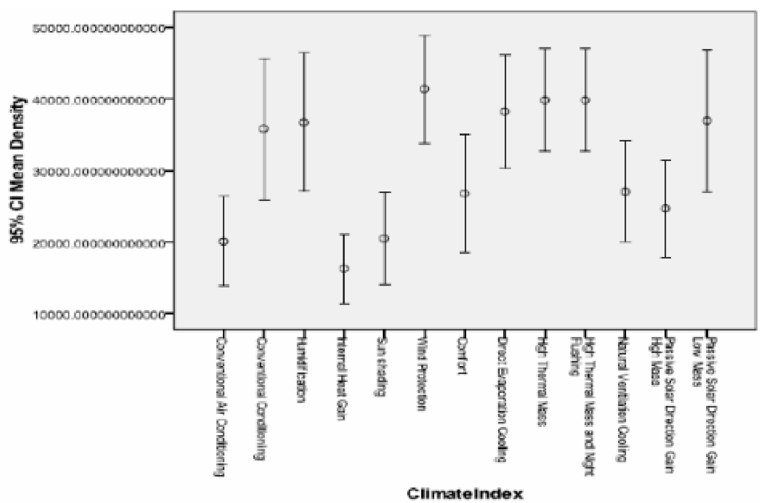


Fig 11: Density Variation among Climate Indicators

From Fig12, there is also statistically significant differences between the mean densities of districts with different parameters, $F (8, 106) = 7.75, p<0.001$.

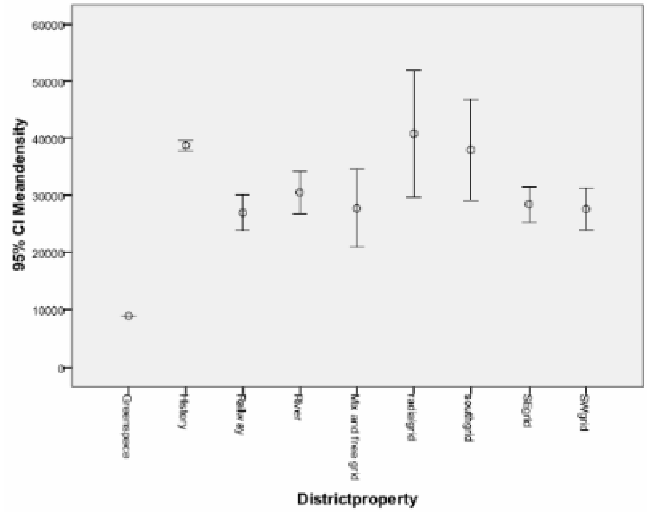


Fig 12: Density Variation among District Parameters

The districts need to be classified into central urban area, outer urban area and periphery urban area according to their proximity to the city centre. The chart below proves the effect of centrality on the urban density.

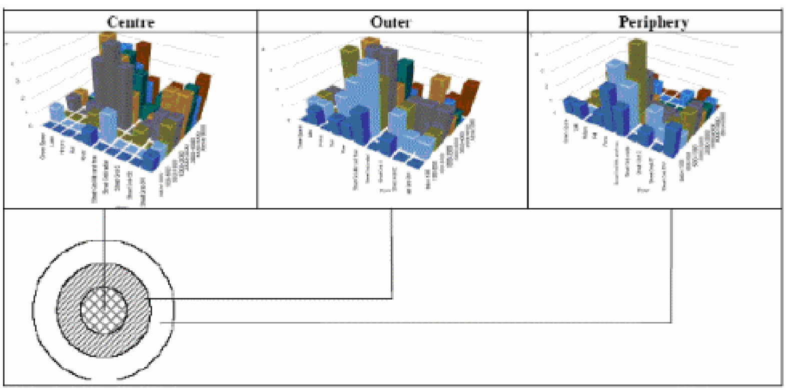


Table 9: Number of Districts Surrounded with Rail and River in each Area

The chart shows the number of cities which have the districts that meet the two variables. The comparison of chart shows that in urban central area, outer central area and periphery, available districts cluster at different density ranges. This makes it necessary to analyse the research results separately in the three areas (Table9). The outcome is displayed in 3D charts and line graphs (Table10, Fig13-15).

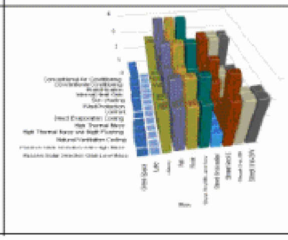
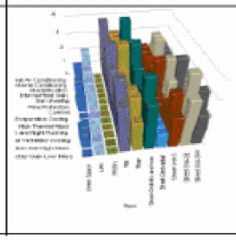
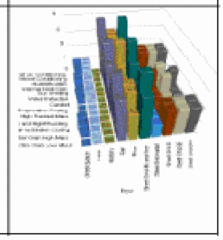
	Centre	Middle	Periphery
Number of Cities			

Table 10: Chart of Qualitative Analyses

Seen from the Fig13, the districts with radial street grid are the mostly consolidated, following the south oriented districts. In contrast, the southeast oriented and southwest oriented districts are less sensitive to the climate differentiations, thus their trend lines appear gentler. The districts surrounded by river and rail rank between the former mentioned two situations. All of them are in accordance with the general trend where the district population densities are generally high in the districts with the significant conventional conditioning, humidification, wind protection, direct evaporation cooling, high thermal mass and passive solar direction gain low mass, whereas the districts with significant conventional air conditioning, internal heat gain, sun shading, comfort, natural ventilation cooling and passive solar direction gain high mass indexes naturally come into relatively average low density districts.

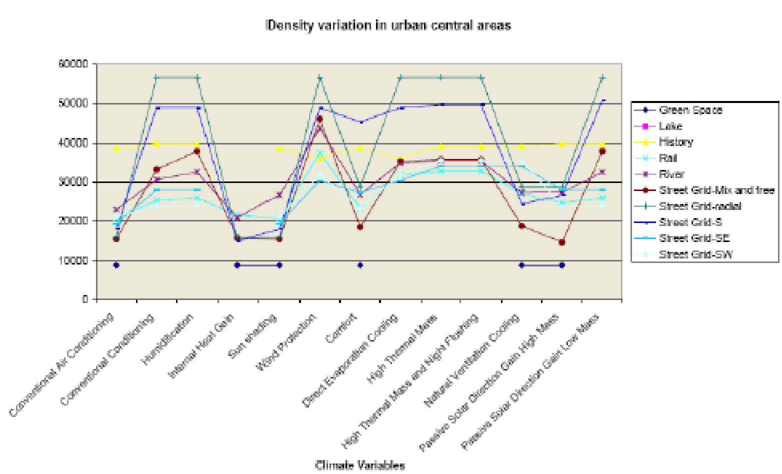


Fig 13: Responsive Variables of Density Variation in Central Urban Areas

Exception exists in the historical districts. The almost horizontal trend line shows that they are not sensitive to the local climate at all and the average density maintains around 40000 (p/km²) since historical districts are all concentrated in the urban central areas.
In the outer area of the central region, the trend is similar to the urban central area (Fig14). The districts with radial street grid continue to have higher average densities with significant conventional conditioning, humidification and passive solar direction gain low mass indexes. But they are overtaken by SE orientation districts with significant wind protection, direct

evaporation cooling and high thermal mass indexes. Railways continue to negatively contribute to the district density but southern and mixed street grids are more negative in the outer central urban area. Definitely, SE and SW street grids would promote the urban district more positively in the urban central area than the central area. The effects of rivers are only obviously positive in districts with significant humidification and wind protection indexes.

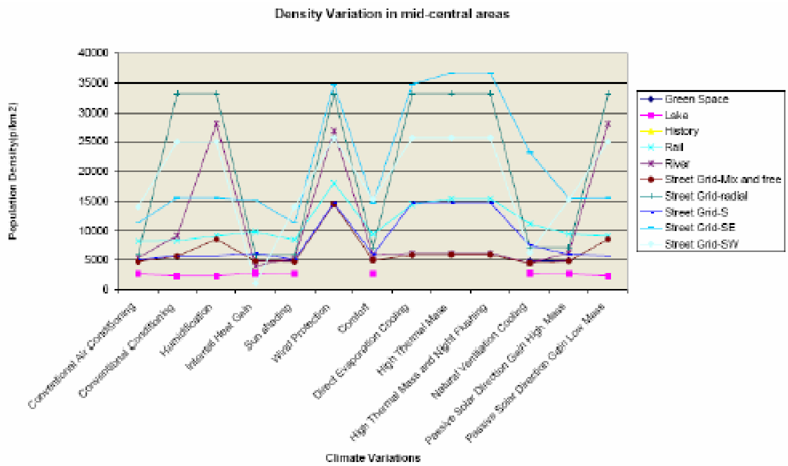


Fig 14: Density Variation in Outer Central Areas

In the periphery of urban areas, the trend with the climate variations still exist, but is much weaker than in conventional conditioning and humidification climate regions (Fig15). SE street grid is the most important factor in the comfort, high thermal mass and natural ventilation cooling significant climate regions, that is, the cities in lower latitude. SW street grid works positively in the same climatic regions, but it is inferior to the SE. On the other hand, southern orientation is best in wind protection, direct evaporation cooling significant climate regions.

Radial street grid is hardly found in the periphery areas since it usually has long history origins. River and rail follows the general trend but they are still neutral in the district density. Their slight distinctions could almost be ignored but they could be viewed as similar in contributing to the population density in urban periphery area.

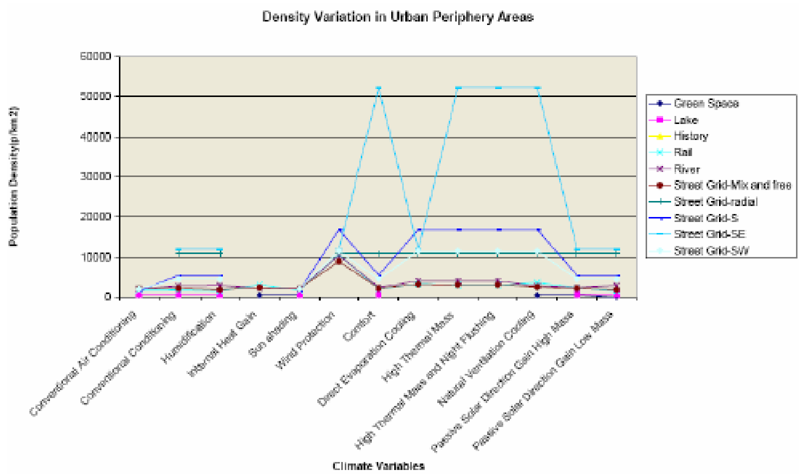


Fig 15: Density Variation in Urban Periphery Areas

Discussion

William Fawcett states that the density is unaffected by geographical latitude because whether the spacing of blocks could achieve a given intensity is wholly independent of building height or the obstruction angle. Instead, it depends on the depth of the building blocks (Fawcett 1983). But he ignored other climate factors that may influence the density. In the first part of the research, statistical studies on 85 Chinese cities shows that natural ventilation cooling is closely related to urban population density. High thermal mass, conventional heating and conditional air conditioning are not statistically significantly related. Two or more climatic factors would affect the urban density much more significantly, for example, sun shading- humidification, comfort-humidification, sun shading-internal heat gain, conventional conditioning-humidification etc (table11). Fewer cluster numbers will display more significant differences in density. But even in two climate clusters, the density difference is not significant enough when the entire six main climate indexes are considered.

Table 11: Compilation of Influencing Climate Indicators for HSEFA

Type	Influencing Climate Indicators for HSEFA
Single Climate Indicators	Natural Ventilation Cooling
Combinational indicators	Sun shading- humidification
	Sun shading-internal heat gain
	Comfort-humidification
	Conventional conditioning-humidification

Recommendations for higher densities in Chinese cities in urban central areas, outer central areas and in the urban periphery areas could be summarized into table12.

Table 12: Recommended Built Environment for Densification

Design Strategies	Cities	Recommended Built Environment for Densification		
		Central areas	Outer central Areas	Periphery Areas
Comfort	TJ, WH, SZ, CQ	S, History	SW, SE	
Sun shading	WH, SZ, CQ	History, River, SW	SW, SE	River
Internal Heat Gain	WH, SZ, CQ	Rail, river	SE, rail	Rail, river
Conventional Air Conditioning	WH, SZ, CQ	Radial, S, History	Radial, SW, SE	SE, Radial, SW
Conventional Conditioning	HB,TJ, WH,CQ	History, River, SW	SW, SE, Rail	Mixed Grids
High Thermal Mass	TJ,CQ	Radial, S	Radial, SE, SW	S, Radial, SE/W
High Thermal Mass/Night Flushing	TJ, CQ	Radial, S	Radial, SE, SW	S, Radial, SE/W
Direct Evaporation Cooling	HB, TJ , CQ	Radial, S	Radial, SE, SW	S, Radial, SE/W
Natural Ventilation Cooling	TJ, SZ, CQ	History, SW, SE	SE	SE
Passive Solar Direction Gain Low Mass	HB, TJ, WH	Radial, S, history	Radial, river, SW	Radial, SE
Passive Solar Direction Gain High Mass	HB, TJ, WH, SZ	History, radial, SE, river	SE, SW, rail	Radial, SE
Humidification	HB, TJ, WH	Radial, S, History	Radial, River, SW	Radial, SE
Wind Protection	HB,TJ	Radial, S	Radial, river, SE	S

In warmer climates, the commonly related design strategies are comfort, sun shading, internal heat gain and conventional air conditioning. Districts with higher density are usually historical blocks in central areas, slightly tilted blocks in outer central areas and river-surrounded blocks in the city periphery.

For example, in comfort zone, like Tianjin, Wuhan, Shenzhen and Chongqing, central city areas have higher densities when the blocks belong to the historical core or south oriented; the outer central areas are more southwest or southeast oriented in high density districts. In sun shading zones, like Wuhan, Shenzhen and Chongqing, central districts surrounding with the river or southwest oriented normally have higher density. In outer areas of sun shading zone, southwest or southeast oriented districts still tend to be higher density districts. In the periphery, rivers will contribute more to the district density.

In colder and drier climate zones, where the related design strategies are passive solar direction gain, humidification and wind protection, historical core continues to have higher density in central districts. Radial streets and southeast streets could achieve higher density in the whole city region.

For instance, Passive Solar Direction Gain Low Mass zone, like Harbin, Tianjin and Wuhan, historical origins, radial and south oriented streets will make a harder city core; Southwest streets and river play an important role in the outer central areas. In the periphery, the street direction turns to southeast in relative higher density districts.

Conclusion

In summary, this paper presents ongoing research based on the quantitative and qualitative analysis methods. Statistical analyses of the densities in 85 cities are followed by the performing of a comparative analysis of 5 cases study cities. Research shows that at the macro scale, the population density of the cities slightly varies when the regional climate changes. Among the six main climate indicators and seven subsidiary climate indicators, only one single indicator is closely related to the urban density. But the combination of two or more other indicators could also be indexes for evaluating the built environment. These indicators will be part of the HSEFA indicator framework (Fig 16).

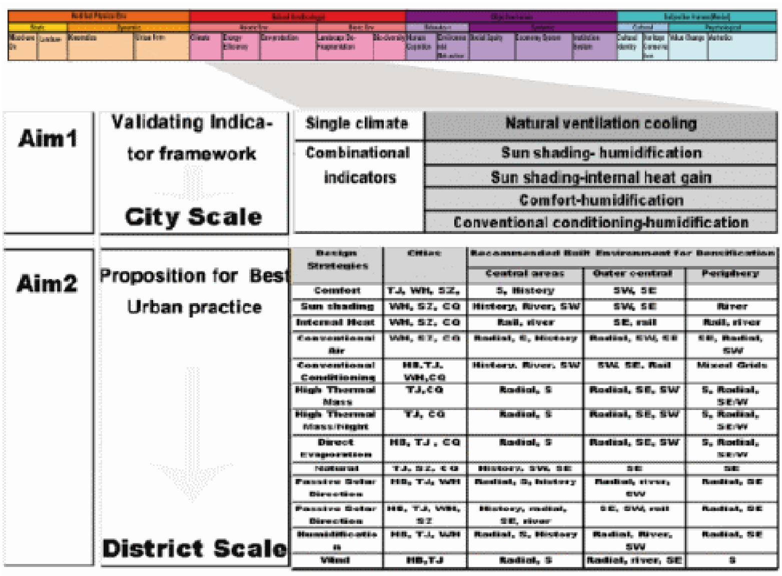


Fig 16: Research Results in the HSEFA Framework

At the micro level, an in-depth investigation on 426 districts presents case studies of five typical Chinese cities in each climatic zone. It verifies the 13 climate indicators in the district level, and extends the vision into the specific parameters of urban form strategies. Recommendations from the five cities are shown in the cross-table for references.

Future Scope of Study

Analytical studies of five Chinese cities provide recommendations on better future solutions for urban densification. However, it is needed to carry out a complementary study to analyse other modalities of sustainability evaluation framework besides bioclimatic modality in future studies. Selected sustainable urban developments in each city will be evaluated with the validated framework to derive tools and recommendations on best urban practices. It is hoped that this paper will provide a discussion document for future research in the increasingly important area of sustainable urban form.

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