NEW SITE PLANNING AND DESIGN METHODOLOGY: MODELLING URBAN MORPHOLOGIES TO IMPROVE AIR POLLUTION DISPERSION FOR BETTER DESIGN PERFORMANCE OF RESIDENTIAL OPEN SPACE IN BEIJING

YU, JUNYA
The University of Melbourne, junyay113@email.com

WALLISS, JILLIAN
The University of Melbourne, jwalliss@unimelb.edu.au

1 ABSTRACT
Numerous researchers highlight the public health implications of long-term exposure to air pollution and investigate the influence of existing urban morphologies on air movement through Computational Fluids Dynamics (CFD) modelling. However, few researches explore the possibility of designing new urban morphologies and the associated open space which can positively influence on air pollution dispersion so as to improve landscape performance. This study aimed to explore this gap. Surrounded by office buildings and industrial sites in a highly polluted district in Beijing, a new residential development site presented a great opportunity to apply a research-driven design methodology that explores the role of digital techniques (CFD) and computational and real-time data in bridging the gap between scientific knowledge and design speculation. The study carried out CFD modelling of conventional and new urban morphologies to identify an optimised building configuration that positively influence on air pollution dispersion in the associated open space, and then to develop a series of microclimate adaptive design strategies that minimize residents’ exposure to pollution in this open space. Through this methodology, we demonstrated the possibility of modifying wind speed and wind direction as a valuable strategy to reduce the effect of air pollution by the massing and siting of residential building blocks and topographic strategies. Then the detailed design of external spaces was developed with the ambition to maximise the usability of open space during low air pollution periods, and to encourage responsive micro-atmospheric behaviours through the combined effects of landform manipulation, spatial and material design.

1.1 Keywords
landscape, design, pollution, performance, China
2 INTRODUCTION: THE INFLUENTIAL FACTORS OF AIR POLLUTION IN BEIJING

The documentary ‘Under the Dome’ by the Chinese journalist Jing Chai significantly raised public awareness of the extent of China’s air pollution, especially in the capital city Beijing. Numerous researchers (Esch, 2015; Excell, 2015; Walton et al., 2015; Bolund & Hunhammar, 1999) highlight the dangers of long-term exposure to air pollution which can lead to respiratory and cardiac diseases, and even premature death. For example the great London Smog of 1952 is believed to have resulted in approximately 12,000 deaths due to ‘a delayed effect’ (Bell, Davis, & Fletcher, 2004). Even though the Clean Air Act has been adopted since 1956 (Excell, 2015), ‘London’s air pollution still affects human health’ (Bell, Davis, & Fletcher, 2004). This demonstrates that any remediation of China’s pollution issue will be a long-term process. Consequently, many generations of Chinese people will continue to suffer from the delayed health effects of pollution, even with the successful application of pollution limiting economic and environmental reforms, policies and regulations.

The extreme pollution levels experienced in Beijing during the winter of 2015 attracted extensive media attention from across the world. According to the Chinese Ministry of Environmental Protection Data Centre (Liu, 2013), Beijing is one of the most polluted of China’s thirty one provinces and municipalities. The reasons behind this high level of pollution are complicated, ranging from poor supervision and enforcement of environmental regulations from vehicles and factories, heavy reliance on coal for energy and rapid population growth resulting in a tremendous increase in energy consumption (Li, Feng & Li, 2015). All of these factors lie outside the influence of design. However, wind is acknowledged as a major contributing factor in air pollution dispersion, transmission and diffusion. A recent report by Peking University (2015) highlighted Shijiazhuang and Tianjin as neighbourhoods which produced high levels of air pollution due to heavy industries such as steel manufacture. Due to wind movement, these emissions contribute to high air pollution levels in Beijing city. This factor, combined with the mountain ranges surrounding Beijing, which run from north to south west, act to trap pollutants in the city. Conditions are particularly severe when the southerly winds prevail (Zhang & Sang 2004; Jianzhong et al., 2014).

Wind direction however is not the only factor to consider – wind speed is of equal importance. Research recommends that wind speed be maintained within a range of 5.4-10.8 m/s for optimum dispersal of air pollution. Further Zhang et al. (2012) and Liu & Bian (2007) comment on wind speeds dual impact on air pollution levels. Within this recommended range of 5.4-10.8 m/s, the wind speed promotes diffusion and dispersion of air pollutants as it gets higher; while over 10.8 m/s, the increased wind speed can aggravate the concentration of Inhalable particulate matter (PM10, particulate matter 10 micrometers or less in diameter) so as to increase Air Pollution Index (API, a quantitative measure that describes ambient air quality). The index is obtained by combining figures for various air pollutants into a single measurement (UN, 1997). Also, if lower than 5.4m/s, the decreased wind speed is unlikely to promote dispersion of air pollutants which can accumulate over time.

In addition to this, the influence of urban morphologies on air pollution levels also presented a great opportunity to engage. From the perspective of urban planning and urban design, this means exploring how built form can influence residents’ exposure to pollution. Building layout (massing and siting) is recognized as one of the major ways in which designers can contribute to minimizing air pollution levels due to its impact on surrounding wind fields. For instance, a 2014 study (Yuan, Ng & Norford) examined the role of Hong Kong’s high, dense urban morphologies on air pollutant dispersion and highlighted the importance of maintaining an active air flow to improve the dispersion of air pollutants in high density cities. Similarly research by Ng (2009) demonstrated how uniform, dense urban high-rise buildings with limited open space between buildings resulted in stagnant air movement which causes accumulation of air pollution at the pedestrian level. In a further study Ng et al. (2011) found that low porosity can limit air flow velocity which acts to retard the dispersion of air pollutants. Collectively this research reveals to planners and designers the importance of considering air pollution dispersal as an influential factor when considering building layout in dense urban contexts such as China.

Influencing wind direction and speed can therefore be an immediate and valuable strategy for designers to use to minimise the effect of air pollution levels on residents. Despite this potential, many urban focused research studies tend to limit their enquiries to the relationship between air pollution levels and existing urban forms, in particular on traffic related emissions on streets or, alternatively, the statistical correlation between meteorological conditions and air pollution levels. Few published studies engage with the design of new urban morphologies and how the density, height and layout of buildings and associated open spaces might positively influence residents’ exposure to pollution. It is therefore important for...
designers to consider how incremental changes might influence pollution exposure. This paper presents a
two-phase research-driven design methodology which investigates the influence of conventional and new
built form on air pollution exposure in the design a new residential development block in Daxing District,
Beijing. The first phase tests urban morphological configurations (heights and siting orientation) using local
data and CFD modelling. The second phase, shifts scale to explore the possibilities of influencing
atmospheric conditions in the detail design of the resulting open space, considering topographic
manipulation, programmatic and spatial relationships and materiality.

3 METHODS: TWO-PHASE STRATEGY

3.1 Phase one: Designing of possible conventional and new urban morphologies for
CFD modelling to identify the optimised building configuration and
microatmospheric conditions in its associated open space

A 14 hectare vacant block in the Daxing District was selected as the site for exploration. The study
began with the consideration of conventional urban design patterns (adopting Chinese standards), which
were then varied over the course of the explorations to achieve the desired wind effects. Importantly the site
topography was accurately established, obtained from the ASTER Global Digital Elevation Model (2016).
According to the Standards China (MCPRC, 2002), the site could accommodate a maximum of 3000-5000
households or a population of 10000-15000. The maximum net density of residential buildings is defined as
35% for lower-rise (1-3 levels), 28% for multi-story (4-6 levels), 25% for mid-rise (7-9 levels) or 20% for high-
rise (≥10 levels) buildings over the total development land (MCPRC, 2002).

In this study, 3, 6, 9, 15 and 21 levels were tested. In addition, the density of conventional building
layout was constrained by spacing requirements which ensure lower level buildings receive adequate solar
exposure in accordance with Chinese standards (Standards Beijing, 2007; Standards China, 2014).
Furthermore, the conventional building layout was divided into four common urban siting configurations
- including row, perimeter, point and a combination of these three. As shown in Figure 1, the combination of
these different building heights and standard siting configurations produced 14 different options. These
formed the starting point for testing the relationships between urban forms and local wind data using CFD
simulations in ArcGIS 10.3. Importantly the influence of the surrounding existing buildings was also
considered as part of the simulation models.
Testing began with the prevailing wind of the District, with local data providing hourly mean wind velocity and directions in the Daxing District from 1951 to 2014. This data revealed that the prevailing winds originated from the north, north-northwest and south-southwest with the corresponding wind velocity ranging from 0.3m/s to 5.4m/s. Testing comprised of two stages. The first stage (Figure 2a) explored the performance of the 14 variations of the conventional building configurations, discussed earlier. This analysis provided an understanding of the behavioural relationships between building height and configuration, density, wind speed and direction with the ambition of encouraging the northern wind within the parameter of 4-5 m/s and minimising the southerly wind. The 3, 6 and 9-levels building patterns were tested as representatives of lower-rise, multi-story, mid-rise buildings configurations. This preliminary study revealed
that none of the conventional building layouts adequately increased the northern wind speed, nor satisfactorily reduced the south-southwest wind at pedestrian level.

Figure 2. (a) Stage one CFD modelling with conventional building configurations (2016). (b) Stage two CFD modelling with new building configurations (2016). (Colour changes from blue to red presented calm wind to high wind speed.) (c) The best building configuration and the generated micro-atmospheric conditions in the associated open space (2016). Diagram by the author J. Yu.
The next stage (Figure 2b) examined the potential of the higher buildings (15 to 21 levels) to produce better outcomes, using the same input of wind parameters. In the case of the 21-storey buildings, as expected the wind velocity increased substantially. However, this building height also produced problematic conditions such as amplifying wind speeds larger than 10.8 m/s in some sections of the site and increasing negative southerly winds. As discussed earlier, research (Peking University, 2015; Zhou et al., 2014) indicates that wind velocity higher than 6 m/s (inclusive) can negatively activate sand dust found at ground level. Therefore, the 21-story buildings were regarded as the maximum threshold for building levels. Equipped with this knowledge, the same building configuration was tested with a lowering of building height on the south-western edge to 18 and 15 levels to explore the potential to reduce the wind velocity to the desired wind scale 4-5 m/s.

Simulations confirmed that a combination of 15 and 21-level buildings (Figure 2c) offered the best possible configuration to maximise the positive impacts of the northerly winds to disperse air pollutants whilst minimising south south-west wind at pedestrian level on the site. Documentation of this simulation process is featured in Figure 2, along with a diagram of the favoured siting configuration which also highlights areas which have the highest potential for air pollutant accumulation. This configuration established the foundation for exploring more detailed site design strategies for open space which also aimed to minimise pollution exposure.

3.2 Phase two: Micro-climate adaptive design response of the associated open space through landform manipulation, spatial and material design associated with local residents’ activity patterns

This next phase shifted from processes of simulation and modelling to examine in more detail how different groups occupy open space in daily life. This review found that senior Chinese people who place value on their physical wellbeing are frequent users of parks and residential open space. Further, the need for parents to work in the city means that many seniors take care of their grandchildren, often taking them to exercise and play in the parks and open space mostly located within 1.2 kilometres of their residential blocks (Fu & Zhao, 2009). This combination of the elderly and the young also represent the most sensitive and vulnerable members of society in regards to air pollution exposure (Campbell, Halliday, & Cresci, 2014). This knowledge further highlights how important it is for landscape architects to consider air quality when designing open space in the Chinese city. But what can be achieved at the scale of detailed site design?

While it is impossible for a designer to reduce the quantity of air pollution, it is possible to minimize the exposure to poor air quality by considering the relationship between the time (daily and yearly) that people use open space and fluctuating pollution levels. For example, a pollution level study by Wang (2014) compared daily average levels of air pollutants such as PM2.5, and concluded that even though the average daily air pollution levels are the highest in winter, the lowest daytime air pollution levels are also experienced in winter, and not summer. Consequently, winter mornings from 8-11am offer residents the least exposure to PM2.5 across the year. From a design perspective, this knowledge presents an opportunity to maximise the usability and performance of open space in winter mornings as a strategy for limiting resident’s exposure to pollution.

This observation formed the starting point for developing a series of atmospherically responsive landscape strategies, premised on increasing the performance of external spaces, especially during winter mornings, (informed by an understanding of seasonal and daily pollution fluctuations). These strategies were developed through the combination of landform manipulation, spatial design and material exploration.
Building on the preferred site configuration from Phase one, the next strategic move was to explore how the manipulation of landform across the external spaces could influence the behaviour of winds to maximise the dispersal of air pollutants while also establishing viable activity space, especially during the winter months. Drawing on the wind field analysis generated during Phase one and a detailed sun shade analysis of the preferred siting configuration, the first design move was to propose a major landform manipulation to maximise winter morning sun exposure and ensure a dynamic spatial experience. As shown in Figure 3, the insertion of a large hill increased morning sun exposure and was also valuable in redirecting cold winter winds. This topographic form also responds to research which highlights how topographic features can increase wind speed at the pedestrian level on the leeward slope. (Mason, Wood, & Fletcher, 2010).

In a further topographic move, pollutant concentrated areas located close to building facades (identified in Phase One) were sunk to trap air pollutants. As will be discussed in the following section, the establishment of these zones presented the opportunity to explore the potential of technological and material innovation evident in architectural design to address pollution more directly.

**Figure 3. Landform Manipulation Strategy: Typical landform with raised ground surface with deciduous dominant to maximum solar accessibility in winter and provide shade in summer (2016). Diagram by the author J. Yu.**
An increasing number of architectural projects have begun to explore the potentials of architectural facades and skins to filter air pollutants and trap solar energy. The design of Manuel Gea González Hospital in Mexico City, for instance, has applied smog-absorbing technology, powered by renewable energy, into the building facade to reduce air pollutants (Zimmer, 2013). Drawing on these precedents, our scheme proposed that the facades of buildings exposed to the pollution bringing southerly winds be designed with an air filtering façade. Importantly, a sunken topographic space immediately adjacent to the façade helps contain these pollutants and channel them along the face of the façade, as shown in Figure 4. Other spatial strategies included strategically programming car parking in poorer performing outdoor conditions, while in shaded areas of the site which experience more optimal wind conditions, heating would be introduced (especially during winter mornings), powered by renewable energy from solar collecting technology.
With the first two strategies establishing the overall framework for the open space, a further layer of performance was developed through the careful consideration of materiality—including the role of living systems. As has been documented by many researchers (Janhäll, 2015; Wang et al., 2015), vegetation can play an important role in deposition and dispersion of air pollutants. Wang et al. (2015) highlights 10 common evergreen trees which have the capacity to absorb air pollutants in Beijing, with *Platycladus orientalis, Pinus tabuliformis, Taxus chinensis, Juniperus chinensis* proven to be the most effective species. Working with these four species, evergreen trees were introduced tactically into the design to redirect winds and reduce wind velocity in activity and shaded space. As deciduous trees, such as *Koelreuteria paniculata* and *Robinia pseudoacacia* can also effectively retain pollutants (Wang et al., 2015), these species were used in areas such as the large hill to maintain maximum sun exposure in winter and provide shade in summer. The
combined effect of the planting, consideration of site relationships and program and the broader topographic manipulations establish a considered atmospheric condition for the external spaces. A series of pathways were then laid into this new landscape which, as much as possible, aligned people’s daily activity routes with cleaner areas of the site.

4 CONCLUSIONS AND FUTURE STUDY

In this study, we hope to highlight the value and the methodology of reconsidering conventional design process to engage with meteorological conditions in the future planning and design of open space. This methodology highlights the potential of computational tools and real-time data in developing performance driven design responsive to address contemporary issues including pollution and climate change. Through integrating the CFD modelling with research of the relationships between building layout, topography, vegetation, materiality and dynamic atmospheric conditions, planners and designers can develop a greater understanding of the performance of open space, considered at the scales of the residential district and detail design. In addition, this study intended to bridge the gap of scientific research and real world design process. For instance, working with the knowledge from research conclusions that winter mornings presented the lowest pollution readings of any time of year and the relationships between residents’ activity pattern and air pollution, the external spaces then can be designed to maximise their usability and reduce residents’ exposure to air pollution during winter mornings to mitigate the urban extreme events.

In this study, we utilised ArcGIS 10.3 to carry out CFD modelling as a mean of understanding the the relationship between conventional and new residential blocks and the invisible and influential atmospheric conditions. The testing results can be potentially validated by either collecting and monitoring real-time data or conducting physical modelling tests in real world in the future. Although the validity of the CFD modelling remains as a question for future verification, it is still considered as a new unexplored territory for planners and designers to be aware of the importance of understanding atmospheric conditions such as pollution and winds in contemporary cities. This extends their comprehension of the invisible behaviours and their influences on the performance of external spaces. Through CFD simulations, this study tested the relationship between the prevailing winds and the residential blocks. The results presented the possibility of modifying building configurations to influence wind distributions, and the potential to identify the best option for maintaining the most desirable wind speeds and direction for encouraging pollution dispersal as a new methodology in urban planning and design process to mitigate the modern atmospheric events of air pollution and climate change for open space. The best building configuration provided the best performance for its associated open space to be further designed with landform, spatial and materials strategies to reduce residents’ exposure to the most polluted areas so as to improve the performance of the residential open space.

This paper is not offering a replicatable approach for every site, but more a methodology for structuring a research-driven design investigation which responds to the particular dilemmas of a site. As more engagement with digital techniques in CFD modelling, this methodology can be further explored from larger scale urban planning to detailed scale of site design to better mitigate urban environmental issues in future planning and design process and to also potentially bridge the gap between scientific research and real world projects.

5 ACKNOWLEDGEMENTS

The authors would like to express their thanks to the visiting professor Wenqi Lin for providing local historical wind data (1951-2014) in Daxing district of Beijing while he was at the University of Melbourne on his sabbatical leave from Tsinghua University in 2016.

6 REFERENCES


