Hong Kong Housing Authority

Air Ventilation Assessment of Public Housing Developments at Tung Chung Areas 99 and 100

Report for Air Ventilation Assessment – Initial Study

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1 Introduction

1.1 Background

Ove Arup & Partners Hong Kong Limited (Arup) has conducted an Air Ventilation Assessment (AVA) – Initial Study for the planning application of the proposed Public Housing Development at Tung Chung Areas 99 and 100 (The Developments).

Expert Evaluation has been conducted in preliminary design stage to identify the existing wind conditions and good design features; wind enhancement features are proposed. Quantitative AVA studies should be conducted to assess their air ventilation performance.

The *Technical Guide for Air Ventilation Assessment for the Developments in Hong Kong (Annex A of Technical Circular No.1/06 for Air Ventilation Assessments)*[1] *(termed as AVA Technical Circular hereafter)* dated 19 July 2006 lay down the foundation of this methodology statement.

1.2 Objective of AVA Initial Study

Among all available wind data, an Initial Study will be conducted by using Computational Fluid Dynamics (CFD) techniques. It aims to achieve the following tasks:

- Initially assesses the characteristics of the wind availability of the Study Site;
- Gives a general pattern and a rough quantitative estimate of the wind performance at the pedestrian level using Velocity Ratio VR, and
- Identify good design features and problematic areas if any and recommend mitigation measures.

2 Location and Site Characteristics

The Proposed Development is located at the part of the Tung Chung New Town Area. TC 99 and TC 100 are close to each other and they are surrounded by existing and future planned high-rise residential developments according to the Recommended Outline Development Plan (RODP) of Tung Chung New Town Area.

The Proposed Developments are surrounded by future high-rise residential development (North), future comprehensive development and residential use (East), future high- rise commercial development (South), Ying Tung Estate (Southwest) as shown in Figure 1.

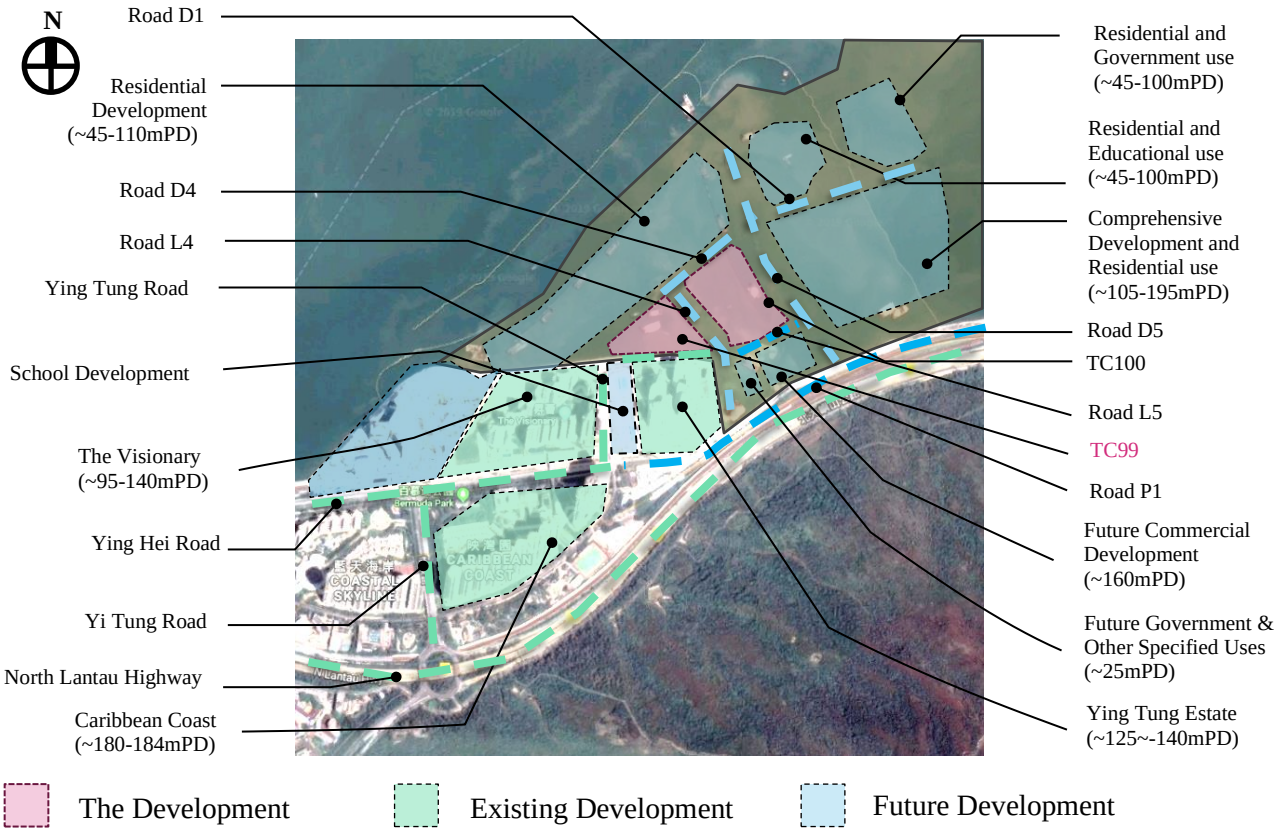

Figure 1 Site Location and Surrounding Developments (Source: Google Map)

3 Wind Availability Data

As per the *AVA Technical Circular*[1], at least 75% of the time in a typical reference year (frequency of occurrence) would be studied under both annual and summer wind condition in the Initial Study when using a Computational Fluid Dynamics (CFD) modelling technique. Since the CFD approach is adopted for the present project's AVA, this criterion together with the following selected wind data are to be applied as the methodology.

3.1 RAMS Wind Data

The site wind availability of the application site and its surrounding is an essential parameter for AVA. As stipulated in the *AVA Technical Circular*, the site wind availability would be presented by using appropriate mathematical models (e.g. RAMS simulation). Planning Department (PlanD) has set up a set of wind availability data of the Territory for AVA study, which could be downloaded at Planning Department Website[1].

The location of the Project Area falls within the location grid (x:035, y:038) in the RAMS information database. The wind availability data at 500mPD of location grid (x:035, y:038) is obtained to adopt in the AVA study.

The annual and summer wind roses for the study are shown in Figure 3 and Figure 4Figure 2. The wind tunnel data shows that the most dominant annual prevailing wind are E wind, ESE wind and ENE wind while the most dominant summer prevailing wind are SSW and SW wind.

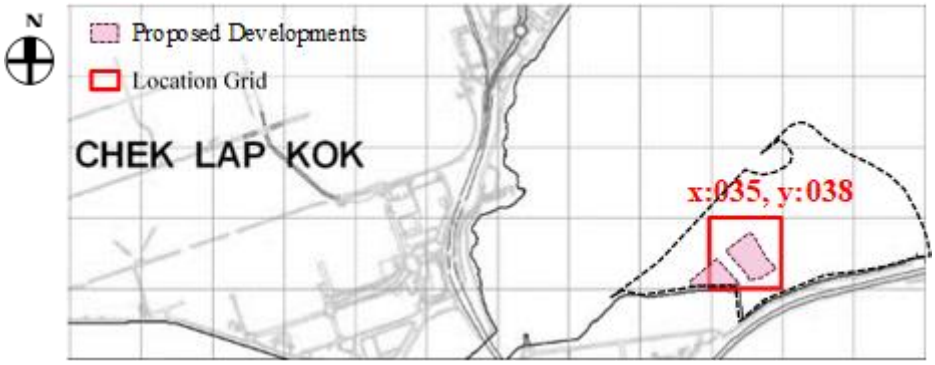

Figure 2 RAMS Grid and the Development Location

[1] http://www.pland.gov.hk/pland_en/info_serv/site_wind/site_wind/

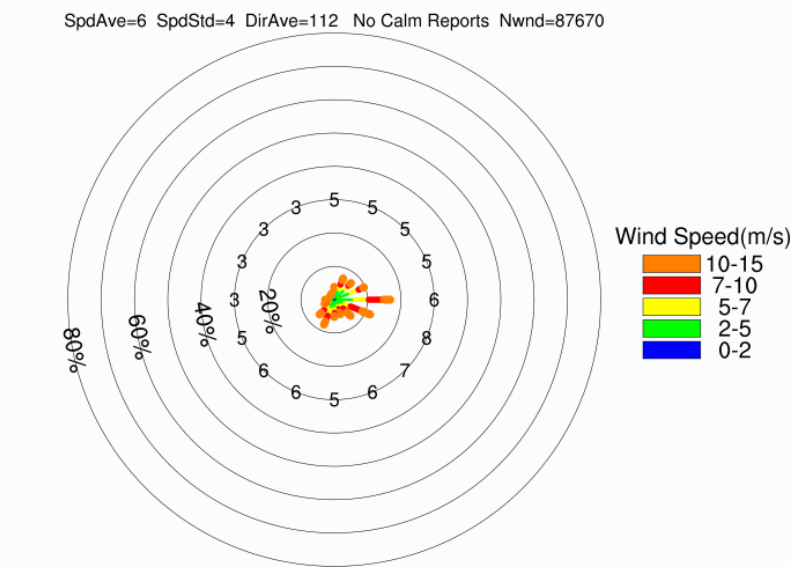

Figure 3 RAMS annual wind rose at 500mPD

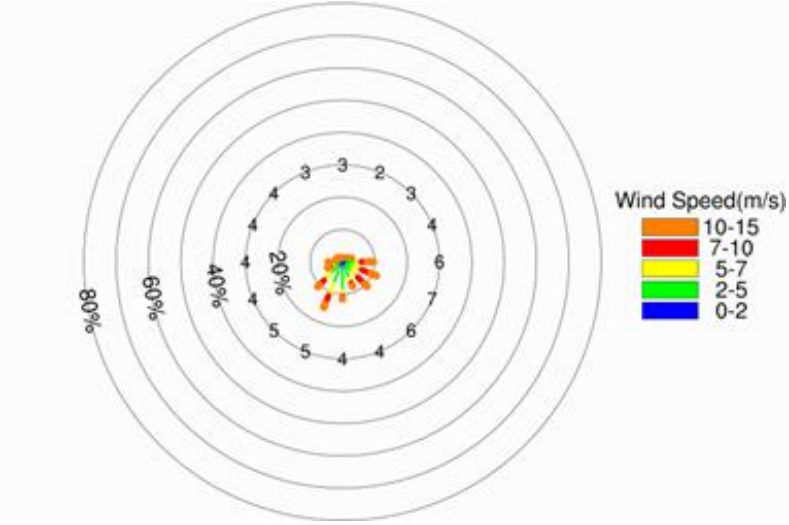

Figure 4 RAMS summer wind rose at 500mPD

3.2 Prevailing Wind Directions

As mentioned above, the RAMS wind data of location grid (x:035, y:038) is adopted for the site wind availability in this study.

3.2.1 Annual Prevailing Wind

Eight prevailing wind directions (highlighted in red colour in Table 1) are considered in the study, which cover 79.4% of the total annual wind frequency. They are north-north-easterly (6.9%), north-easterly (7.1%), east-north-easterly (9.7%), easterly (17.2%), east-south-easterly (12.0%), south-easterly (7.1%), south (5.3%), south-south-westerly (8.2%) and south-westerly (6.4%) winds.

Table 1 Annual Wind Frequency of the Wind Directions

Wind Direction	N	NNE	NE	ENE	E	ESE	SE	SSE	
Frequency	3.9%	6.9%	7.1%	9.7%	17.2%	12.0%	7.1%	4.8%	
Wind Direction	S	SSW	SW	WSW	W	WNW	NW	NNW	**SUM**
Frequency	5.3%	8.2%	6.4%	3.2%	2.8%	1.6%	1.7%	2.1%	**79.9%**

** The wind directions in red are selected for the study for annual condition*

3.2.2 Summer Prevailing Wind

Eight prevailing wind directions (highlighted in red colour in Table 2) are considered in this AVA Study which covers 80.9% of the total summer wind frequency. They are easterly (7.3%), east-south-easterly (10.0%), south-easterly (8.0%), south-south-easterly (7.5%), southerly (10.2%), south-south-westerly (16.5%), south-westerly (14.6%) and west-south-westerly (6.8%) winds.

Table 2 Summer Wind Frequency

Wind Direction	N	NNE	NE	ENE	E	ESE	SE	SSE	
Frequency	1.3%	1.5%	1.4%	2.8%	7.3%	10.0%	8.0%	7.5%	
Wind Direction	S	SSW	SW	WSW	W	WNW	NW	NNW	**Sum**
Frequency	10.2%	16.5%	14.6%	6.8%	4.9%	2.9%	2.6%	1.5%	**80.9%**

** The wind frequency showing in red colour represents the recommended wind direction for the CFD simulation.*

3.3 Wind Profiles

The profiles of wind speed from the PlanD RAMS database (x:035, y:038) is studied and the selected extracted. In the RAMS data the vertical profiles of the normalised mean wind speed were provided and the exact profile will be modelled in the CFD model for each corresponding wind directions to be studied. The vertical wind profile for all wind directions to be studied is shown in

Figure 5.

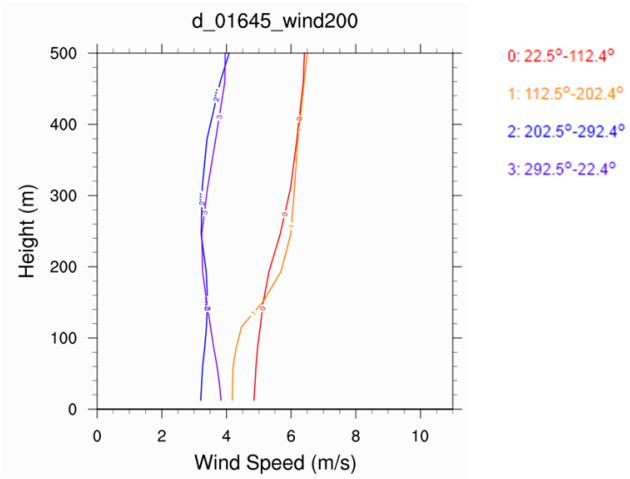

Figure 5 Vertical Wind Speed Profile

4 Design Schemes for Initial Study

To investigate the ventilation impacts of the Development and effectiveness of wind enhancement features. Two schemes, the Baseline scheme and the Proposed scheme are to be analysed and compared in this AVA Initial Study.

4.1 Baseline scheme

TC 99

TC 99 consists of 4 nos. of 40 storeys tall residential building blocks. Block 1 and Block 2 sit atop a large podium structure with shops and restaurants; a non-domestic block is located beneath Block 3 and Block 4 and connecting the 2 blocks.

A 20m-wide non-building area (NBA) is provided in SE-NW direction. An enclosed Public Transport Interchange (PTI) is located at the southwestern portion of TC 99. Another 1-storey non-domestic block is located to the immediate north of the PTI.

The NBA would serve as a breezeway and the relatively low-rise PTI and non-domestic block allow the prevailing wind to skim across TC99.

The NBA, the non-domestic blocks, the domestic blocks and the PTI are shown in Figure 6.

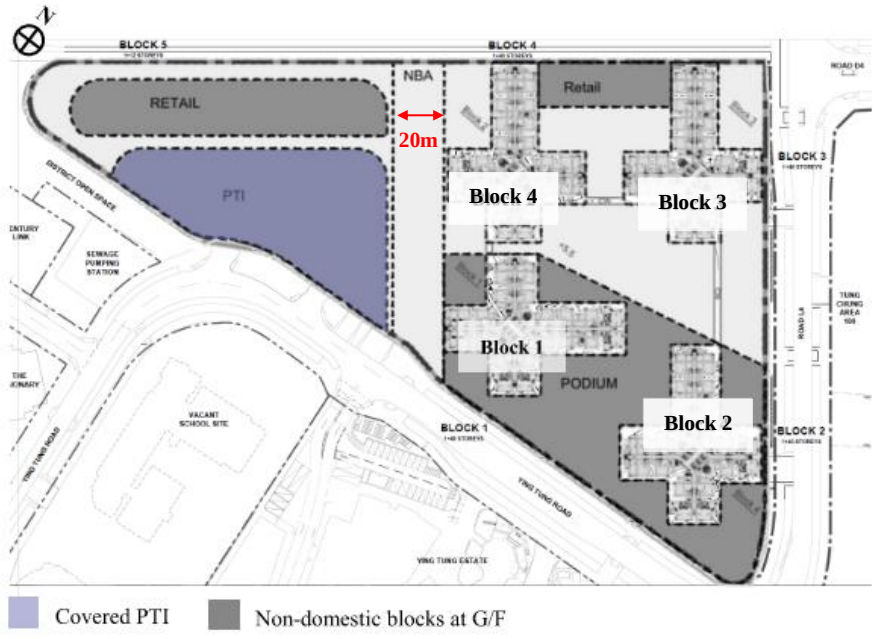

Figure 6 TC99 Baseline Master Layout Plan

Figure 7 Northerly view of TC99 Baseline scheme

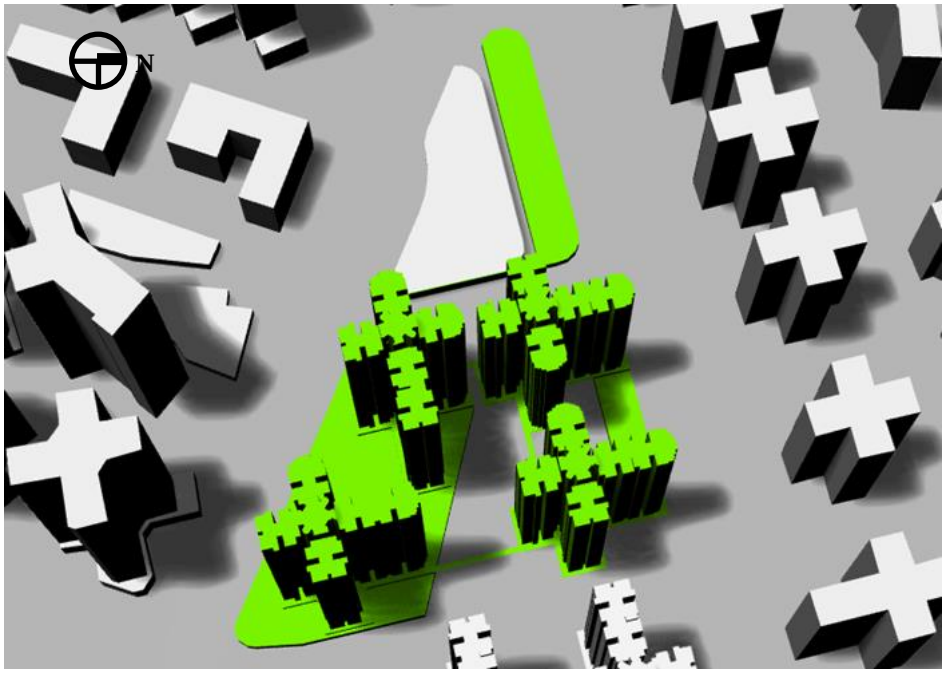

Figure 8 Easterly view of TC99 Baseline scheme

Figure 9 Southerly view of TC99 Baseline scheme

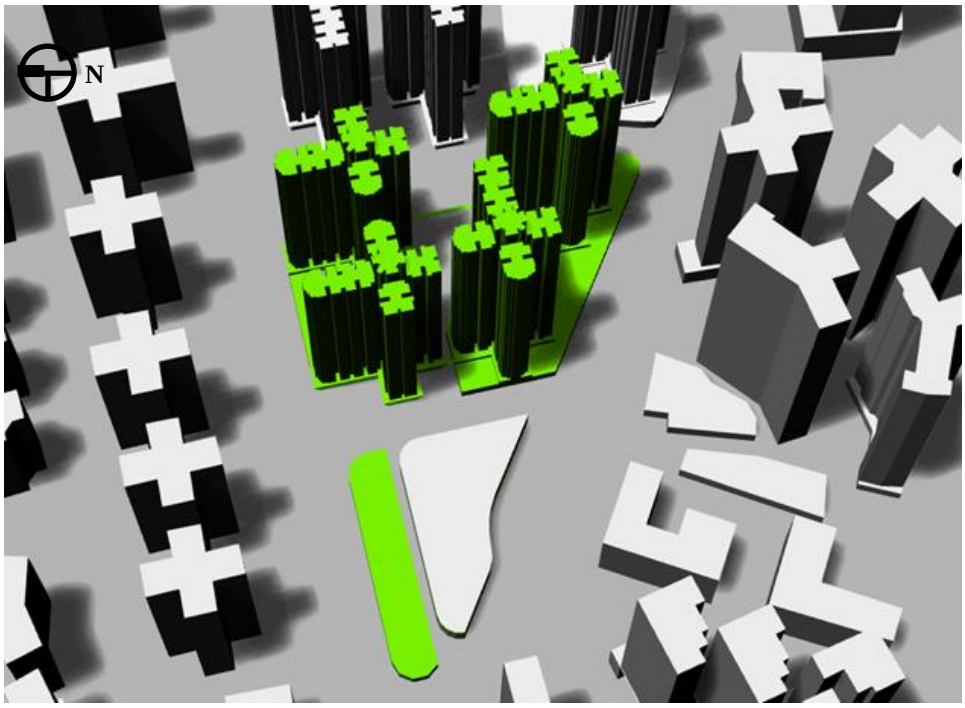

Figure 10 Westerly view of TC99 Baseline scheme

TC 100

The TC 100 Development consists of 5 domestic blocks of 40 storeys. Block 1 to 3 would sit atop podium structures, with Block 1 and 2 atop one large podium structure, and Block 3 atop a non-domestic block.

A 20m-wide NBA is provided in NE-SW direction, which would serve as the wind path of the development, particularly for the dominant annual easterly winds. The large open space in the north corner, designed for use as a sports court, would act as the wind entrance for the eastern prevailing wind.

There is also building separations between Blocks 1 and 2 and Blocks 3 and 4 which facilitate wind penetration in the North-South direction.

The NBA, the non-domestic blocks and domestic blocks are shown in Figure 11.

Figure 11 TC100 Baseline Master Layout Plan

By referring to the CAD drawings of the Baseline scheme, the 3D model was constructed as shown in

Figure 12 to Figure 15.

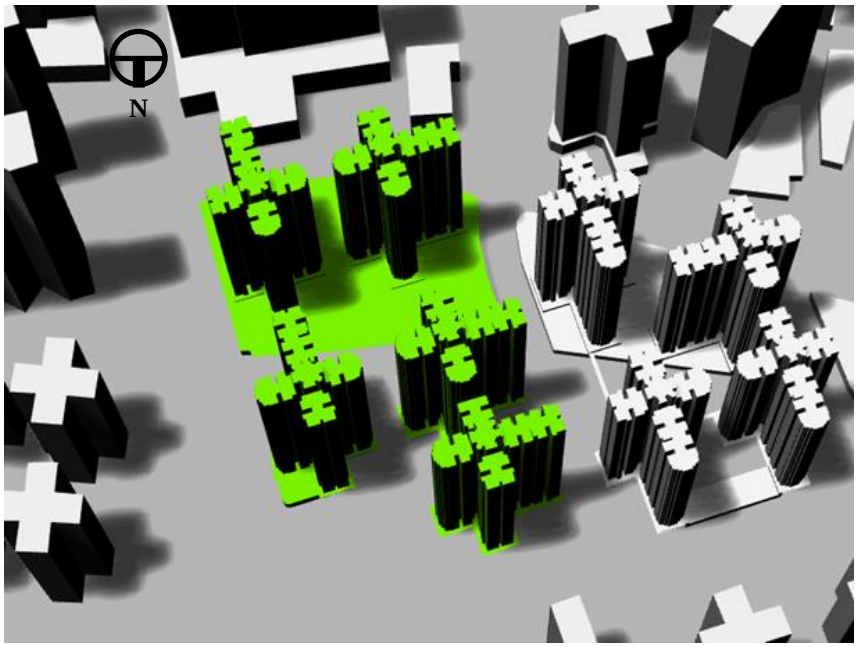

Figure 12 Northerly view of TC100 Baseline scheme

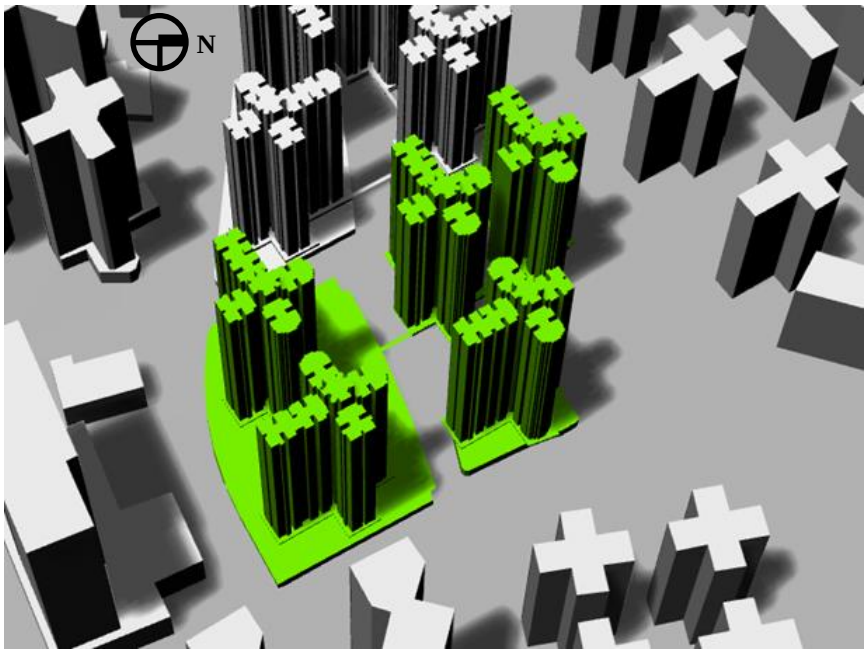

Figure 13 Easterly view of TC100 Baseline scheme

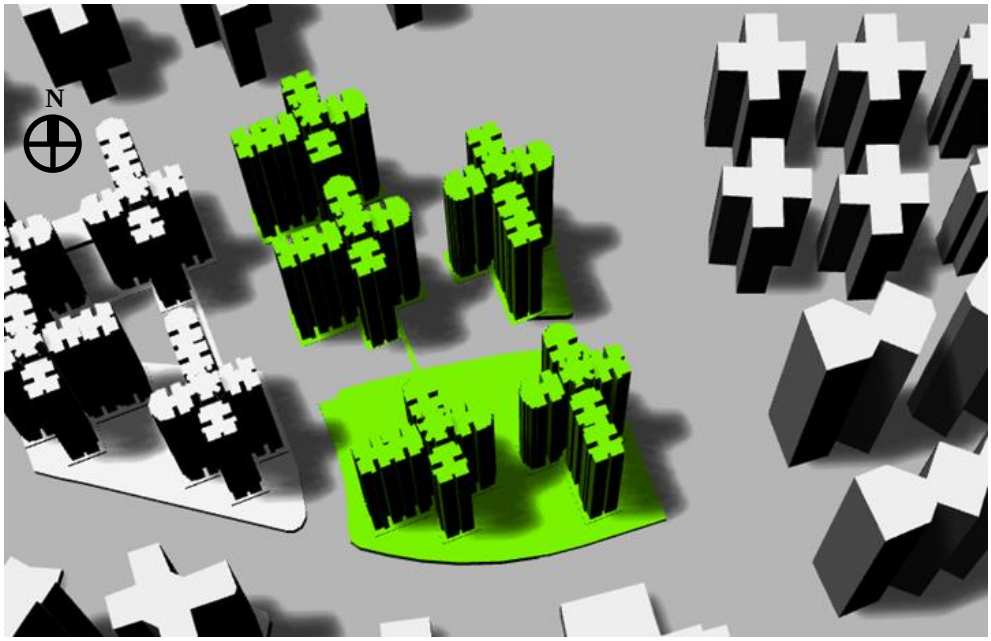

Figure 14 Southerly view of TC100 Baseline scheme

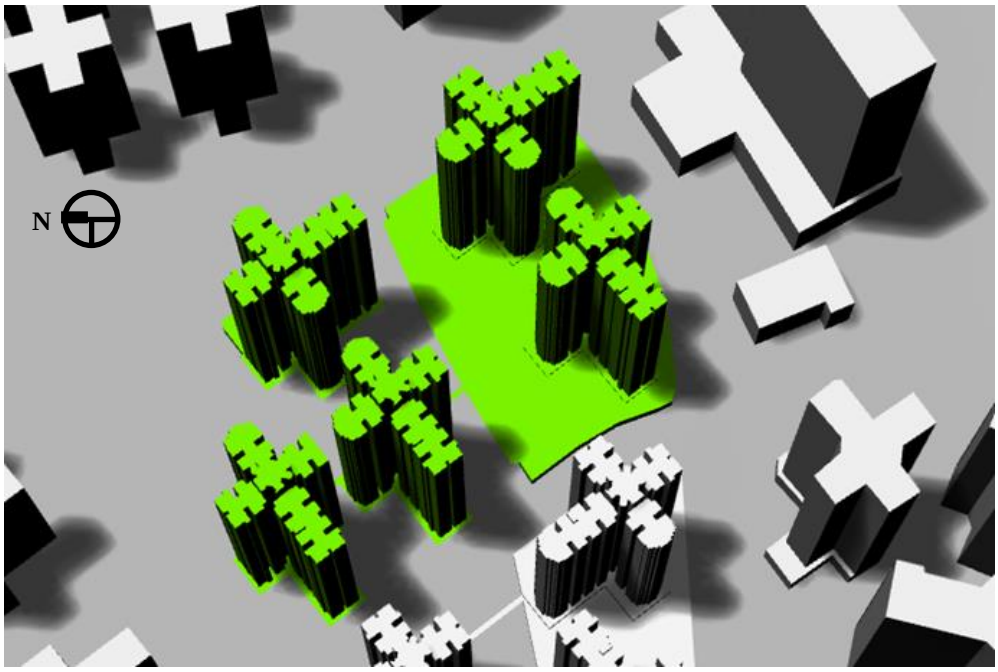

Figure 15 Westerly view of TC100 Baseline scheme

4.2 Proposed scheme

The number and height of the residential towers of the Baseline and Proposed Scheme are similar. Major changes include the massing and distribution of the podium, as well as changes to the PTI and the introduction of domestic block 'Block 5' in TC99, to cater for the increasing housing demand. The majority of these changes have been made to improve the wind performance of the development.

TC 99

The TC 99 Development consists of 5 building blocks in which Block 1 to Block 4 are 40 storeys and Block 5 is 12 storeys. Block 1 and 2 sit atop a podium structure with shops and restaurants, and Block 4 sits atop a kindergarten. Block 5 sits on top the array of street shops. Block 3 sits on the top of its own one storey of the ground level.

Recreational areas are on Ground Level and Podium Level, including the Basketball Courts, Community Farm and CPAs. The Sports Courts, including basketball court, are located on north portion of the Development between Block 3 and Block 4 and he CPAs mainly located along the NBA and podium deck, creating open spaces for ventilation in these areas of the Development. The covered PTI is permeable and located near Block 5 at the southern portion of the Development.

	Main Roof Level mPD
Block 1	124.19
Block 2	124.19
Block 3	124.19
Block 4	124.19
Block 5	47.19

To maintain and enhance the wind performance of the Proposed scheme, following wind enhancement features have been adopted:

- Increase the permeability of the PTI;
- Reorient Blocks 1-4 to introduce new breezeways, particularly in NW-SE and E-W direction;
- Reshape Blocks 2 and 3, and open space at north to create breezeway through development in a NW-SE direction;
- Introduce G/F separation between Blocks 2 and 3 by relocating the non-domestic portion;
- Increase the permeability of the podium underneath Blocks 1 to Block 4.

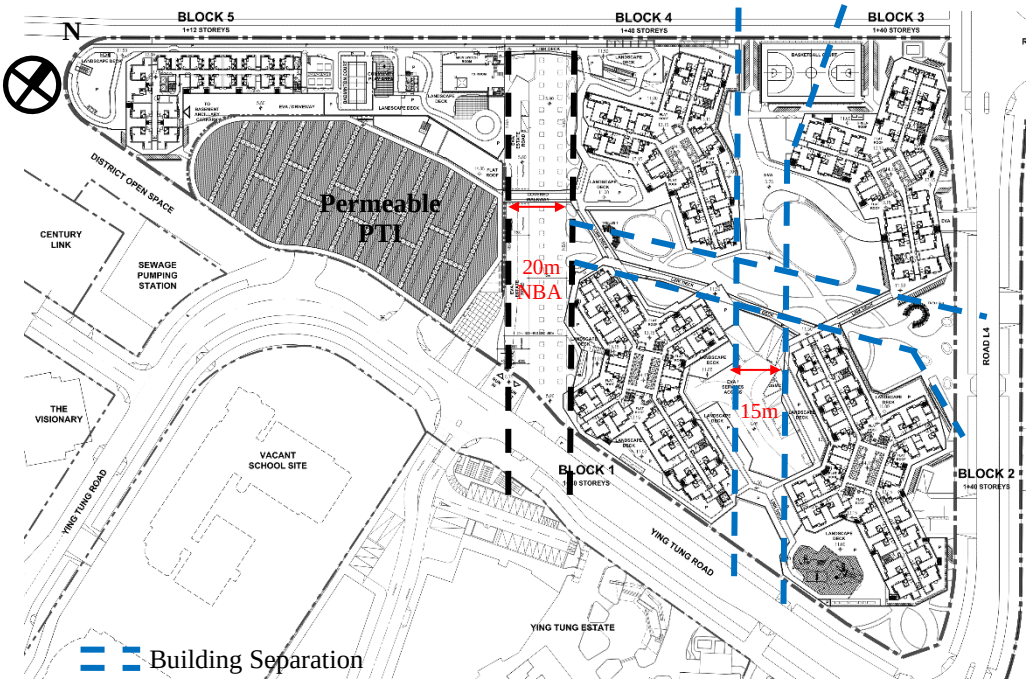

Figure 16 Wind Enhancement Features for Proposed Development at TC99

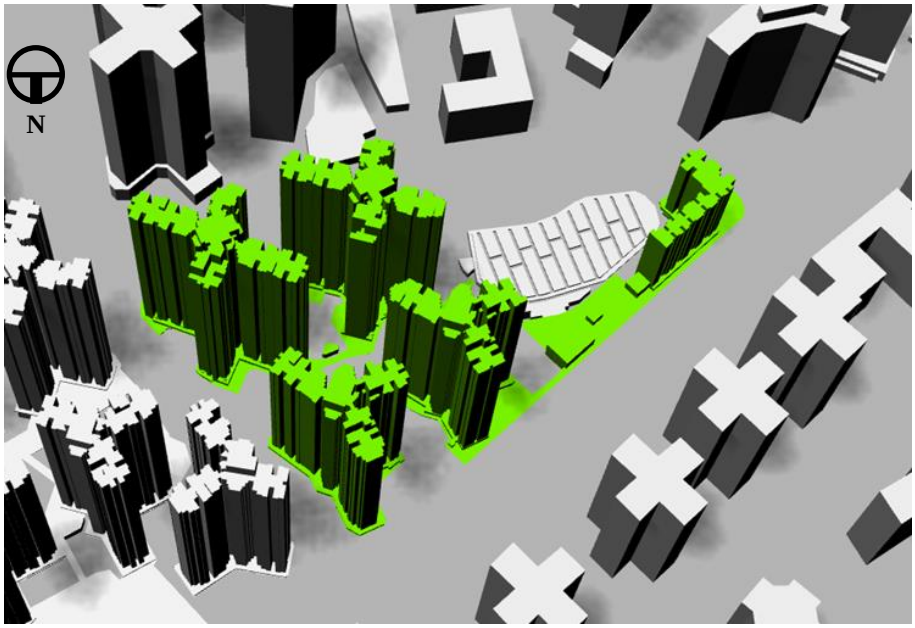

Figure 17 Northerly view of TC99 Proposed scheme

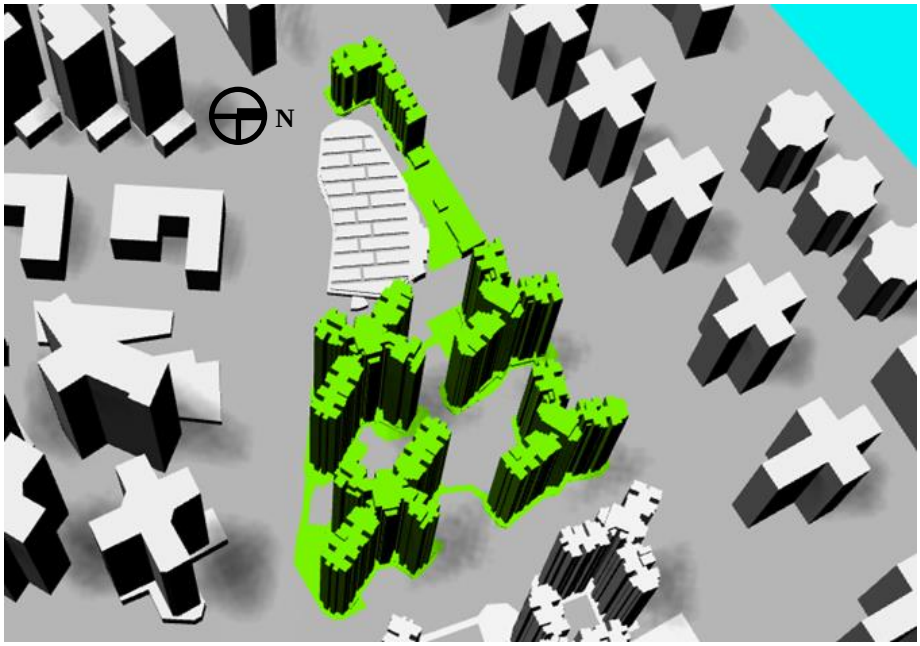

Figure 18 Easterly view of TC99 Proposed scheme

Figure 19 Southerly view of TC99 Proposed scheme

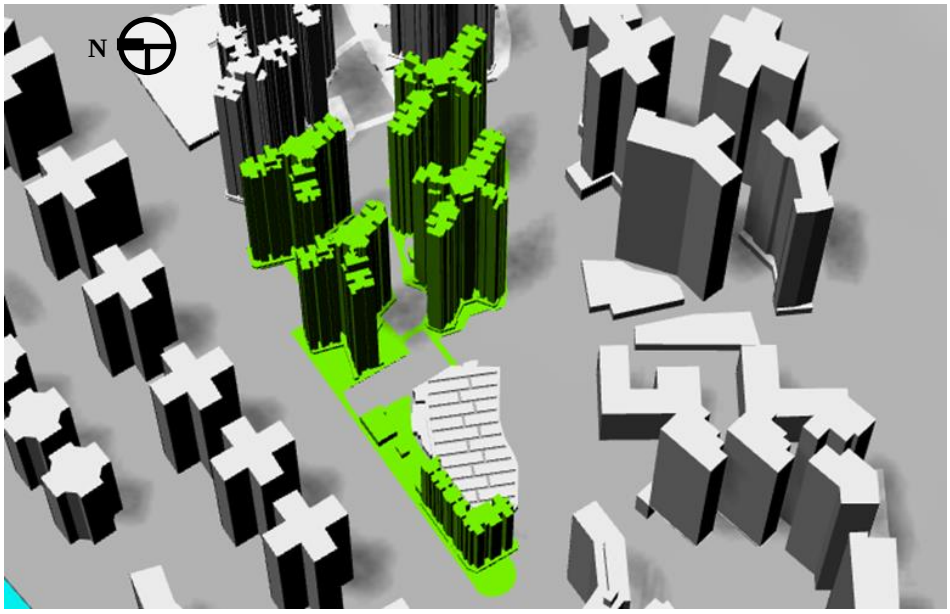

Figure 20 Westerly view of TC99 Proposed scheme

TC100

The Proposed scheme consists of 5 building blocks of ~124mPD. Block 1 and 2 sit on top a semi-permeable podium structure. Block 1 and 2 are separated from Blocks3, 4 and 5 by the 20m NBA. Block 3 and 4 also sit on top a podium structure, interspersed with recreational facilities and sitting-out areas. Block 5 is a standalone tower. On the north-side of the development, there is a low-level covered car-park. On top of the car-park, at the podium level, there are a number of recreational facilities including a football pitch and two badminton courts.

The Proposed scheme reduced the footprint on the ground floor which facilitate the natural ventilation at the pedestrian level, as shown in below 3D model.

	Main Roof Level mPD
Block 1	124.19
Block 2	124.19
Block 3	124.19
Block 4	124.19
Block 5	124.19

To maintain and enhance the wind performance of the Proposed scheme, following wind enhancement features have been adopted:

- Increase the permeability of the podium between Blocks 1 and 2 by redistributing the podium mass across the development;
- Increase the tower setback of Blocks 1 and Block 2 from Road L5 to widen the wind path along Road L5;
- Increase the tower setback of Block 3 from Road D5 to facilitate the North Easterly prevailing wind entering the NBA.;

- Increase the tower separation between Blocks 4 and 5 to introduce a breezeway for the annual prevailing wind towards the Road L4 and TC99;
- Increase the tower separation between Blocks 1 and 2 to introduce a breezeway for the summer prevailing wind towards the NBA;
- Chamfers to the podium southwest corner beneath Block 2 to facilitate the travelling of wind towards Road D5 and Road L5.

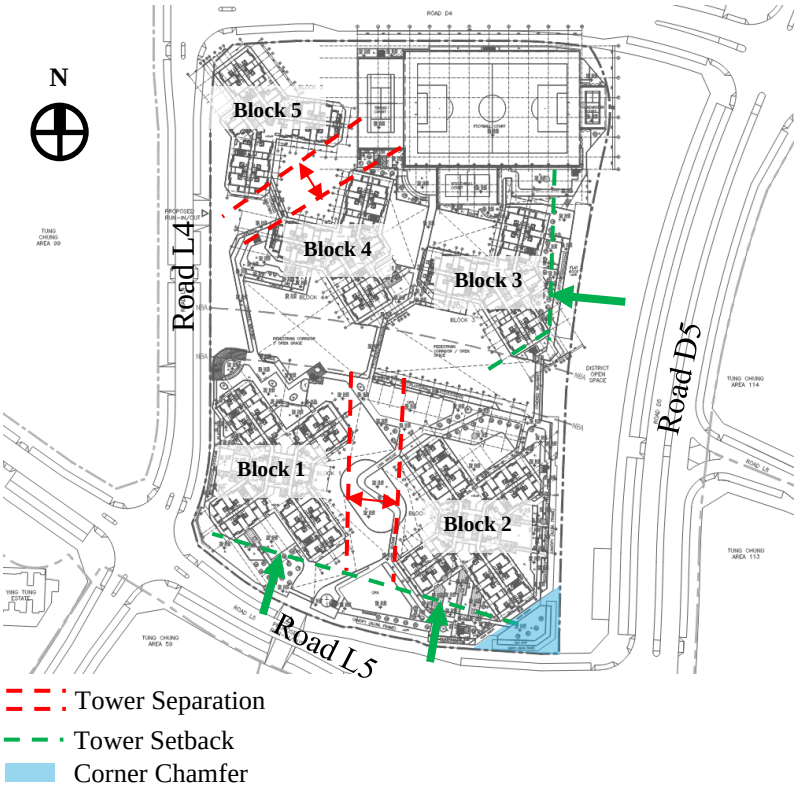

Figure 21 Wind Enhancement Features for Proposed Development at TC100

By referring to the CAD drawings of the Baseline scheme, the 3D model was constructed as shown in Figure 22 to Figure 25.

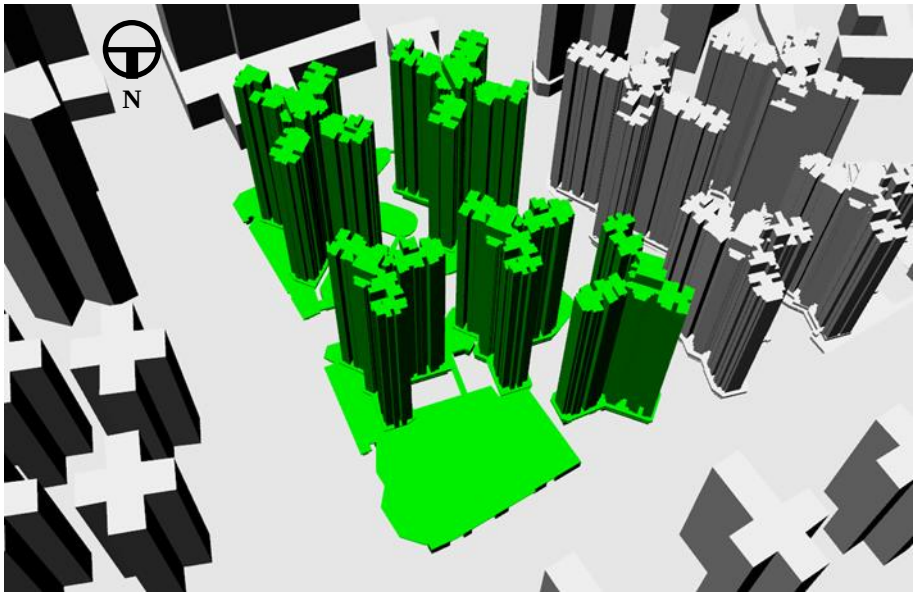

Figure 22 Northerly view of TC100 Proposed scheme

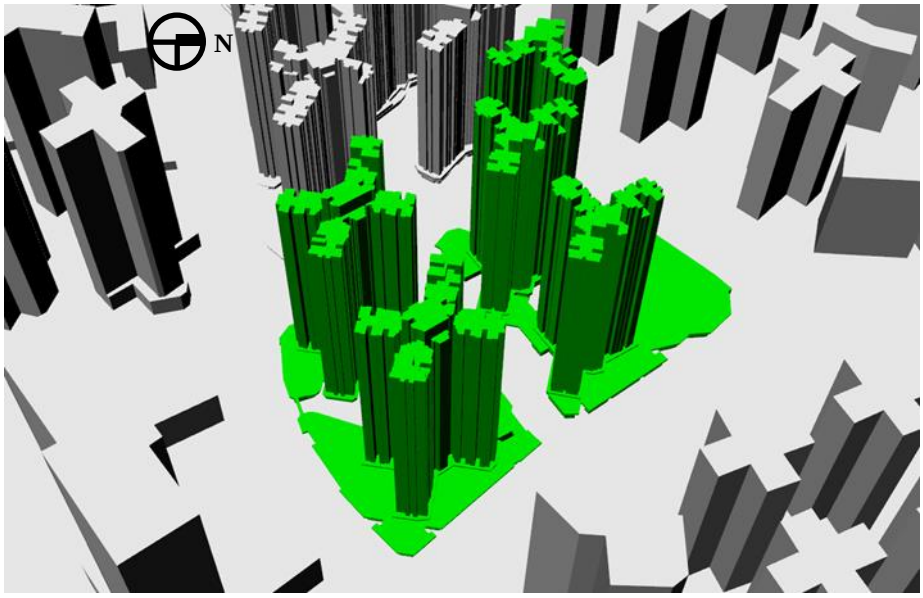

Figure 23 Easterly view of TC100 Proposed scheme

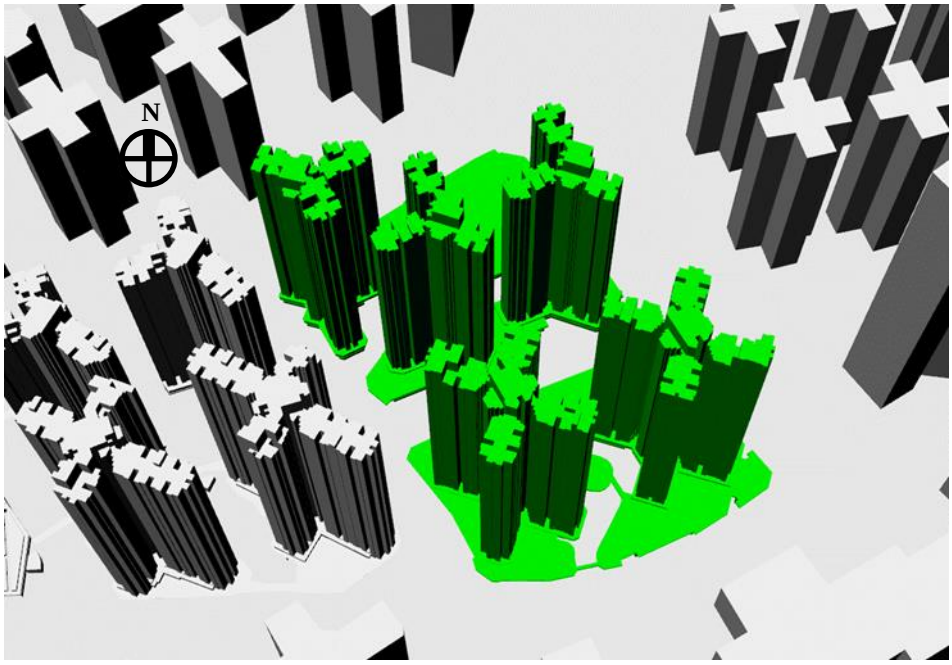

Figure 24 Southerly view of TC100 Proposed scheme

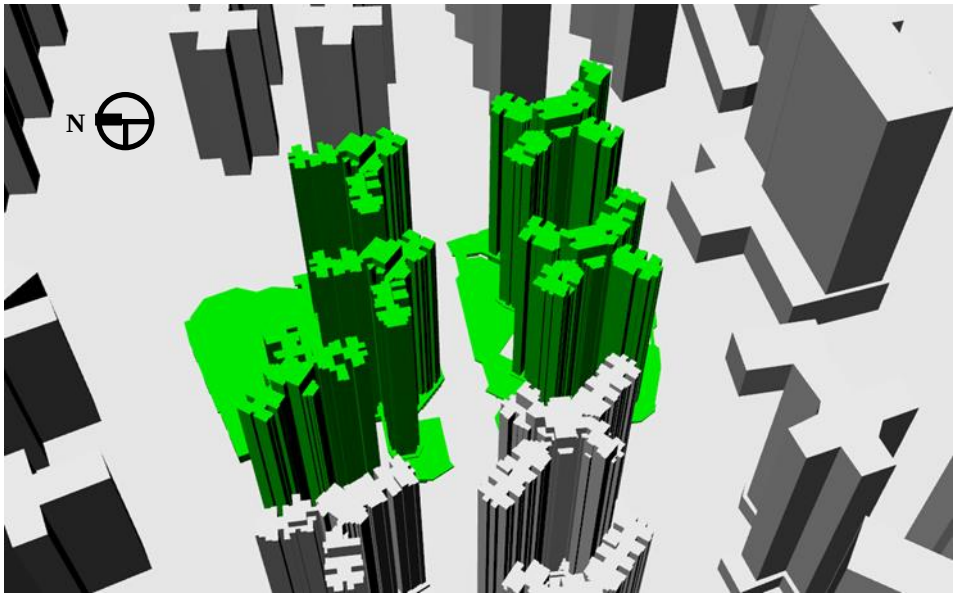

Figure 25 Westerly view of TC100 Proposed scheme

5 Methodology

5.1 Assessment and Surrounding Areas

For TC 99&100, the Assessment Area must include the area within 1H from the site boundary where H is the height of the tallest building of the Development. Surrounding Area would include the area up to 2H from the site boundary.

The tallest building of the both TC99 and TC100 has a building height of about 120m, so 1H and 2H would be 120m and 240m respectively. The Assessment Areas and the Surrounding Areas of the two sites are combined to form the overall Assessment Area and Surrounding Area. The site boundary, Assessment Area, and Surrounding Area of the study are presented in Figure 26.

The study domain is approximately 5200m (L) x 5200m (W) x 4000m (H). It covers the Development and provides sufficient consideration on surrounding topography. The model contains information of the surrounding buildings and topography from Geographical Information System (GIS) platform.

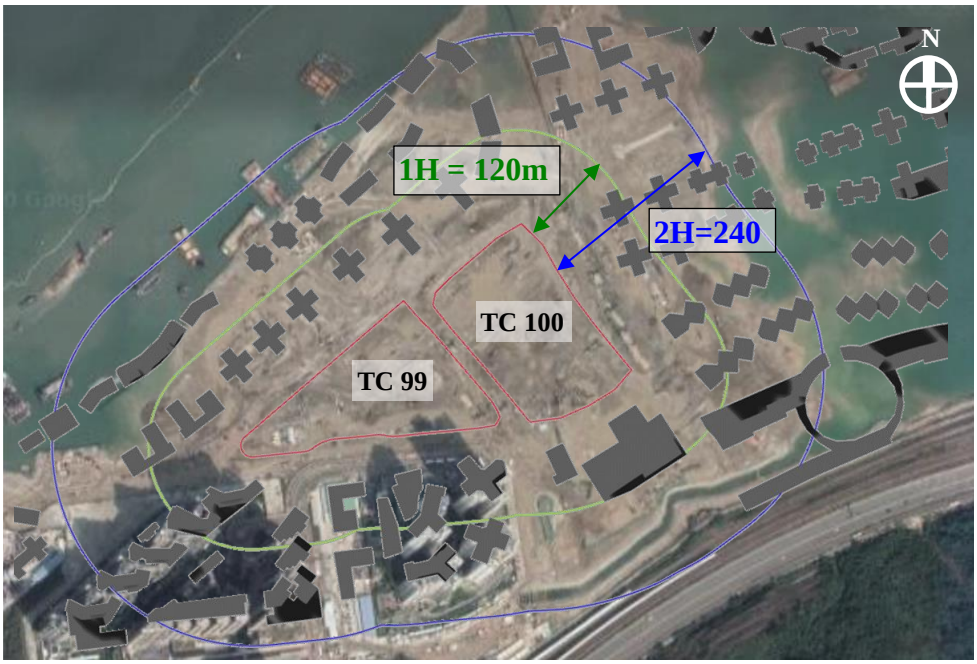

Figure 26 Site Boundary (red), Assessment Area (green) and Surrounding Area (blue)

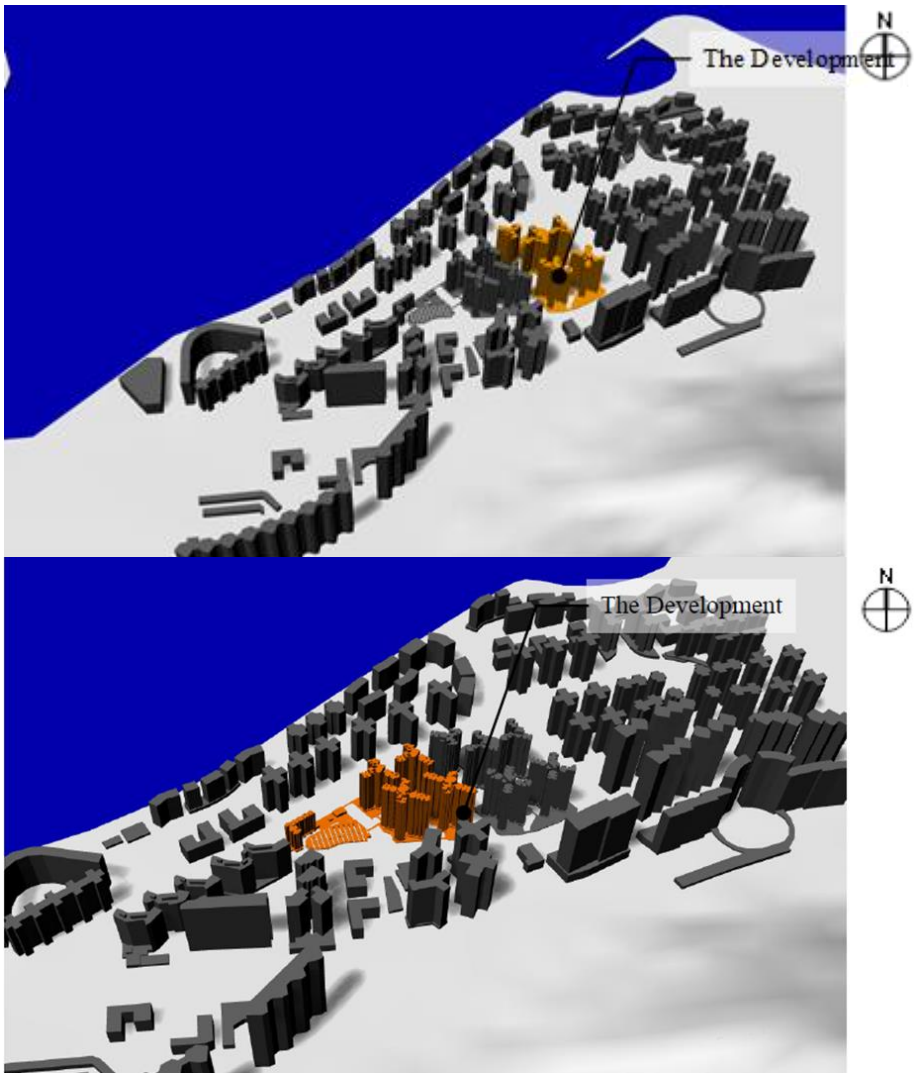

Figure 27 3D View of the Domain (TC100 - Top, TC99 – Bottom)

5.2 Technical Details for CFD simulation

5.2.1 Assessment Tools

Computational Fluid Dynamics (CFD) technique is utilized for this AVA study. With the use of three-dimensional CFD method, the local airflow distribution can be visualized in detail. The velocity distribution within the flow domain, being affected by the site-specific design and the nearby topography, will be simulated under selected wind directions as stated in Section 3 for annual and summer wind conditions.

5.2.2 CFD Model

Following the *AVA Technical Circular*, buildings within Surrounding Area shall be built in the CFD model. In order to simulate the approaching wind turbulence effect in a more accurate manner, the CFD model is built to include the highways or bridges as they may affect the approaching wind, even it is falling outside the Surrounding Area. In addition, the model domain is built far beyond the Surrounding Area as required in the Technical Circular in order to eliminate the boundary effects. Therefore, the studied size of CFD model of the development is approximately 5200m (L) x 5200m (W) x 4000m (H) which contains more than 7,000,000 cells as shown in Figure 28.

The computational domain covers the site of the Development and provides sufficient consideration on surrounding topography. The model contains information of the surrounding buildings and site topography via Geographical Information System (GIS) platform. The site topography would be modelled within the whole computational domain. Body-fitted unstructured grid technique is used to fit the geometry and reflect the complexity of the development geometry. A prism layer of 3m above ground (totally 6 layers and each layer of 0.5m thick, shown in Figure 29 is incorporated in the meshing so as to better capture the approaching wind and wind condition at pedestrian level. A mesh expansion ratio of 1.3 is adopted and the blockage ratio was less than 3%.

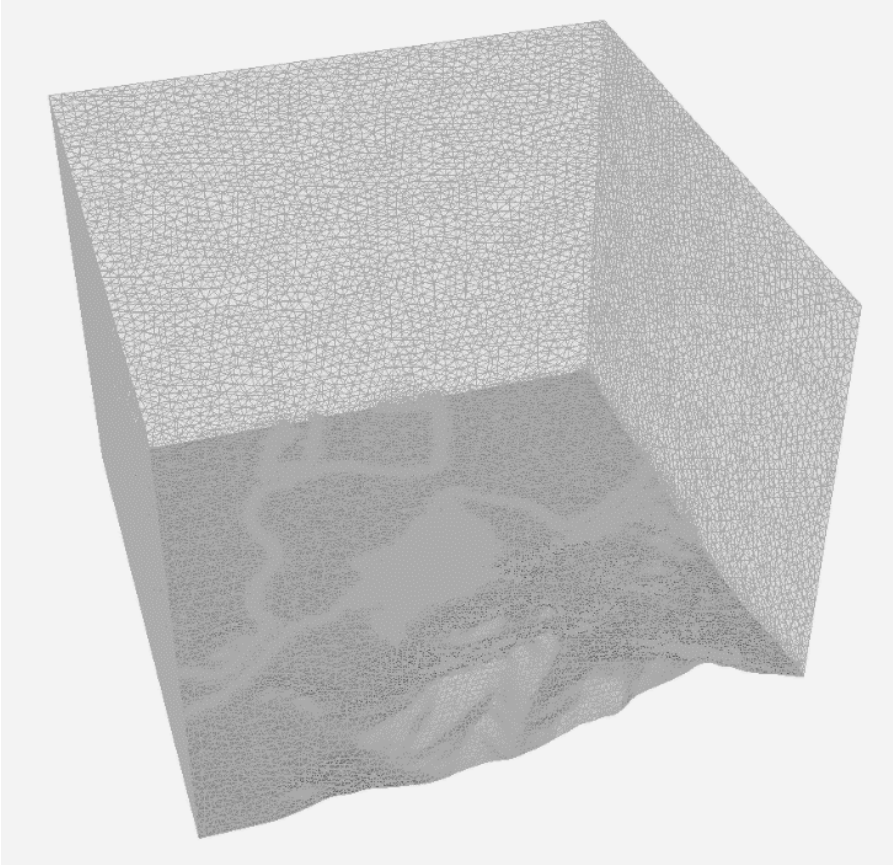

Figure 28 Mesh of Computational Domain

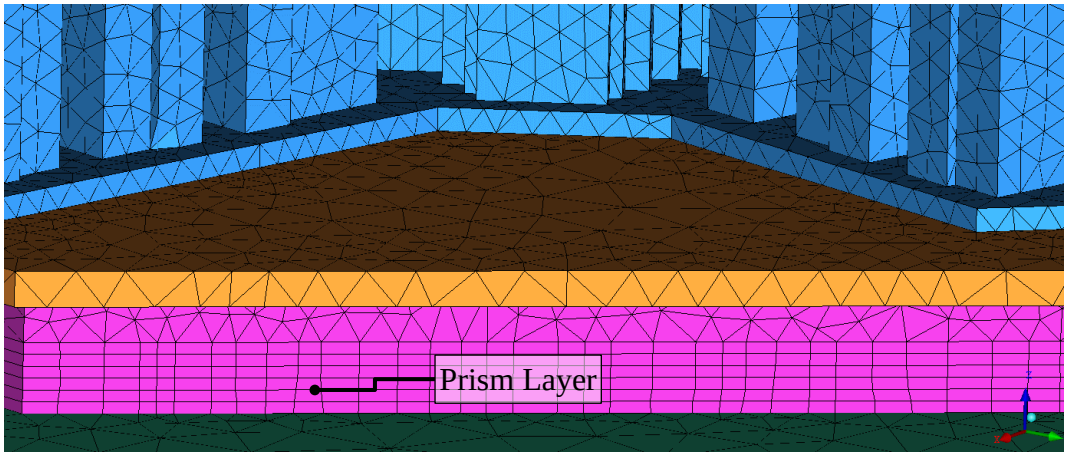

Figure 29 Prism Layers

Table 3 Detail parameters to be adopted in the CFD

	CFD Model
Physical Model Scale	Real model, 1:1 scale
Model details	Only include Topography, Buildings blocks, Streets/Highways, no landscape is included
Domain	5200m(L) x 5200m(W) x 4000m(H)
Assessment Area	1H from Site Boundary
Surrounding building Area	2H from Site Boundary
Grid Expansion Ratio	The grid should satisfy the grid resolution requirement with maximum expansion ratio = 1.3
Prismatic layer	6 layer of prismatic layers and 0.5m each (i.e. total 3m above ground)
Inflow boundary Condition	Incoming wind profile approximated as described in Wind Profile Section
Outflow boundary	Pressure boundary condition with dynamic pressure equal to zero
Wall boundary condition	Logarithmic law boundary
Solving algorithms	Rhie and Chow SIMPLE for momentum equation Hybrid model for all other equations Releasable k-ε turbulent model
Blockage ratio	< 3%
Convergence criteria	Below $0.5x10^{-3}$

5.3 AVA Indicator

The wind speed information at pedestrian level (2m above ground) will be acquired to determine the Wind Velocity Ratio (*VR*) as stipulated in the *AVA Technical Circular*[1] and as defined as follows:

$$VR = \frac{V_p}{V_\infty}$$

where V_p is the wind speed at the pedestrian height (2m above ground) and V_∞ is the wind velocity at the top of the boundary layer (defined as the height where wind is unaffected by urban roughness and determined by the topographical studies). Measurement will be taken within the Assessment Area.

The Average VR is defined as the weighted average VR with respect to the percentage of occurrence of all considered wind directions. This gives a general idea of the ventilation performance at the considered location at both annual and summer wind condition.

5.3.1 Assessment Parameters

CFD simulations will be conducted to study the wind environment. As specified in the *AVA Technical Circular*, indicator of ventilation performance should be the Wind Velocity Ratio (VR), defined as the ratio of the wind velocity at the pedestrian level (2m above ground) to the wind velocity at the top of the wind boundary layer. Site spatial average velocity ratio (SVR) and a Local spatial average velocity ratio (LVR) should be determined.

Table 4 Terminology of the AVA Initial

Terminology	Description
Velocity Ratio (VR)	The velocity ratio (VR) represents the ratio of the air velocity at the measurement position to the value at the reference points.
Site spatial average velocity ratio (SVR)	The SVR represent the average VR of all perimeter test points at the site boundary which identified in the report.
Local spatial average velocity ratio (LVR)	The LVR represent the average VR of all points, i.e. perimeter and overall test points at the site boundary which identified in the report.

5.4 Locations of Test Points

As per the *AVA Technical Circular*, two types of test points – perimeter test point and overall test point will be adopted to assess the wind performance within the Assessment Area. Special test points are supplemented to assess the effectiveness of the air paths. The allocation of these test points will be distributed evenly as stated in the *AVA Technical Circular* [1].

5.4.1 Perimeter Test Points

A total number of 40 perimeter test points (**Red spots**), namely P points, are positioned at intervals of around 15m along the project site boundary in accordance with the *AVA Technical Circular*[1]. The locations of perimeter test points are shown in Figure 30.

5.4.2 Overall Test Points

A total number of 84 overall test points (**Black spots**), namely O points, are evenly distributed in District Open Areas within the assessment area, such as the streets and places where pedestrian frequently access. Their locations are shown in Figure 30.

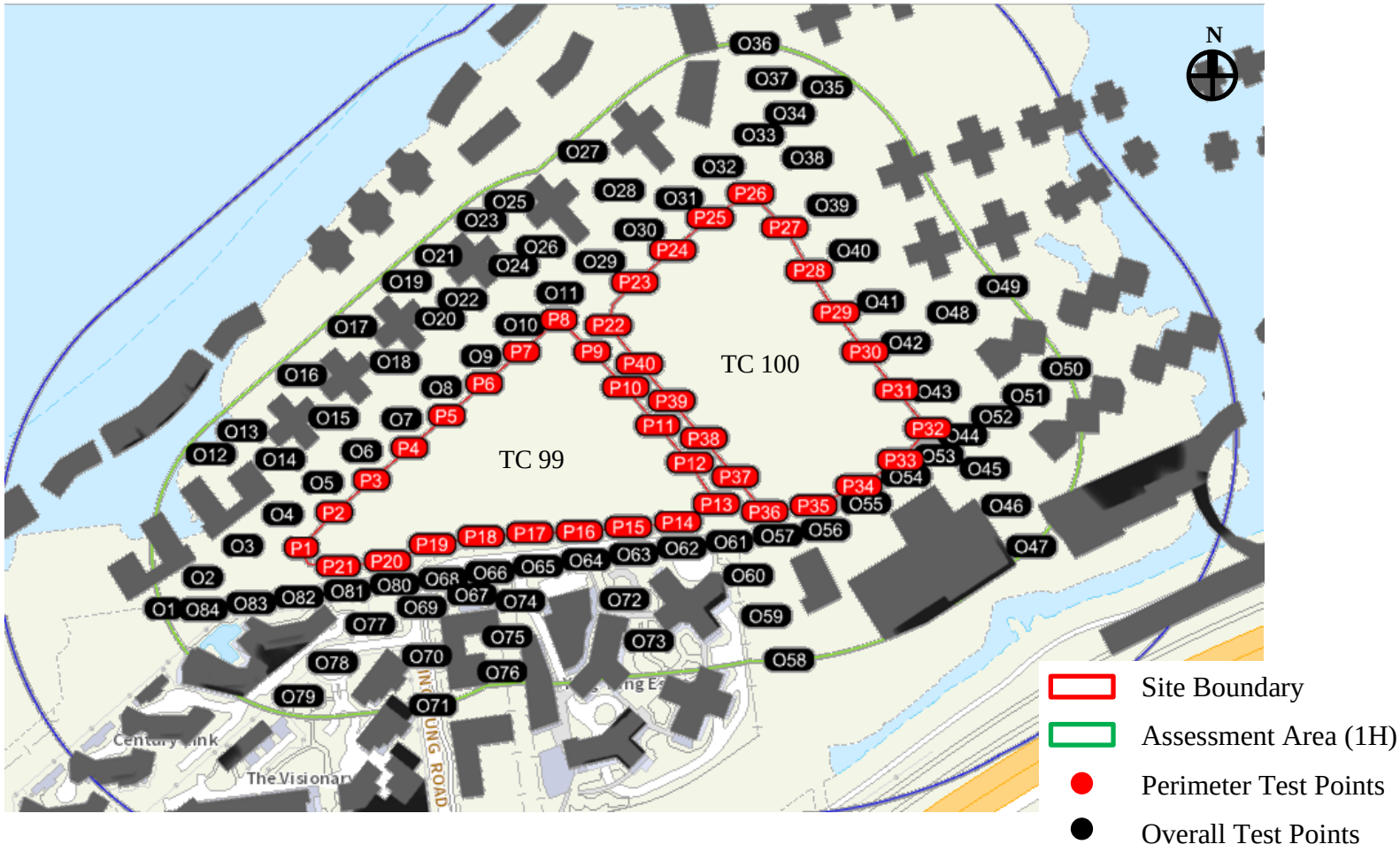

Figure 30 Location of Perimeter and Overall Test Points

5.5 Focus Areas

Within the proposed Assessment Area given in Figure 30, a total of 13 focus areas are proposed within the application site. The associated test points for focus areas are tabulated in Table 5. The location of the focus areas area shown in Figure 31.

Table 5 Focus Areas and Corresponding Test Points

	Focus Area	Test Points
1	TC99 North District Open Area	O1 - O11, P1-P7
2	Lot 103	O12 - O24
3	Lot 109	O25 – O28
4	Road D4	O29 - O35, P23 – P25
5	Road D5	O34, O36 – O47, P27 – P32
6	Road L8	O48 – O49
7	Road L5	O50 – O57, P33 – P35
8	New Road South	O58 – O60
9	Ying Tung Road	O61 – O71, P14 – P19
10	Ying Tung Estate	O72 – O73
11	New School	O74 – O76
12	The Visionary	O77 – O84, P20 – P21
13	Road L4	P8 – P13, P22, P36 – P40

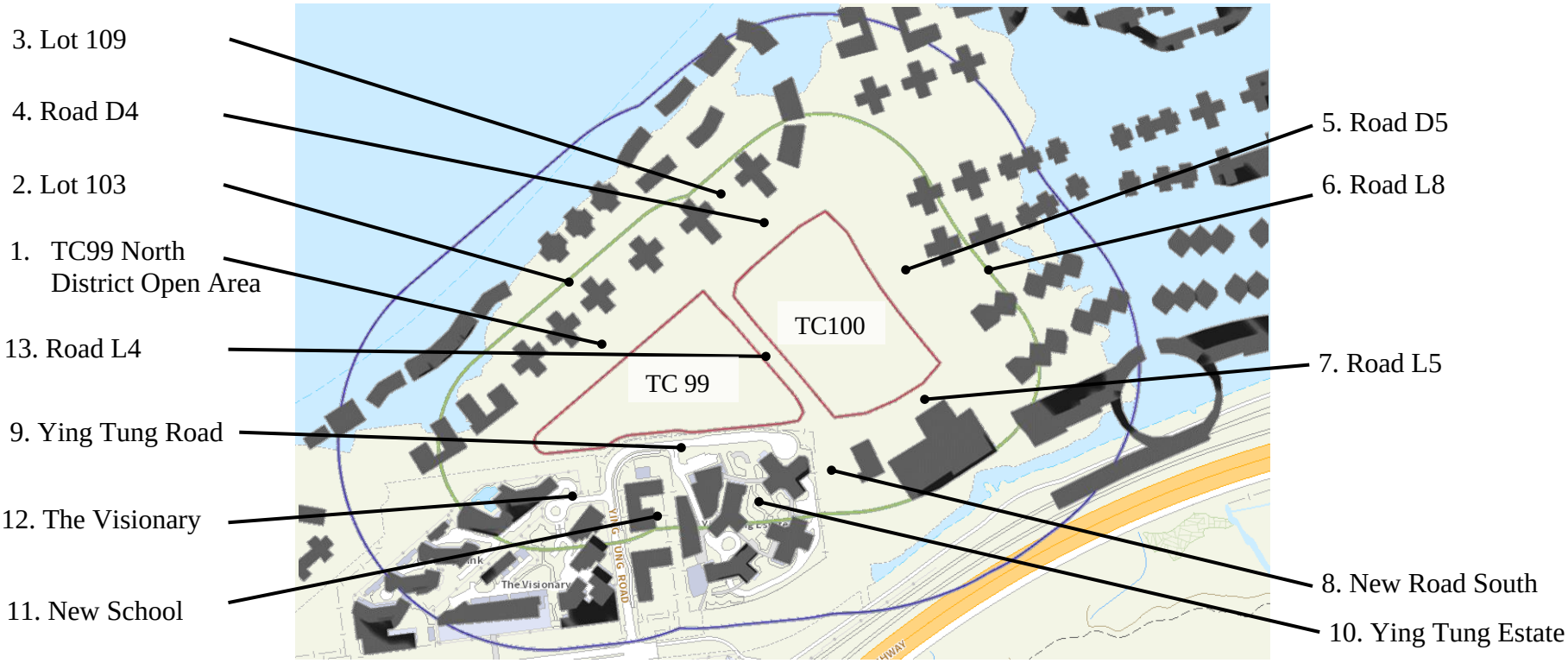

Figure 31 Location of Focus Areas outside the Application Site

6 Results and Discussion

The contour and vector plots for each studied wind directions may refer to Appendix B and Appendix C of this report.

6.1 Annual Weighted Average VR

The contour plots of annual weighted VR for the Baseline scheme and Proposed scheme are shown in Figure 32 and Figure 33.

The majority of the annual prevailing winds comes from the eastern quadrant, which flows along Roads D1 and L8 and along the NBA of TC100 towards the central District Open Areas of TC99. The reorientation of the blocks in TC99 and TC100 in the Proposed scheme, as well as the redistributed podium massing across both sites increases the wind permeability of the development.

During Southerly winds, the increased separation between TC100 and the Future Commercial Development to the South, as well as the reorientation of Blocks 1 and 2 in TC100, increase the downwash on Road L5 (red circle).

The reoriented blocks along Road L4 create a clearer wind path, (purple circle), which facilitates wind penetration to the leeward side, resulting in higher VR in areas such as the Lot 109 (orange circle).

The permeable PTI in the Proposed scheme facilitates southerly winds to enter the development. This encourages more wind flow along Ying Tung Road at the pedestrian level, leading to an improved VR in upwind areas around The Visionary and Ying Tung Road (**black** circle).

On the other hand, the introduction of a much taller Block 5 in TC99 in the Proposed scheme redirects southerly winds into the development. This has the effect of reducing the wind that reaches the District Open Area on leeward side which therefore has a slightly better VR in the Baseline scheme (blue circle).

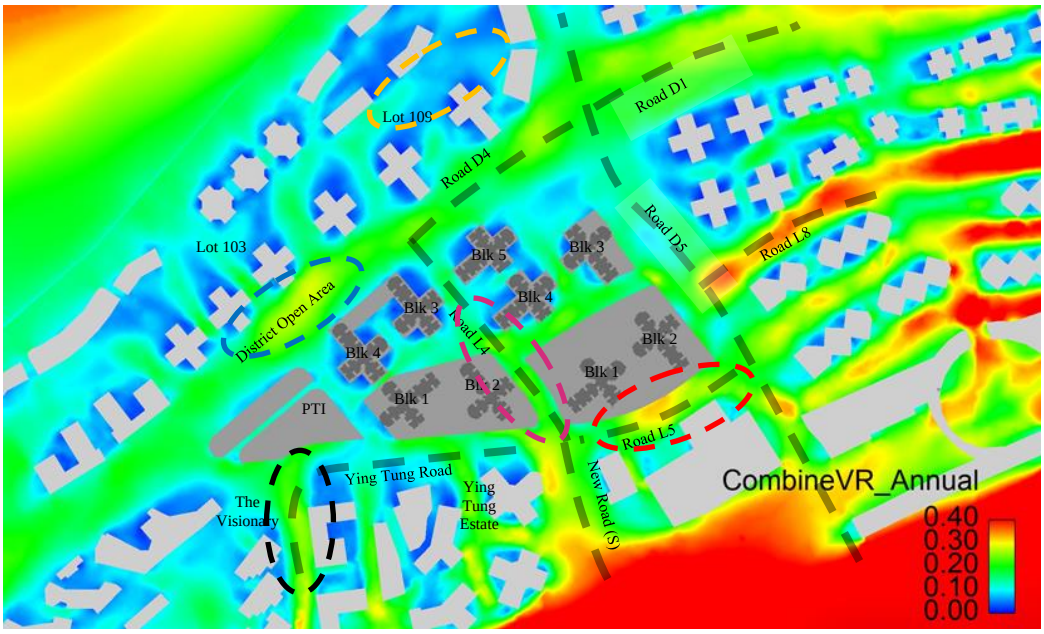

Figure 32 Contour Plot for Annual Weighted Average VR for Baseline scheme

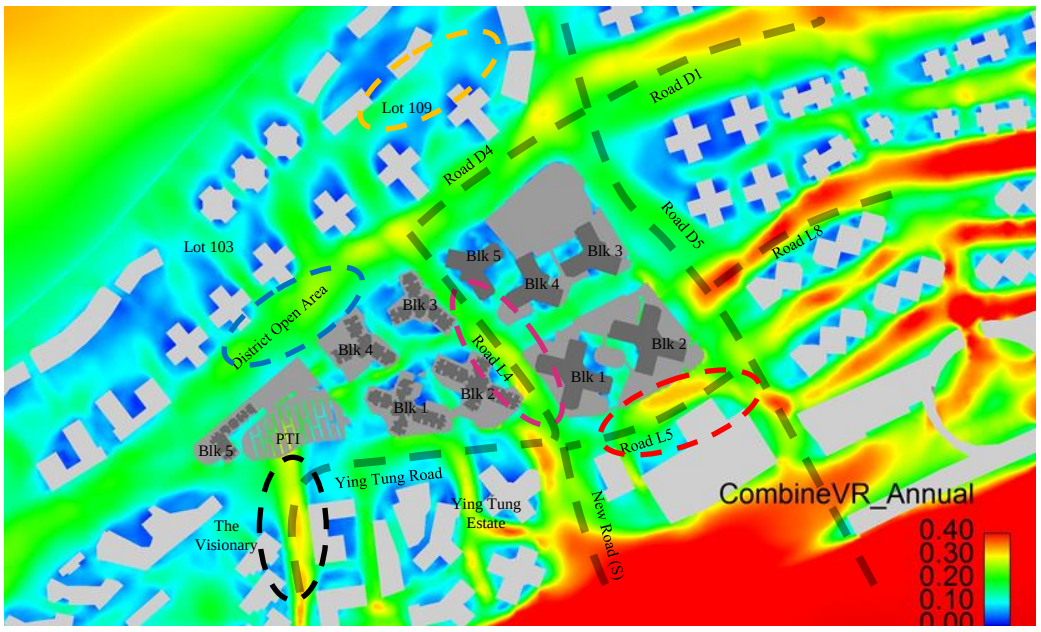

Figure 33 Contour Plot for Annual Weighted Average VR for Proposed scheme

6.2 Summer Weighted Average VR

The contour plots of summer weighted VR for the Baseline scheme and Proposed scheme are shown Figure 34 and Figure 35.

The majority of the summer prevailing winds comes from the southern quadrant. The upstream buildings of the Ying Tung Estate and the Visionary, as well as the Future Commercial Development, have a significant effect on the winds which reach the development – the wind approaches along distinct paths such as Ying Tung Road, New Road (S) and Road D5.

For the Proposed scheme, by reorienting Block 2 of TC99 and redistributing the podium massing on the South Eastern corner of TC99, obstructions to the wind path along Road L4 are removed and the quality of the wind path is significantly improved (**black** circle). Furthermore, reorienting Block 1 and 2 of TC100 increases the downwash onto Road L5, improving the wind environment along Road L5 (green circle).

In the Proposed scheme, the reshaping of Block 1 and 2 of TC99 also increases the downwash onto Ying Tung Road (brown circle).

On the other hand, in the Proposed scheme, the introduction of Block 5 in TC99 and the increased building separation between Block 1 and Block 4 in TC99, redirects the Southerly wind into the centre of the development. This means that less wind reaches the District Open Area, leading to a lower VR there in the Proposed scheme (purple circle).

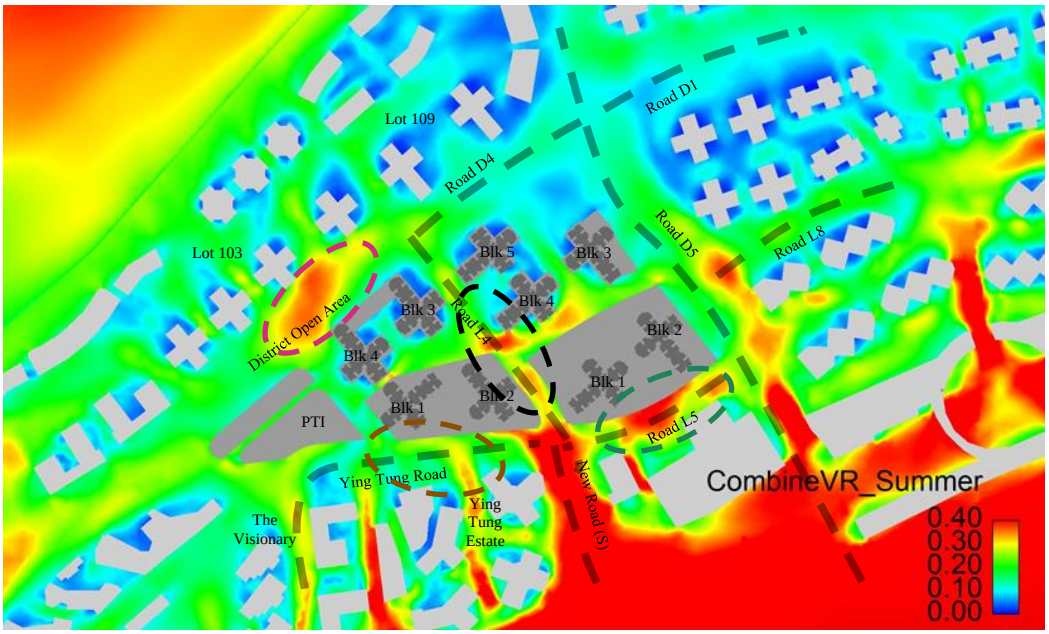

Figure 34 Contour Plot for Annual Weighted Average VR for Baseline scheme

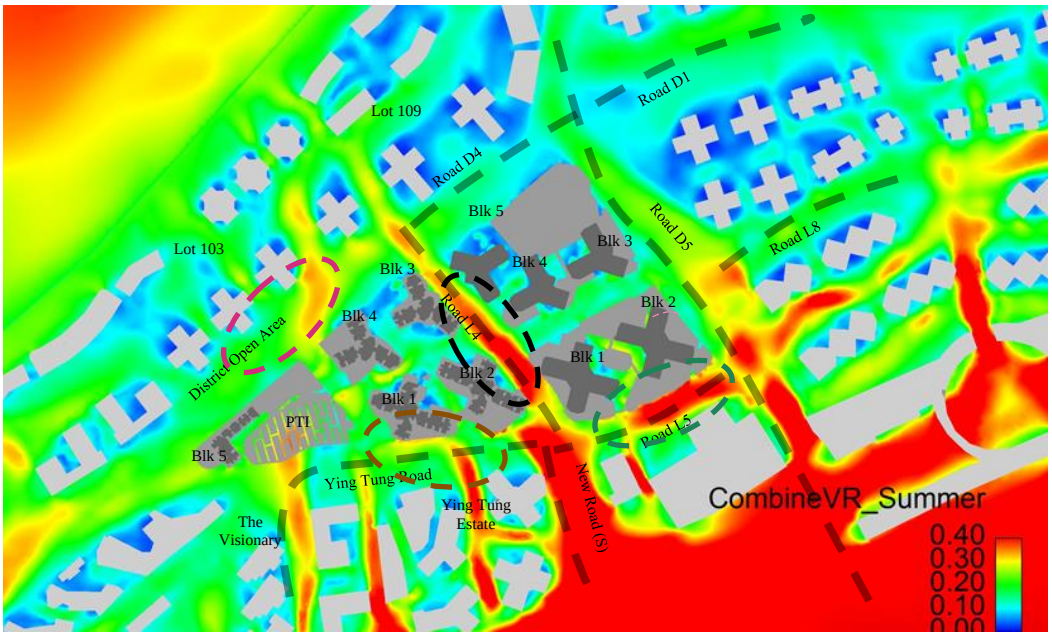

Figure 35 Contour Plot for Annual Weighted Average VR for Proposed scheme

6.3 Directional Analysis

6.3.1 NNE Wind Direction

Under NNE wind, the incoming wind travels along Road D1 and North section of Road D5 towards the development. A wind entrance is created by Blocks 3 and 5 in TC100 where the wind is channelled through the development (**black** arrow). A portion of the wind passes through the building separation between Blocks 3 and 4 towards the NBA while another portion passes through the building separation between Blocks 4 and 5 and across Road L4 into TC99. The permeability of the development allows the NNE wind to penetrate through, providing a positive wind condition on the leeward side of the development as can be seen on Ying Tung Road. Some of the NNE wind is also downwashed on the North-East face of Block 3 of TC100, adjacent to Road D5.

A secondary wind path approaches TC100 along Road L8 is deflected south by Block 2 (purple arrow). This portion of wind travels along Road D5, where it is deflected by the 160mPD Future Commercial Development along Road L5.

A portion of the NNE wind approaching from the sea filters through Lot 103 and Lot 109. This windstream reaches the northside of TC99 where it downwashes onto Road D4 and the District Open Area.

Baseline scheme

As the incoming NNE wind reaches TC100, the smaller podium and the separation between Blocks 3 and 4 allows the wind to effectively enter the development. The better penetration here is offset by the large podium below Blocks 1 and 2 which effectively obstructs this wind path, causing a wind shadow on the Ying Tung Road and New Road (S) (brown circle).

Proposed scheme

The enhanced separation between the Future Commercial Development and Block 2 of TC100 created by reorienting the block and increasing the setback from Road L5 widens the wind path, improving the wind environment along Road L5 (red arrow). The chamfered edge of the podium in the Proposed scheme also facilitates a smoother wind path towards Road L5 which improves the wind environment along New Road (S) and Ying Tung Road (brown circle).

The car park at the north side of TC100 helps to redirect wind along Road D4. Due to the larger quantity of diverted wind, the District Open Area has an improved wind environment (pink circle).

The increased permeability of the TC99 development allows the wind from TC100 and the District Open Area to penetrate the development and reach Ying Tung Road, enhancing the wind environment (brown circle).

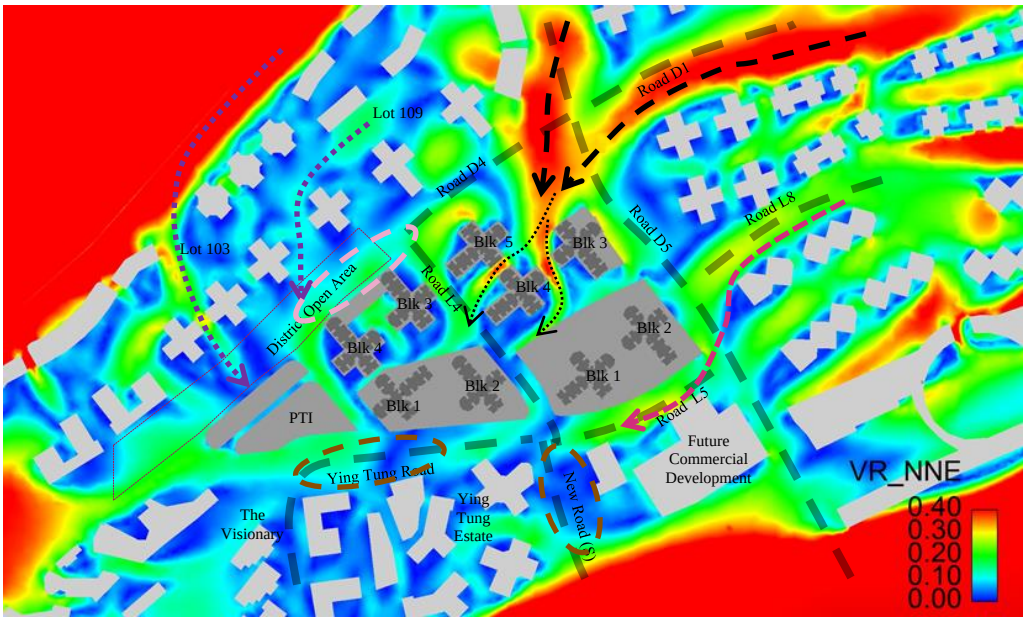

Figure 36 Contour Plot of VR for Baseline scheme under NNE Wind

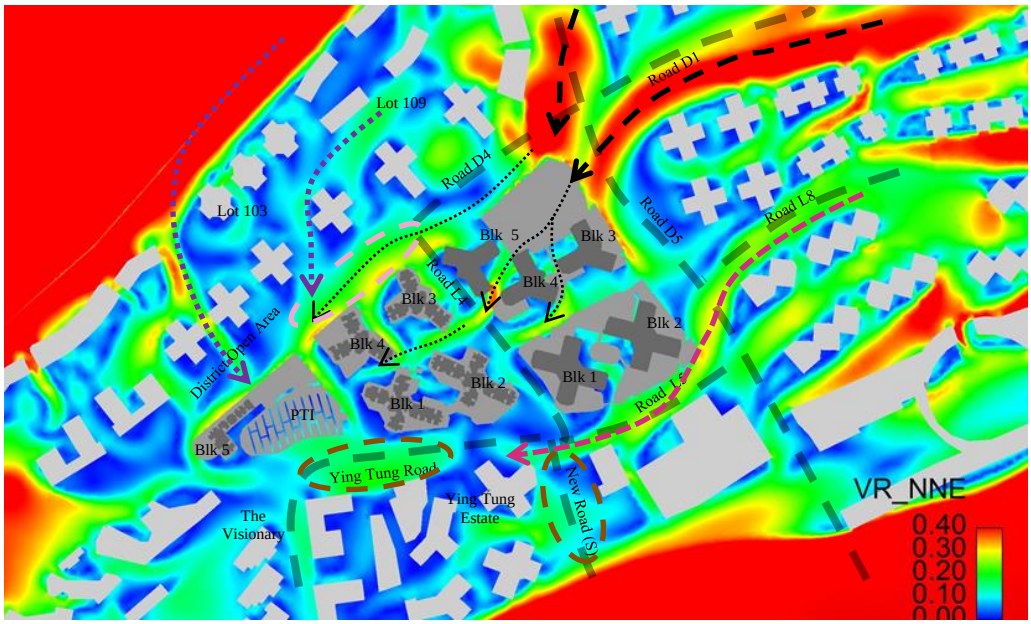

Figure 37 Contour Plot of VR for Proposed scheme under NNE Wind

6.3.2 NE/ENE Wind Direction

Under NE/ENE wind, a large wind path travel along Roads D1 and D4. This, however, does not interact significantly with the development. A majority of the wind travels along Road L8 where it is downwashed by Blocks 2 and 3 of TC100 onto Road D5 (pink circle).

This wind path is also partially redirected either side of the podium below Block 2 in TC 100. The wind directed along the NBA in the middle of TC100 further penetrates through to TC99. The wind redirected to Road L5 where this wind path is downwashed by the Future Commercial Development.

Baseline scheme

A greater proportion of the wind from Road L8 enters the NBA of TC100 as opposed to being downwashed onto Road 5. The NBA in TC100 is aligned with building separation between Blocks 2 and 3 in TC99 to form an extensive wind path through the development. As the wind permeates through TC99, it's progress is impeded by the podium between Blocks 2 and 3.

Proposed scheme

The reoriented Blocks 2 and 3 of TC100 capture more prevailing wind, causing significantly more downwash and redirecting the wind down to the pedestrian level. Combined with the extensive podium frontage, the wind environment along Road D5 is improved (orange circle).

The reorientation of Block 4 of TC100 and the reduced mass of the podium below Blocks 1 and 2 in TC99 improves the wind path along the NBA. The removal of the podium between Blocks 3 and 4 of TC99 allows the wind to penetrate towards the District Open Area and re-joins the main wind path along Road D4, enhancing the wind environment in the District Open Area (pink circle).

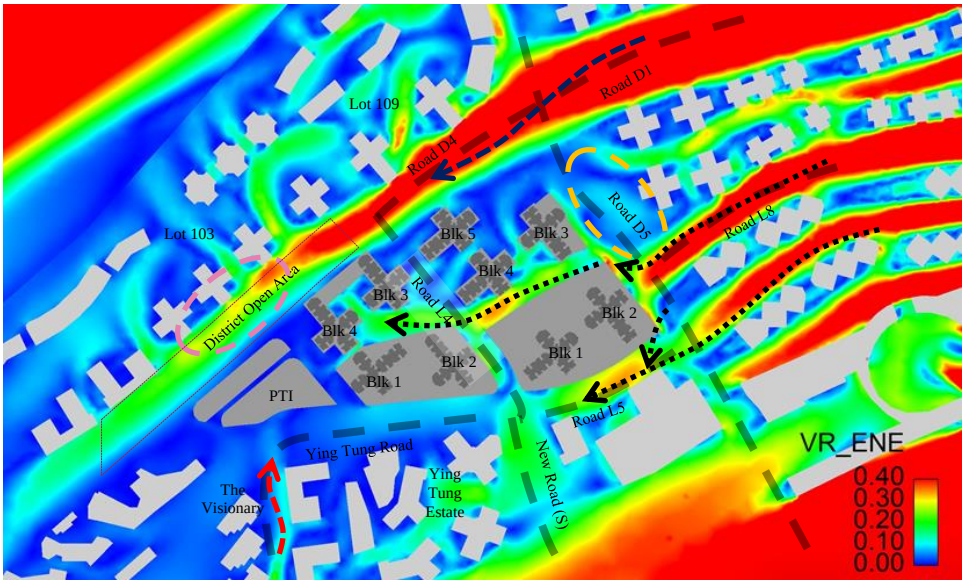

Figure 38 Contour Plot of VR for Baseline scheme under ENE Wind

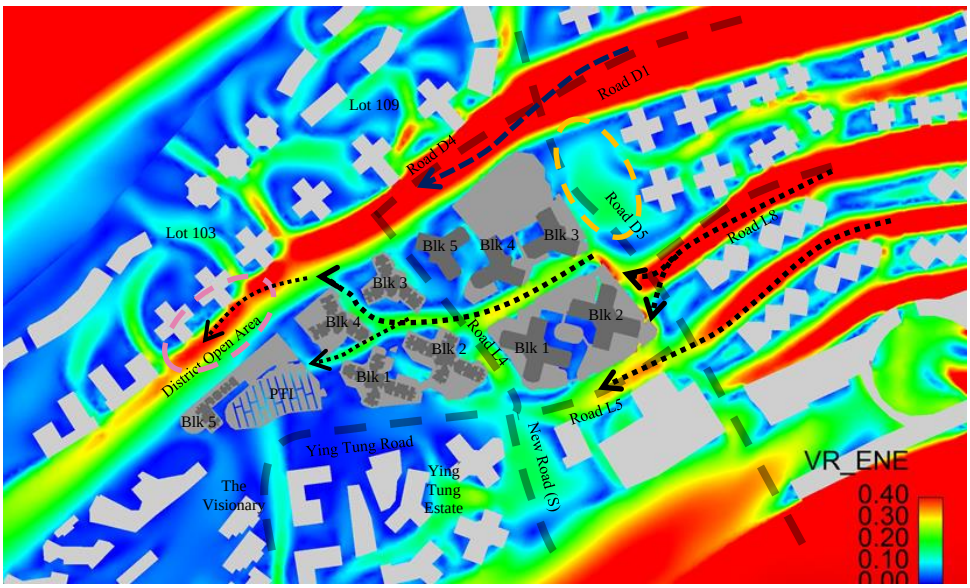

Figure 39 Contour Plot of VR for Proposed scheme under ENE Wind

6.3.3 E/ESE Wind Direction

There are a large number of wind paths that come into contact with the development. One portion of the E/ESE wind travels along Road L8 and is diverted both north along Road D5 by Blocks 2 and 3 of TC100 and along the TC100 NBA where it permeates through the development. A second stream reaches the South-eastern corner of TC100 where the podium redirects the wind path along Road L5.

The majority of the ESE wind travels along the North Lantau Highway and reaches the southern edge of TC99 via two major wind paths. One portion travels along Road L4 through to the leeward side of the development, predominantly Road D4. Another portion is redirected by the podium below Blocks 1 and 2 along Ying Tung Road and is channelled through the NBA of TC99.

The final major wind path comes along the North-South section of Ying Tung Road, between The Visionary and Ying Tung Estate. This wind path passes over the low level PTI, reaching the NBA of TC99, through to the District Open Area on the leeward side.

Baseline scheme

As the incoming ESE wind reaches TC100, the NBA and building separation allow wind penetration through the development (purple arrow). The orientation of Block 3 of TC100 effectively redirects the wind stream north along Road D5 (orange arrow).

At TC99, the NBA and low height covered PTI and retail block allow the wind approaching from the south to pass over the development, providing a quality wind environment across the District Open Area and Lot 103 (purple arrow).

Proposed scheme

At TC99, the incoming wind from Ying Tung Road passes through the permeable PTI and is also diverted by Block 5 of TC99 to the centre of the development. There is less wind penetration towards the leeward areas such as the District Open Area and Lot 103. Above the podium of Block 5, at the eastern side, the wind can pass over and reach the pedestrian level at Lot 109 (purple arrow).

The introduction of Block 5 redirects wind coming from the North-South section of Ying Tung Road. This improves the wind environment for The Visionary. Because more wind is diverted in this direction, less wind reaches the District Open Area (red circle).

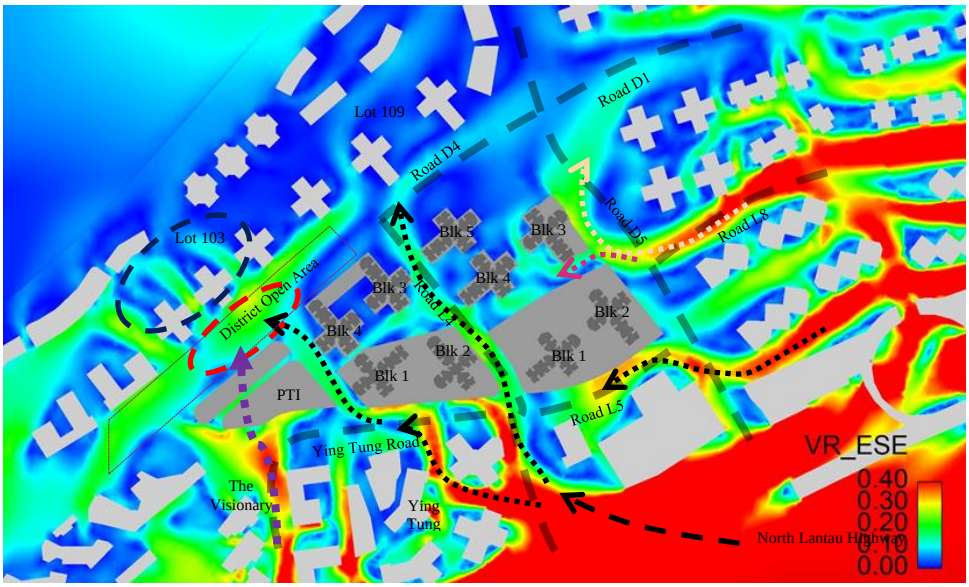

Figure 40 Contour Plot of VR for Baseline scheme under ESE Wind

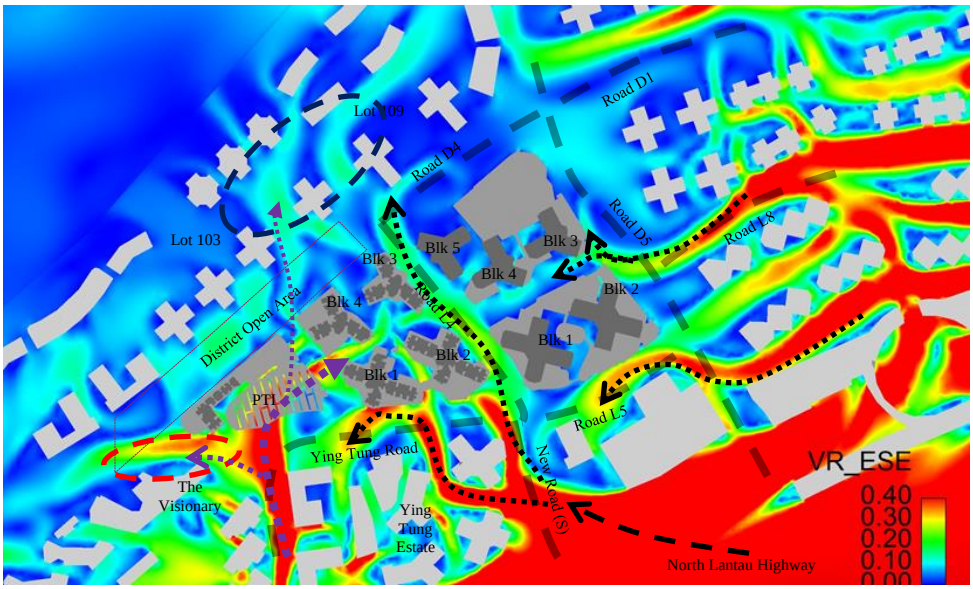

Figure 41 Contour Plot of VR for Proposed scheme under ESE Wind

6.3.4 SE/SSE/S Wind Direction

Under SE/SSE/S wind, the incoming wind travels along roads parallel to the wind direction such as Ying Tung Road and New Road (s). The major wind path travels from New Road (S), directly down Road L4 which separates TC99 and TC100. This travels to the leeward side uninterrupted to Lot 109 and Road D4.

Another major wind path travels along the North-South portion of Ying Tung Road where is passes over the low-level PTI. This wind path continues across the District Open Area and passes through Lot 103 and Lot 109. The Blocks of Lot 103 also cause significant downwash onto the District Open Area.

Baseline scheme

At TC99, the NBA and low height covered PTI and retail block allow the SSE wind from Ying Tung Road to pass over the development, providing a quality wind environment across the eastern side of the District Open Area and Lot 103 (blue arrow).

Proposed scheme

The windstream from Ying Tung Road is redirected towards the centre of the development by the mid-level section of the new Block 5 in TC99. A wind path is created between Block 5 and Block 4 of TC99 which continues through to Lot 103 (white arrow). There is significant downwash onto the District Open Area by the buildings in Lot 103 (purple circle).

The major wind path passing from New Road (S) to Road L4, penetrates further into Lot 109 because of the clearer wind path. Block 3 in TC99 and Block 5 in TC100 are oriented parallel to the wind path which facilitates this penetration (**black** arrow**)**.

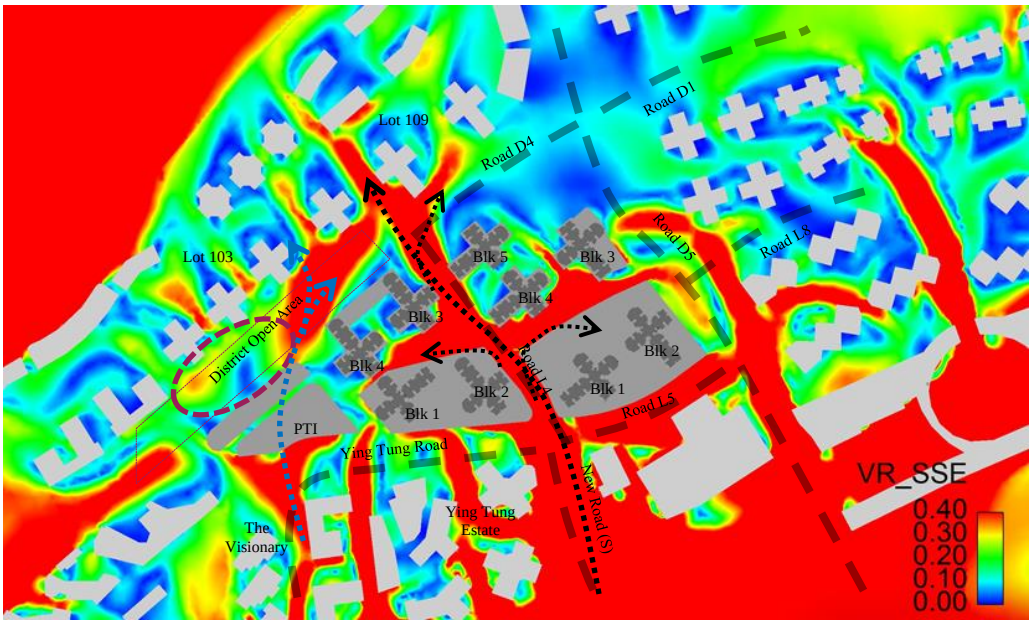

Figure 42 Contour Plot of VR for Baseline scheme under SSE Wind

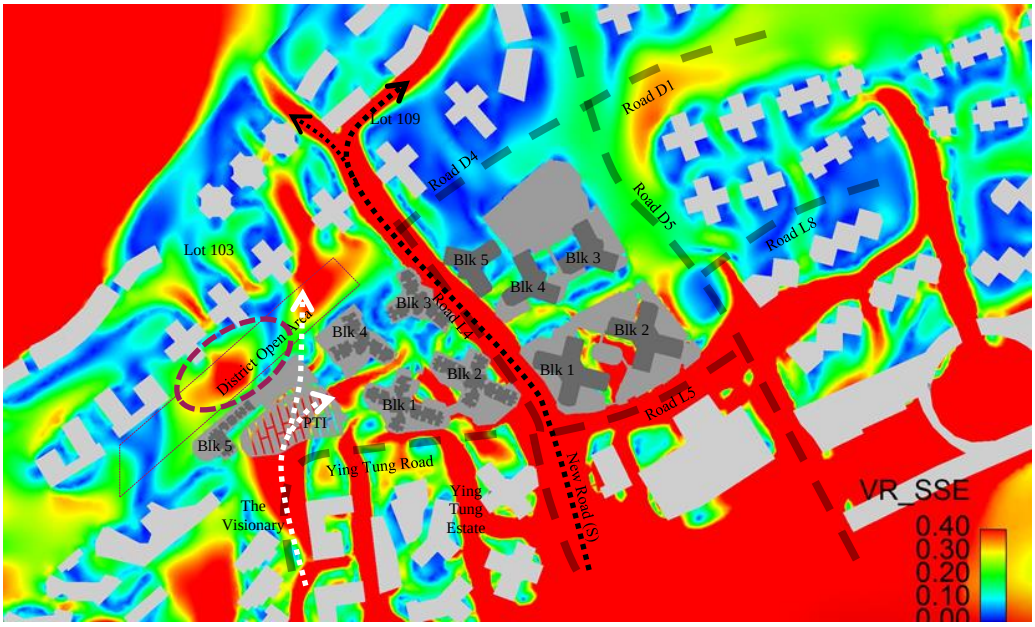

Figure 43 Contour Plot of VR for Proposed scheme under SSE Wind

6.3.5 SSW Wind Direction

Under the SSW wind direction, wind filters through developments to the South. One major wind path follows Road D5, to the east of TC100.

Another wind path approaches via New Road (S) and follows Road L4 through to the leeward side of the development in Lot 109 and Road D4. Wind approaching from the same area also filters between the Future Commercial Development and is redirected by the podium below Blocks 1 and 2 in TC100 along Road L5.

The SSW wind that approaches via Ying Tung Road filters through the NBA of TC99 to the District Open Area.

Baseline scheme

The wind path adjacent to the Future Commercial Development is interrupted by the bulky podium underneath and Blocks 1 and 2 of TC100 (blue arrow). The lack of building set back from this Road L5 and lack of permeability of the development causes significant downwash back onto Road L5. The orientation of Block 2 blocks some SSW wind from travelling along Road D5 (purple circle).

The low-level PTI in TC99 and the NBA of TC99 allow the SSW wind to effectively permeate through the development to the leeward side, reaching the District Open Area, Lot 103 and Lot 109 (pink arrows).

Proposed scheme

The reorientation and reshaping of Block 2 of TC99 and Block 1 of TC100 improves the wind path along Road L4 (orange path). The progress of this wind path is facilitated by the reorientation of Block 3 of TC99 and Block 5 of TC100 which further encourages the wind through to the leeward side at Road D4.

The permeable podium below Blocks 1 and 2 allows some wind to penetrate through the development (purple circle). This has the effect of improving the wind environment of Road L5 and limiting interference on the Road D5 wind stream. This allows the Road D5 windstream to penetrate further to the north (**black** circle).

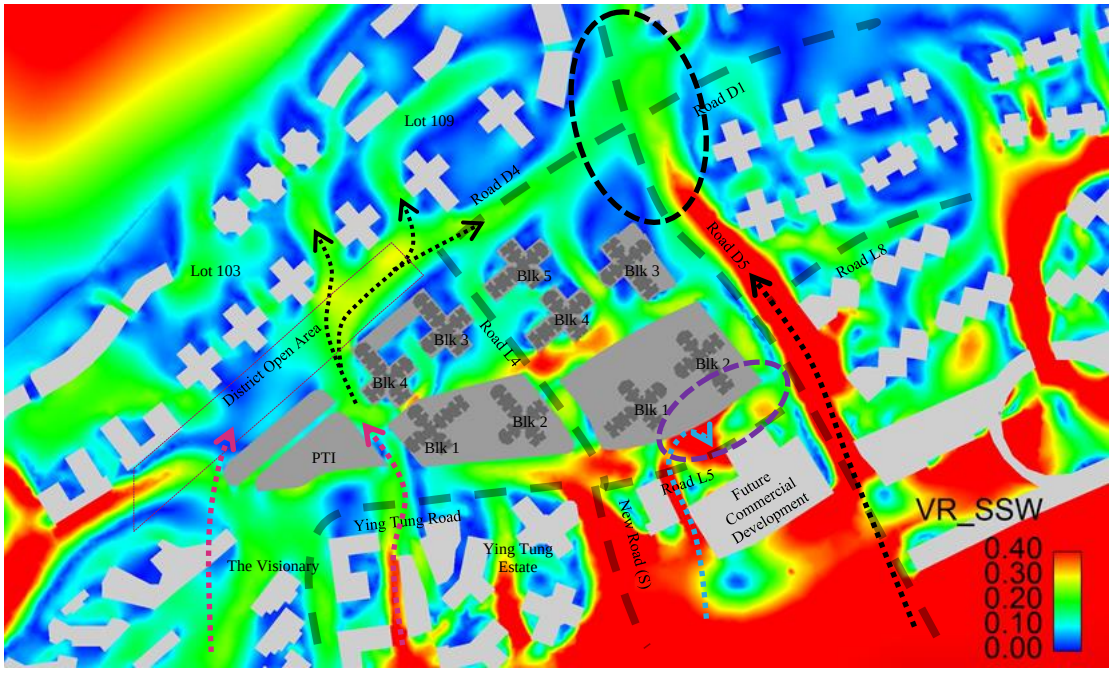

Figure 44 Contour Plot of VR for Baseline scheme under SSW Wind

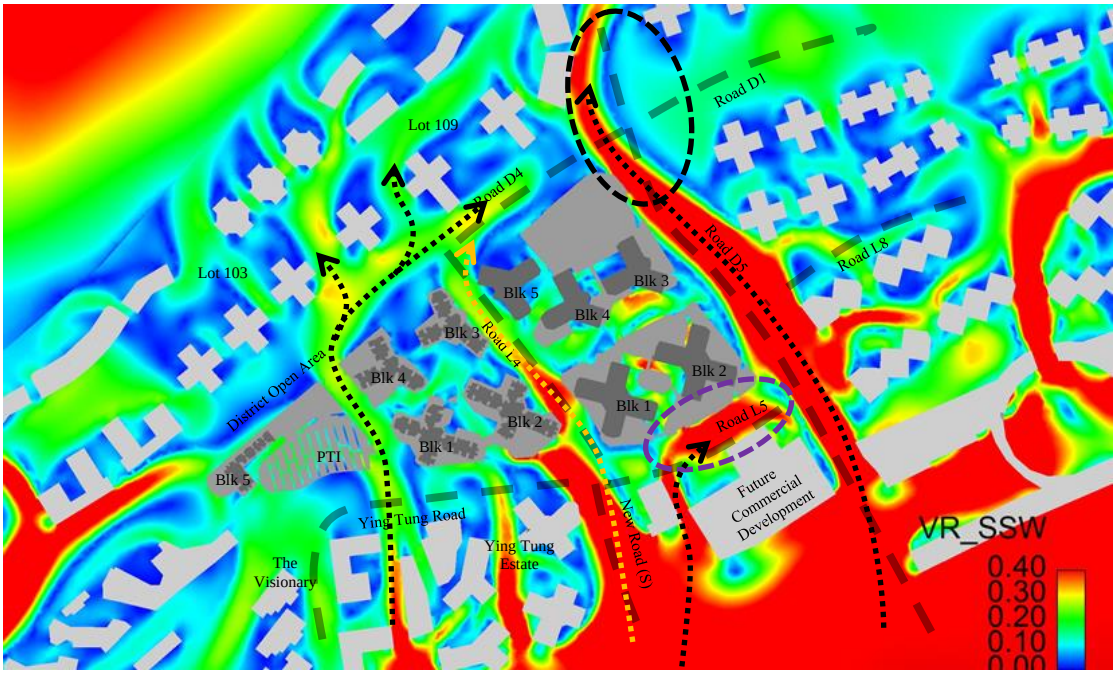

Figure 45 Contour Plot of VR for Proposed scheme under SSW Wind

6.3.6 SW/WSW Wind Direction

Under SW wind conditions, the incoming is redirected either side of the development by the western edge (Block 5 in Proposed Scheme / Retail Block in Baseline Scheme) in of TC99, forming wind paths to the north and to the south of the development. The prevailing wind diverted to the north to travel along the District Open Area and then downwash at the vicinity of Block 4 of TC99. The prevailing wind diverted to the south would travel towards Ying Tung Road and The visionary.

Baseline scheme

As the incoming SW/WSW wind reaches TC99, it passes over the low-level retail block and PTI. One portion of wind to the north is downwashed (**black** circle) by Block 4 onto the District Open Area, before continuing along to Road D4 and the north-side of TC100 (orange circle).

Another portion to the South is downwashed by Block 1 of TC99 onto Ying Tung Road, before continuing along to Road L5 (red circle).

Without Block 5 in TC99, less wind is diverted south onto Ying Tung Road. This improves the wind condition at Road L5, New Road (S) and Road D5 (white circles).

Proposed scheme

The introduction of Block 5 in TC99 causes a large change in the wind environment surrounding the development. The incoming SW wind is primarily redirected north through the District Open Area. This wind path is aided by the lengthened low-level car park at the north edge of TC100 (orange circle).

Another portion travels through the PTI, with the enhanced building separation between Blocks 1 and 4 of TC99 increasing the permeability of the development. This allows this wind path to penetrate through to Road L4, enhancing the wind environment (purple arrow).

Block 5 also diverts a portion of the wind south along Ying Tung Road. This improves the wind condition in this area but means less wind reaches Road L5, New Road (S) and Road D5 (white circles).

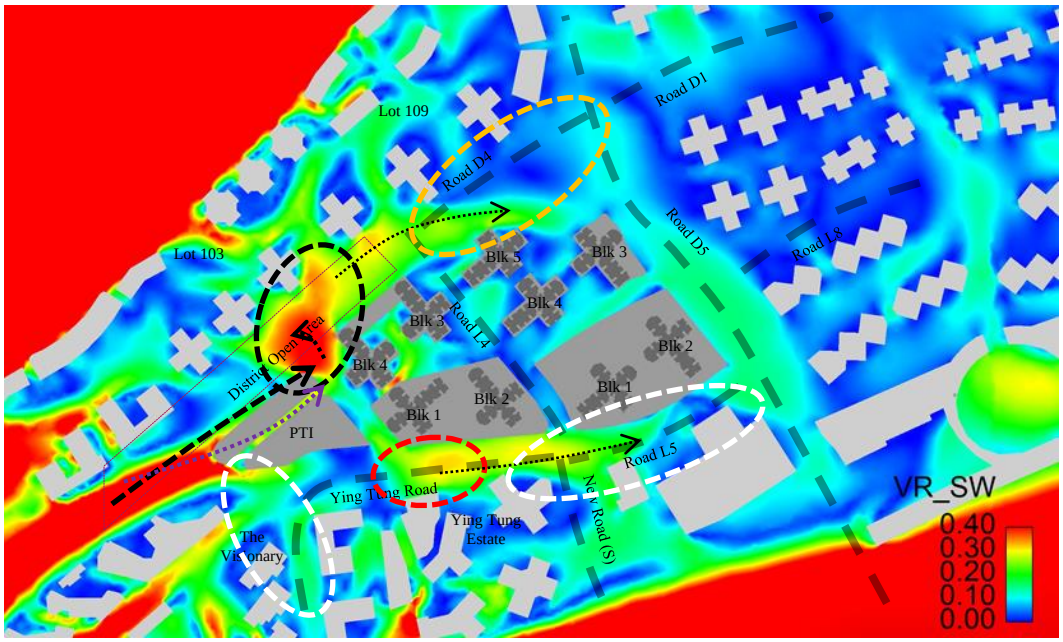

Figure 46 Contour Plot of VR for Baseline scheme under SW Wind

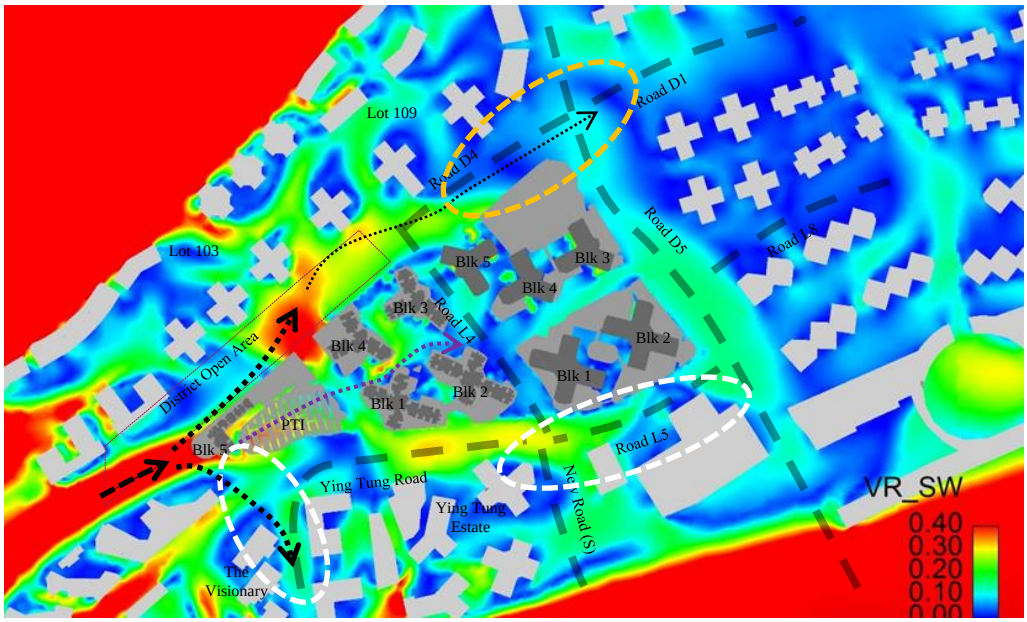

Figure 47 Contour Plot of VR for Proposed scheme under SW Wind

6.4 VR Results of Test Points

Table 6 summarizes the values of SVR and LVR among Baseline scheme and Proposed scheme. The VR of individual test points may refer to Appendix D of this Report.

Table 6 Comparison of the SVR and LVR among Baseline scheme and Proposed scheme

	Annual Weighted VR		Summer Weighted VR	
	Baseline scheme	**Proposed scheme**	**Baseline scheme**	**Proposed scheme**
SVR	0.17	0.18	0.22	0.24
LVR	0.18	0.19	0.23	0.24

Under annual condition, Proposed scheme obtained a slightly higher SVR and LVR comparing to Baseline scheme. The result indicates that the Proposed scheme would achieve a slightly better wind environment in areas in close proximity to the development as well as the Assessment Area. Through the detailed discussion in Section 0, the major reason for the slightly higher ventilation would be due to the wind downwashed by reoriented building blocks and revised building shape.

The reorientation and reshaping of Blocks in both TC99 and TC100 also significantly improve the width, alignment and therefore quality of the wind paths throughout the development. This can be seen especially in focus areas close to the development, such as Road L4, which sees significant improvements through clearer wind paths.

Under summer condition, Proposed scheme obtained a slightly higher SVR and LVR comparing to Baseline scheme. The result indicate that the Proposed scheme would achieve a slightly better wind environment at close proximity and the Assessment Area. Winds channelled by developments to the South are facilitated to travel along Road L4 by the podium mass redistribution below TC99 and TC100, as well as the reoriented Blocks, as a result a higher SVR and LVR would be achieved by Proposed scheme.

6.5 Focus Areas

There are a total of 19 focus areas identified within the Assessment Area for this study. Table 7 summarized the Spatial Average VR (SAVR) for each focus areas under annual and summer conditions.

Table 7 Spatial Averaged VR (SAVR) for Each Focus Area

Focus Areas		Annual Condition		Summer Condition	
		Baseline scheme	Proposed scheme	Baseline scheme	Proposed scheme
1	District Open Area	0.18	0.18	0.22	0.21
2	Lot 103	0.14	0.14	0.20	0.20
3	Lot 109	0.12	0.13	0.15	0.16
4	Road D4	0.20	0.21	0.14	0.13
5	Road D5	0.18	0.20	0.19	0.23
6	Road L8	0.31	0.31	0.27	0.25
7	Road L5	0.27	0.27	0.33	0.36
8	New Road South	0.28	0.29	0.45	0.47
9	Ying Tung Road	0.17	0.19	0.24	0.25
10	Ying Tung Estate	0.20	0.22	0.25	0.28
11	New School	0.15	0.15	0.27	0.26
12	The Visionary	0.14	0.14	0.21	0.21
13	Road L4	0.17	0.21	0.25	0.32

6.5.1 Annual Condition

In general, the Baseline and Proposed schemes achieve a similar average VR for the following focus areas: District Open Area, Lot 103, Road L8, Road L5, New School and The Visionary. This indicates that the ventilation performances are considered comparable in the aforementioned areas.

Proposed scheme has a higher VR for Lot 109, Road D4, Road D5, New Road South, Ying Tung Road, Ying Tung Estate and Road L4.

6.5.2 Summer Condition

In general, the Baseline and Proposed schemes achieve a similar average VR for the following focus areas: Lot 103 and The Visionary. This indicates that the ventilation performances are considered comparable in the aforementioned areas.

Proposed scheme has a better ventilation performance at Lot 109, Road D5, Road L5, New Road South, Ying Tung Road, Ying Tung Estate, Road L4.

Baseline scheme would have a slightly higher VR at the District Open Area, Road D4, Road L8 and the New School.

7 Conclusion

7.1 Overview

An Air Ventilation Assessment (AVA) – Initial Study was conducted to assess the ventilation performance of Baseline scheme and Proposed scheme in accordance with the *AVA Technical Circular*

Two schemes were assessed using Computational Fluid Dynamics (CFD) techniques. A series CFD simulation using Realizable k-ε turbulence model were performed under annual and summer wind conditions with reference to the *AVA Technical Circular No. 1/06*. For annual wind condition, NNE, NE, ENE, E, ESE, SE, S, SSW and SW were selected which gives total wind frequency of 79.9% over a year while E, ESE, SE, SSE, S, SSW, SW and WSW were selected for summer condition, which gives total wind frequency of 80.9%.

The Velocity Ratio (VR) as proposed by the *AVA Technical Circular* was employed to assess the ventilation performance under different schemes and its impact to the surroundings.

With reference to the *AVA Technical Circular*, 40 perimeter test points and 84 overall test points were allocated to assess the local and overall ventilation performance in the Assessment Area.

7.2 Results

Upon the CFD simulation Proposed scheme achieved higher SVR of 0.01 and 0.02 and a higher LVR of both 0.01 when compared to the Baseline scheme under annual and summer condition respectively.

The results of the SVR, LVR are summarized as below.

	Annual Condition		Summer Condition	
	Baseline scheme	Proposed scheme	Baseline scheme	Proposed scheme
SVR	0.17	0.18	0.22	0.24
LVR	0.18	0.19	0.23	0.24

8 Reference

[1] Annex A of Technical Circular No. 1/06 issued by the Housing, Planning and Lands Bureau pertaining specifically to Air Ventilation Assessments, 19th July, 2006

(https://www.devb.gov.hk/filemanager/en/content_679/hplb-etwb-tc-01-06.pdf)

[2] Planning Department RAMS Data (http://www.pland.gov.hk/pland_en/info_serv/site_wind/site_wind/)

Appendix A

Master Layout Plan of Baseline and Proposed scheme

A1 Baseline scheme

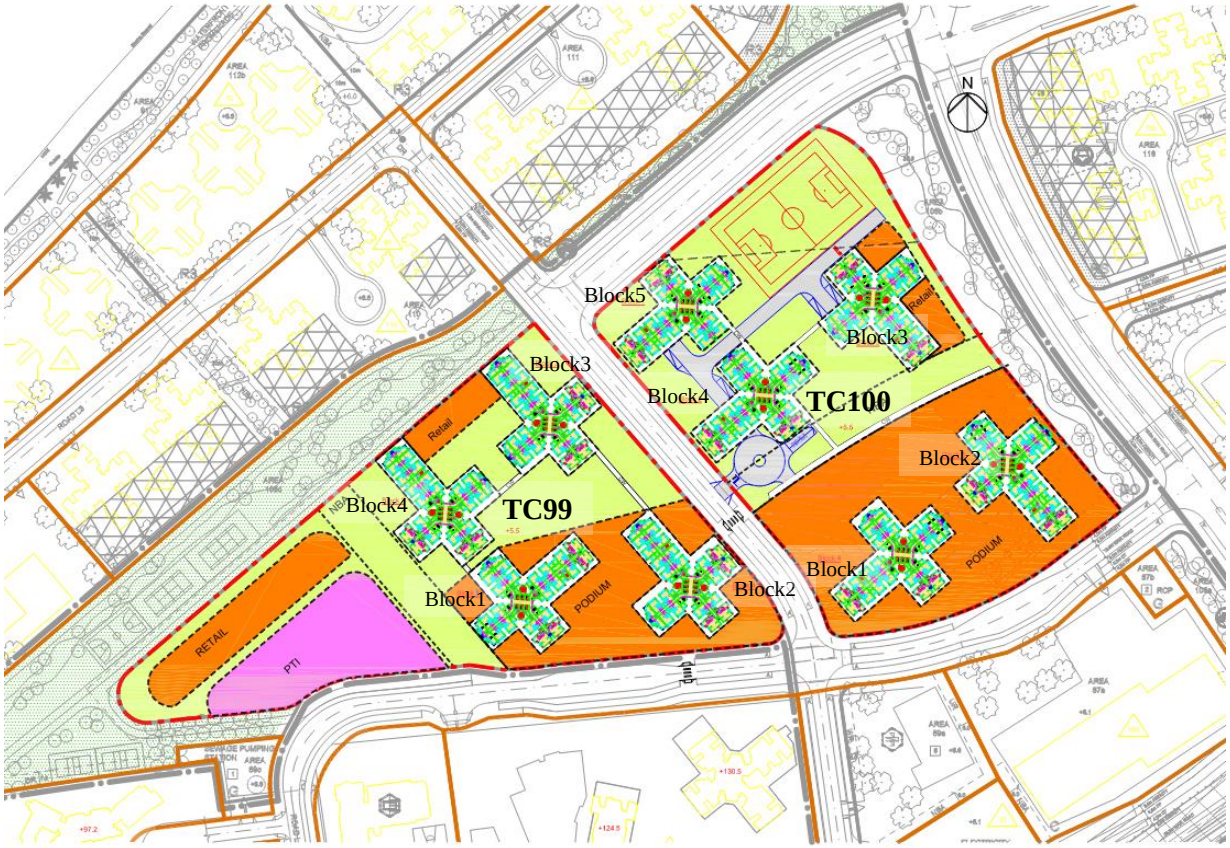

Figure B1 Master Layout Plan of TC99&100 Baseline Scheme

A2 Proposed scheme

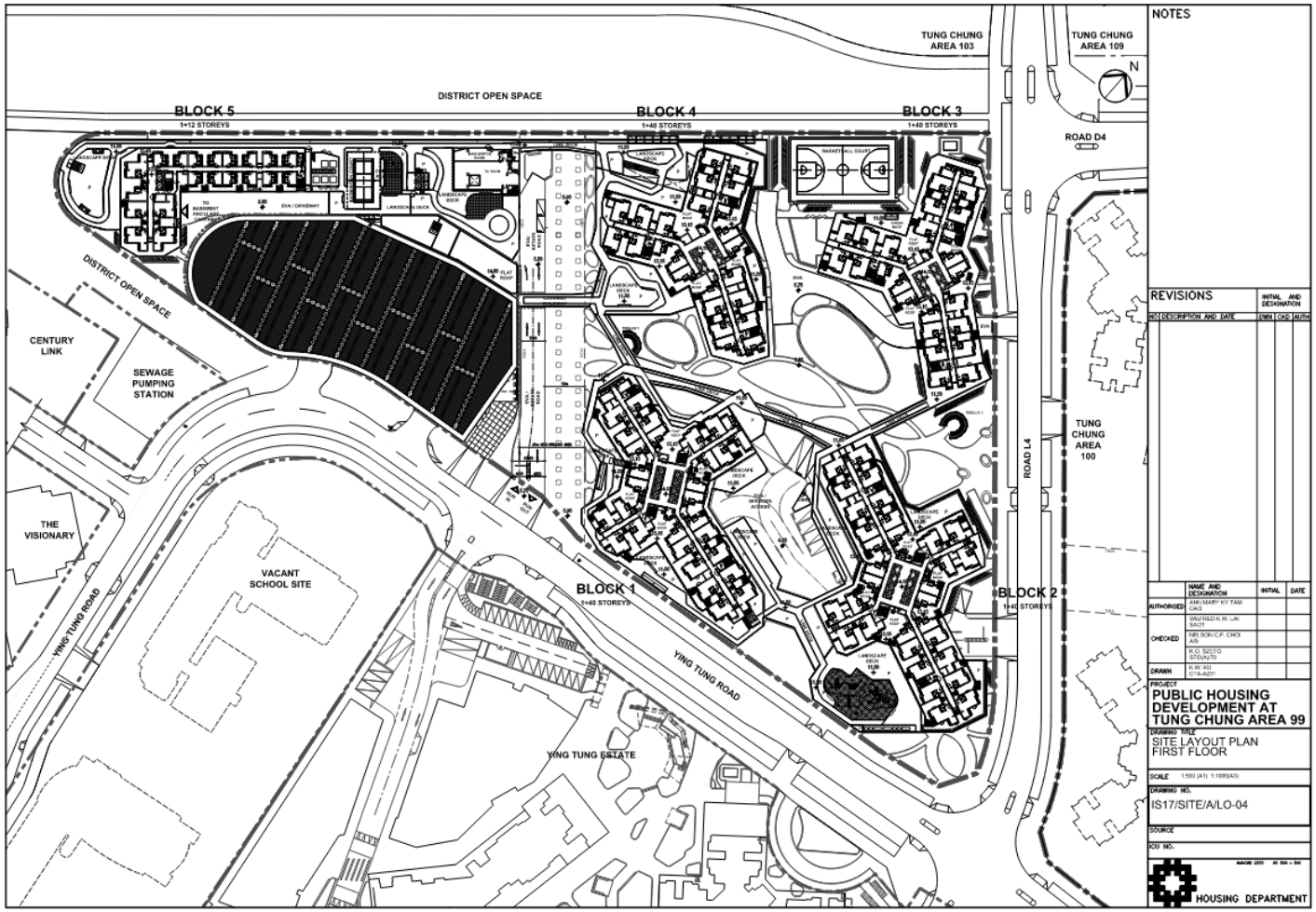

Figure B2 Master Layout Plan of TC99 Proposed scheme

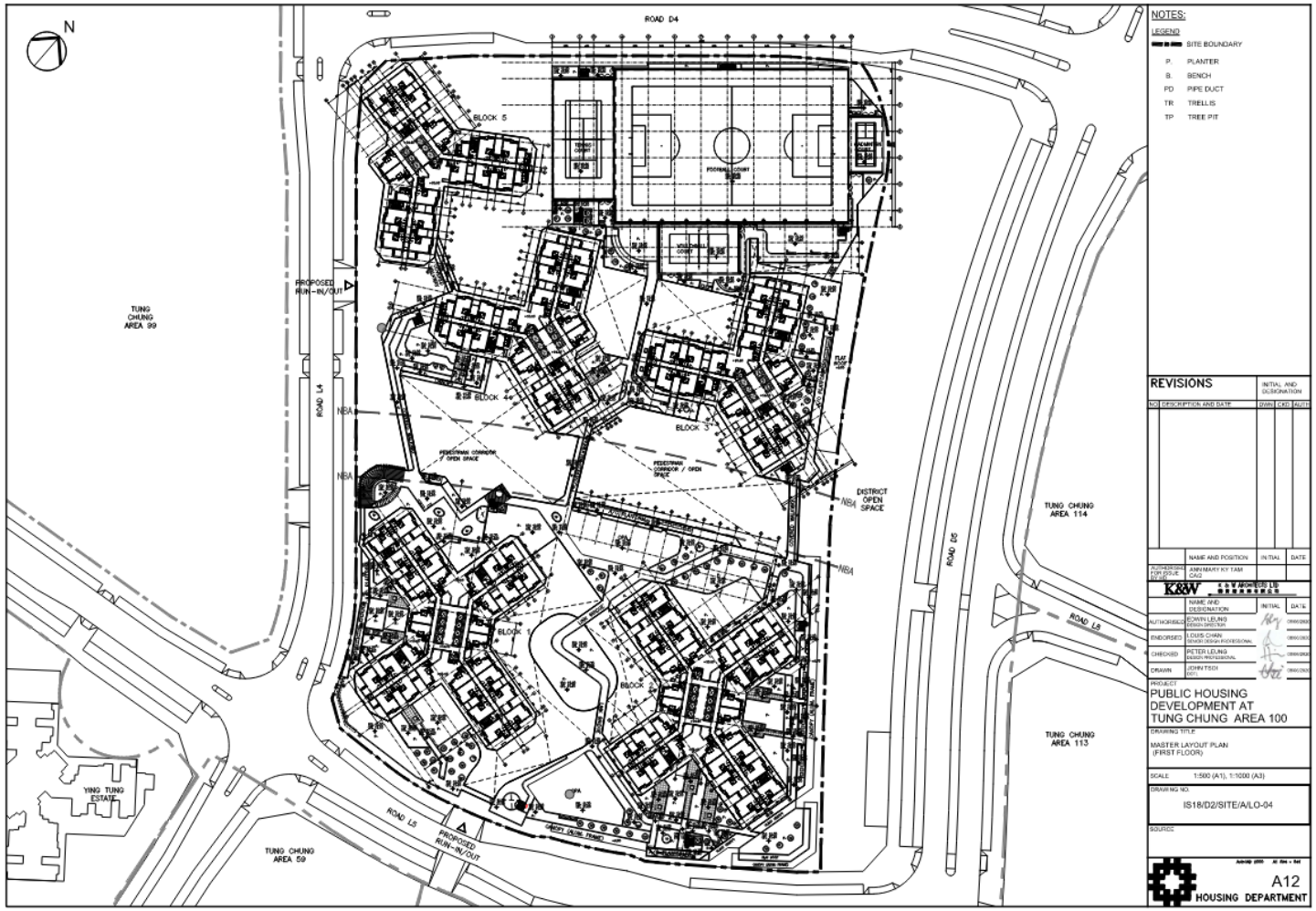

Figure B3 Master Layout Plan of TC100 Proposed scheme

Appendix B

Contour Plots of Velocity Ratio

D1 Baseline scheme

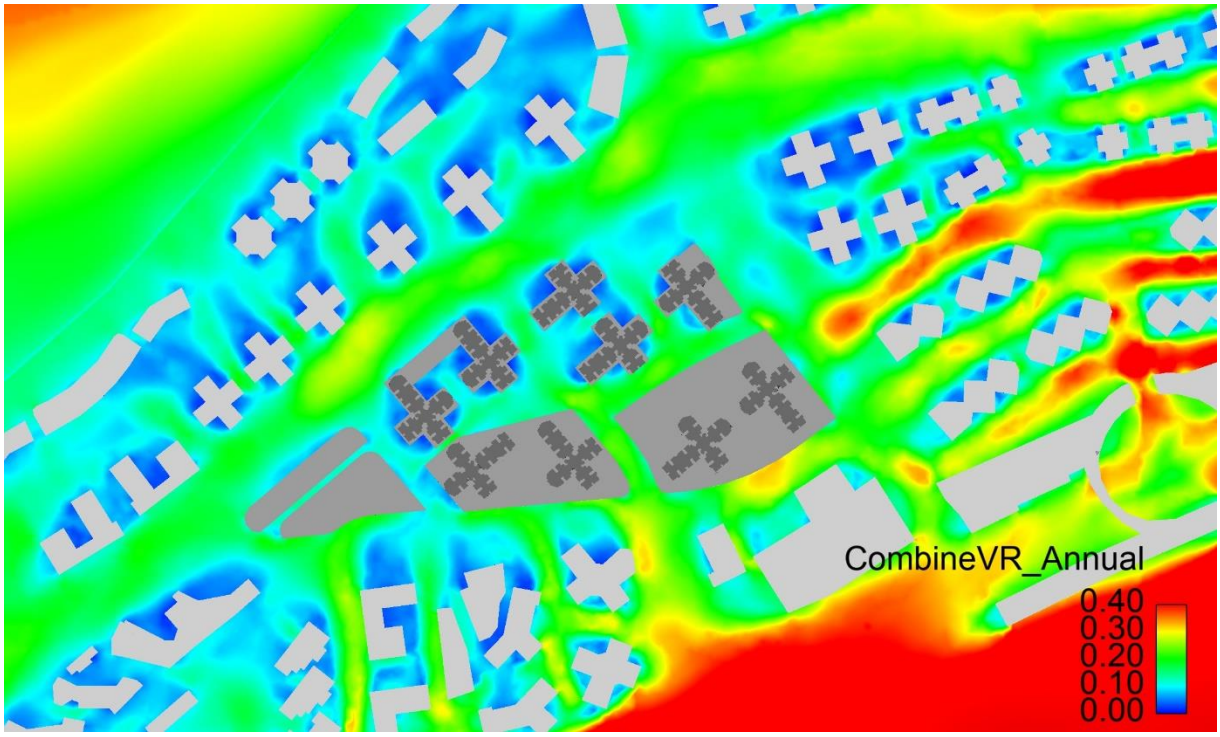

Figure B4 Contour Plot of VR under Annual Wind

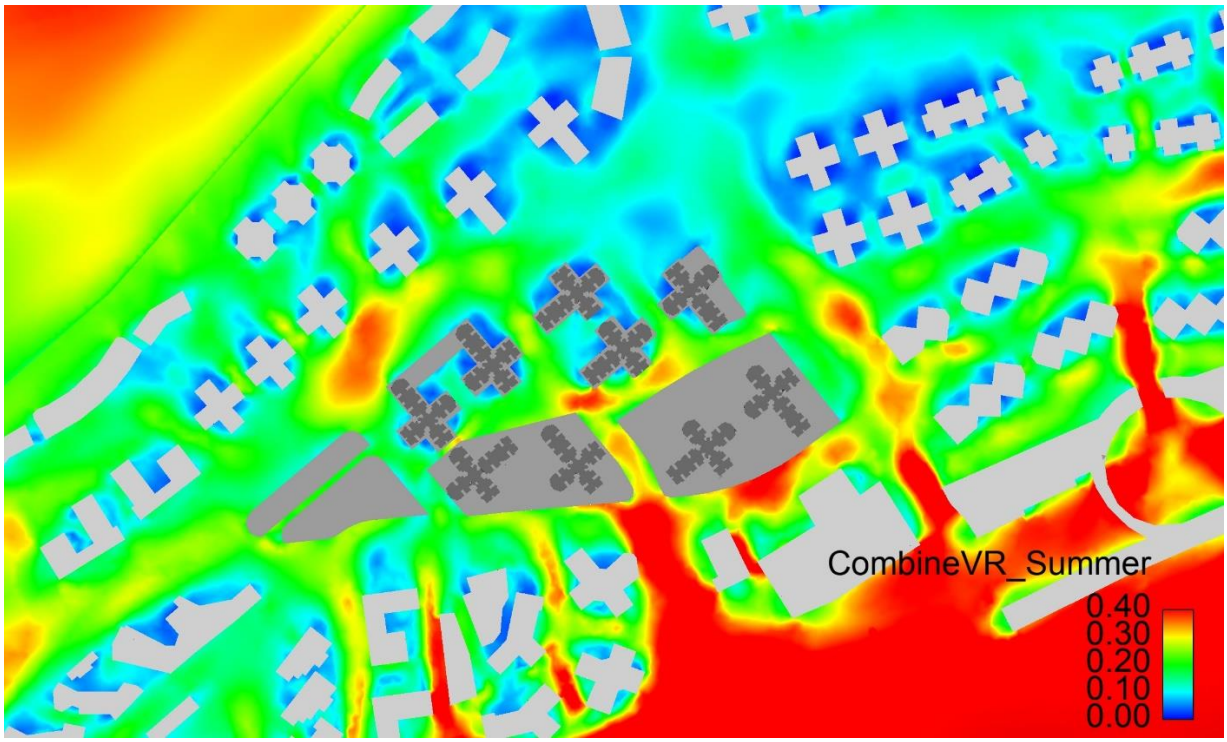

Figure B5 Contour Plot of VR under Summer Wind

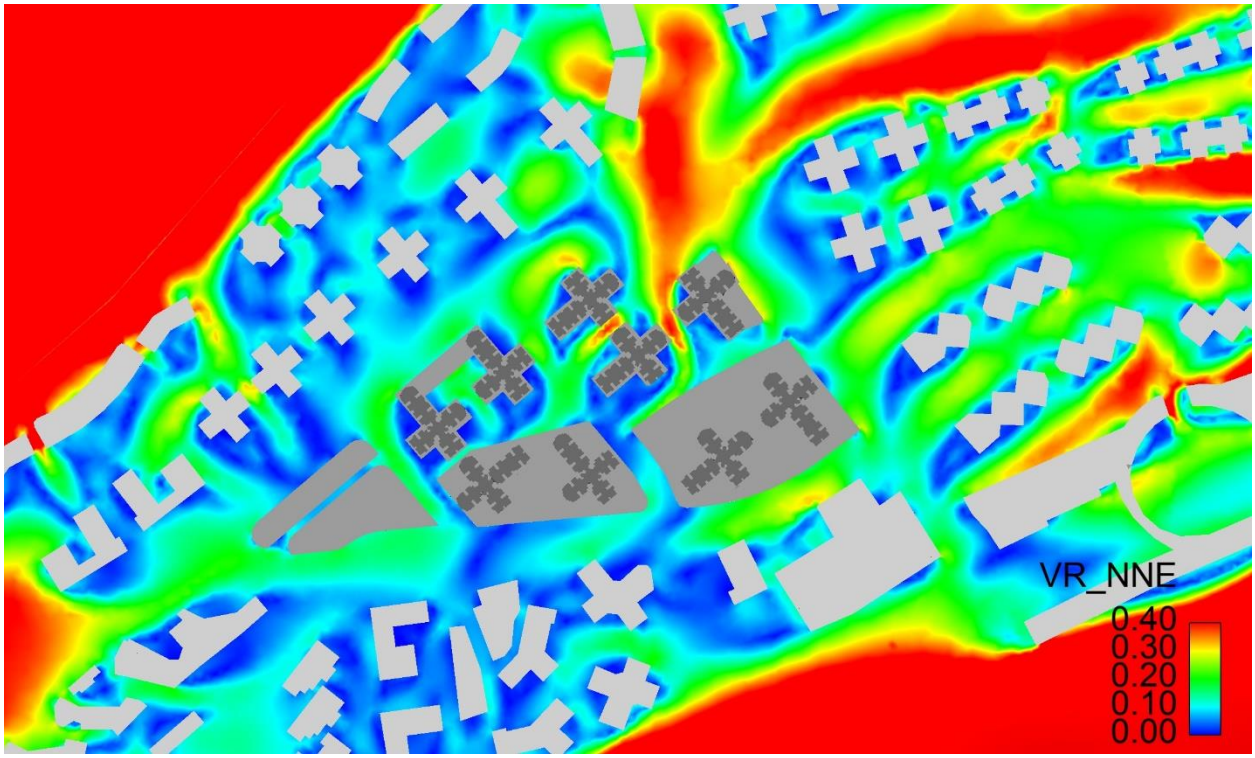

Figure B6 Contour Plot of VR under NNE Wind

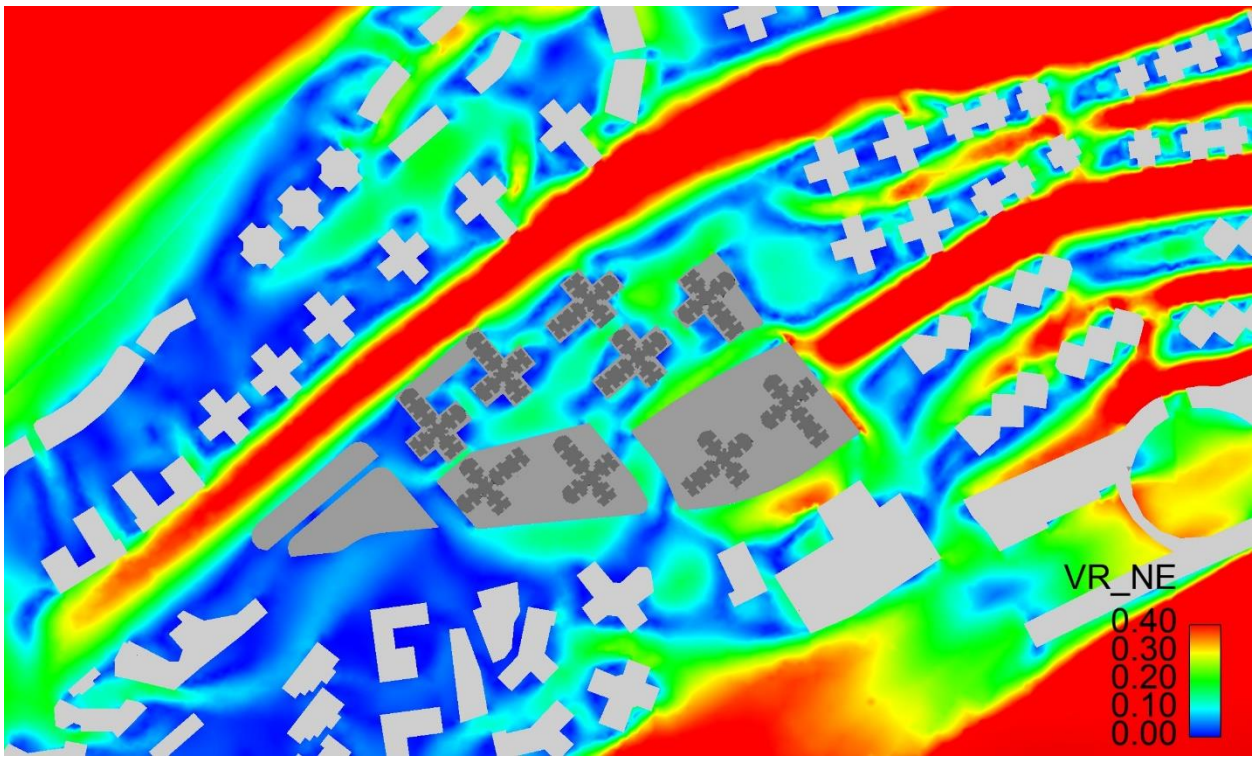

Figure B7 Contour Plot of VR under NE Wind

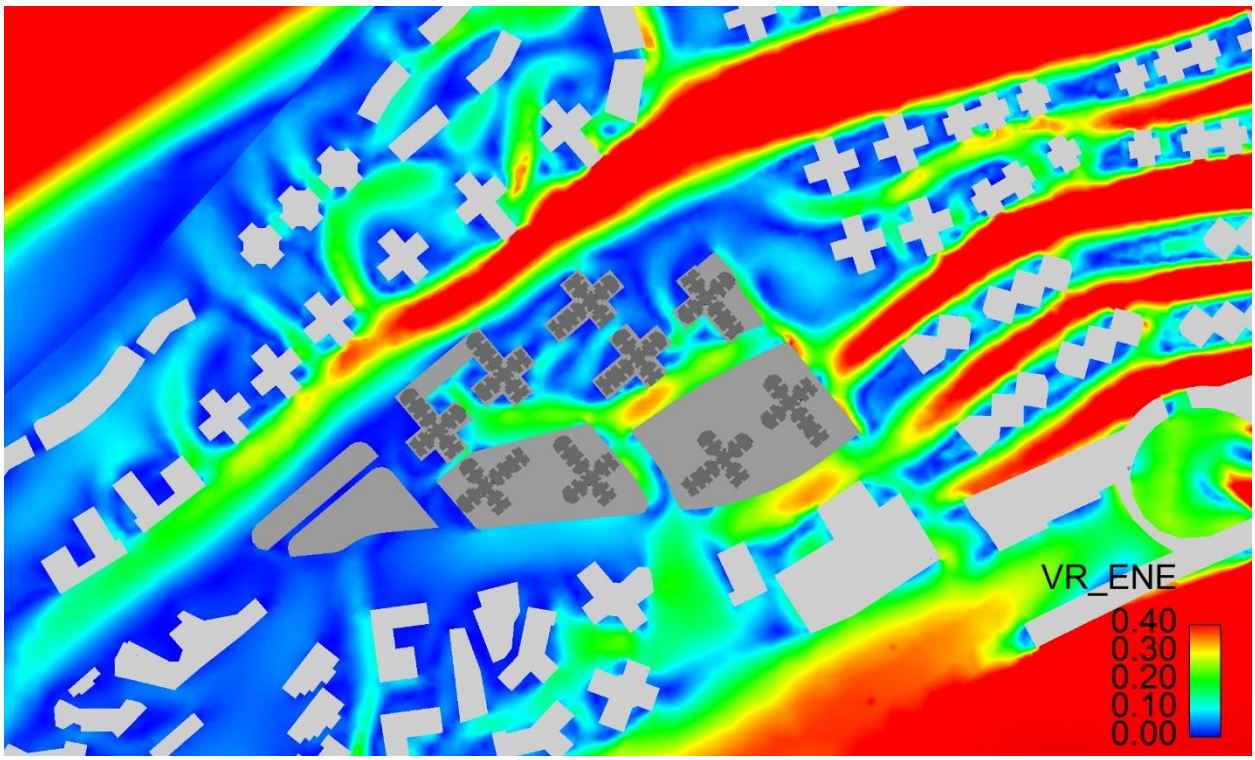

Figure B8 Contour Plot of VR under ENE Wind

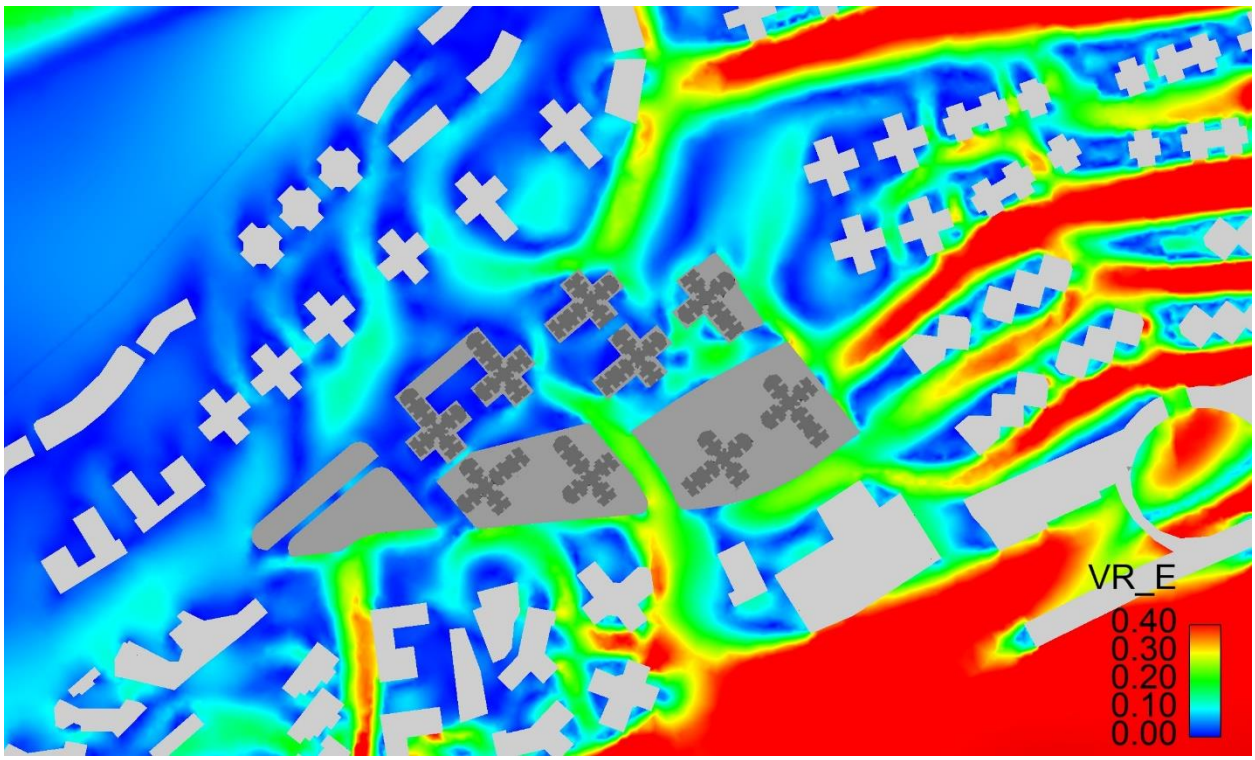

Figure B9 Contour Plot of VR under E Wind

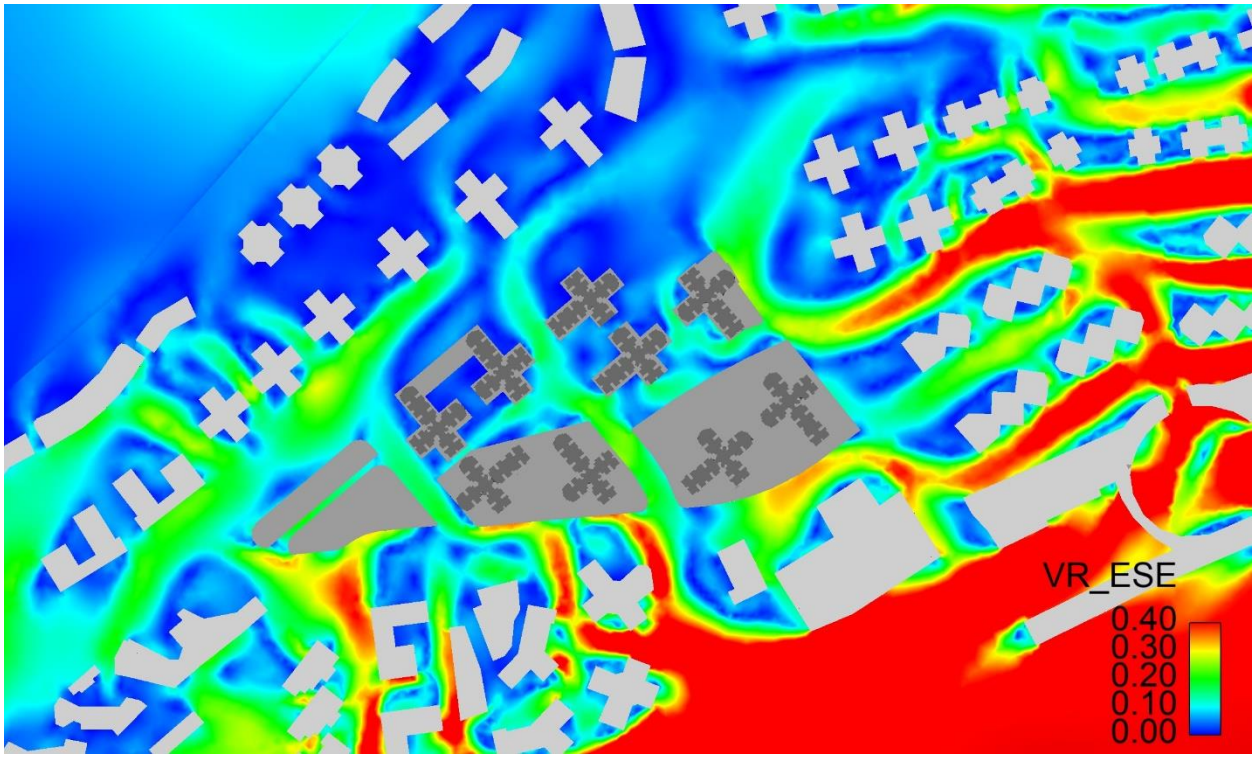

Figure B10 Contour Plot of VR under ESE Wind

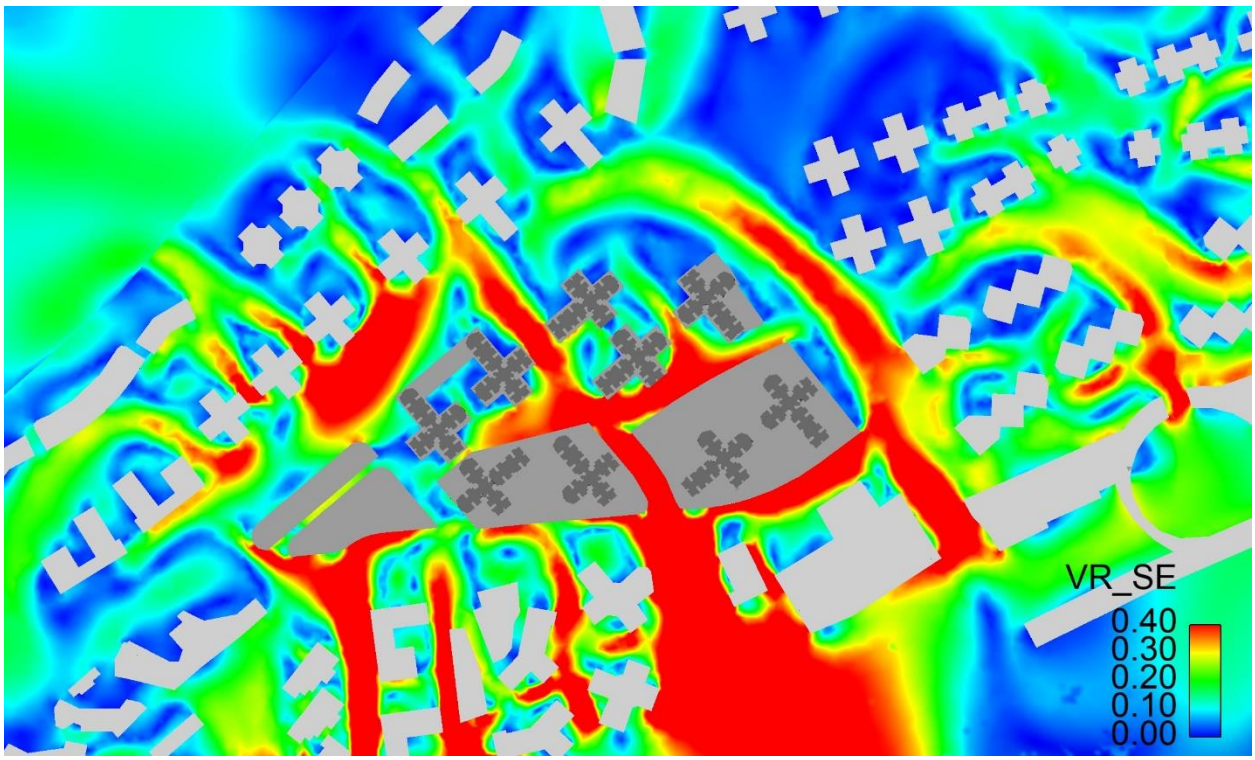

Figure B11 Contour Plot of VR under SE Wind

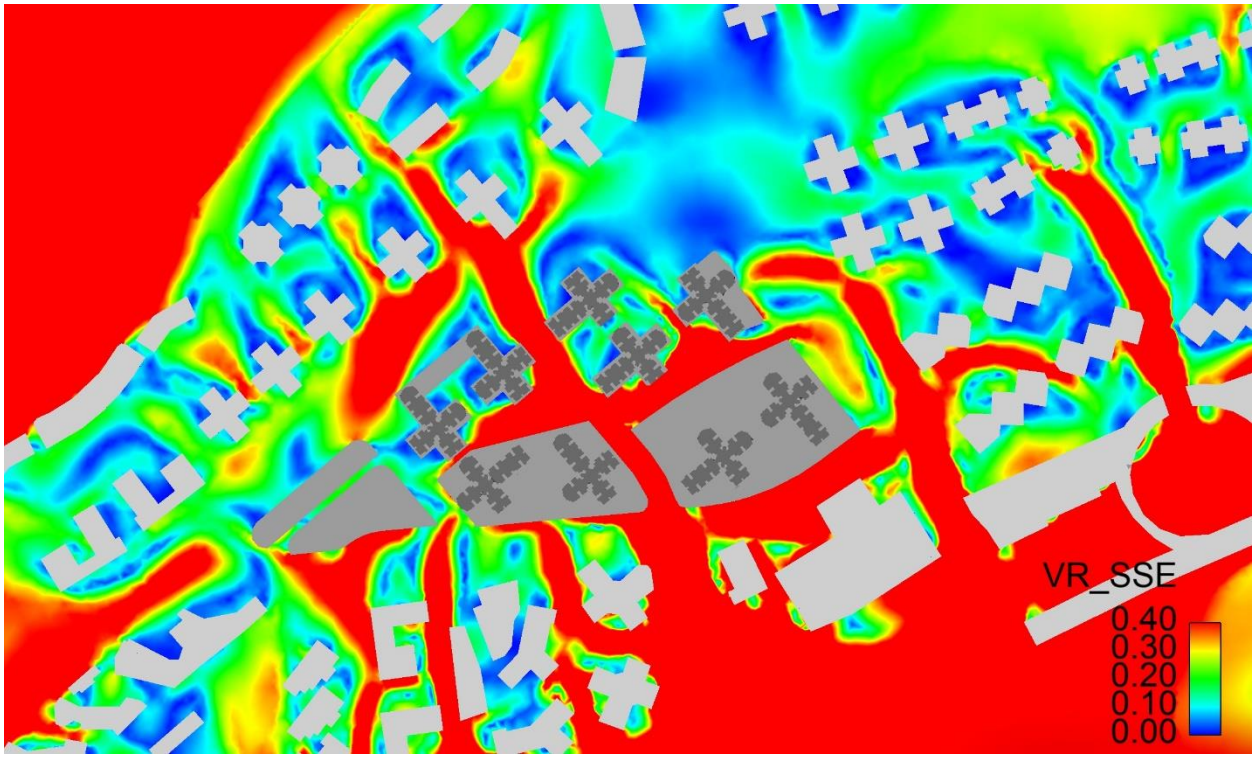

Figure B12 Contour Plot of VR under SSE Wind

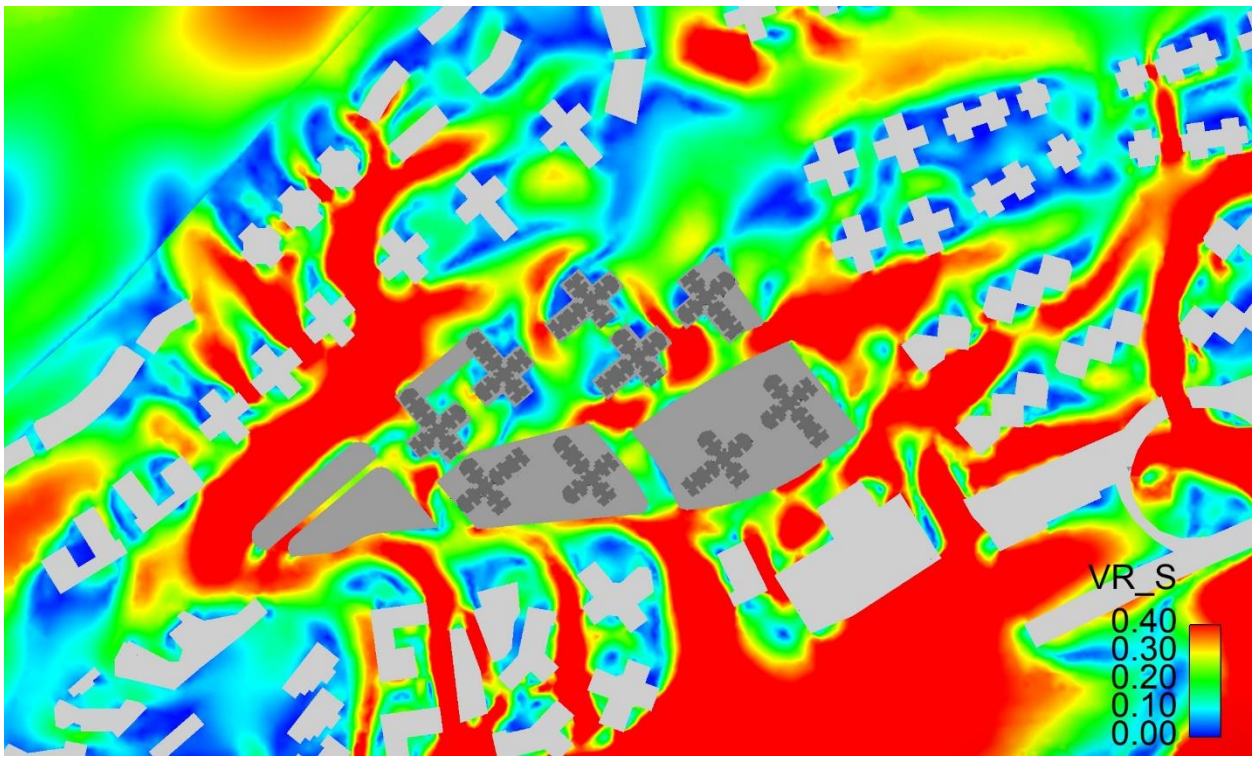

Figure B13 Contour Plot of VR under S Wind

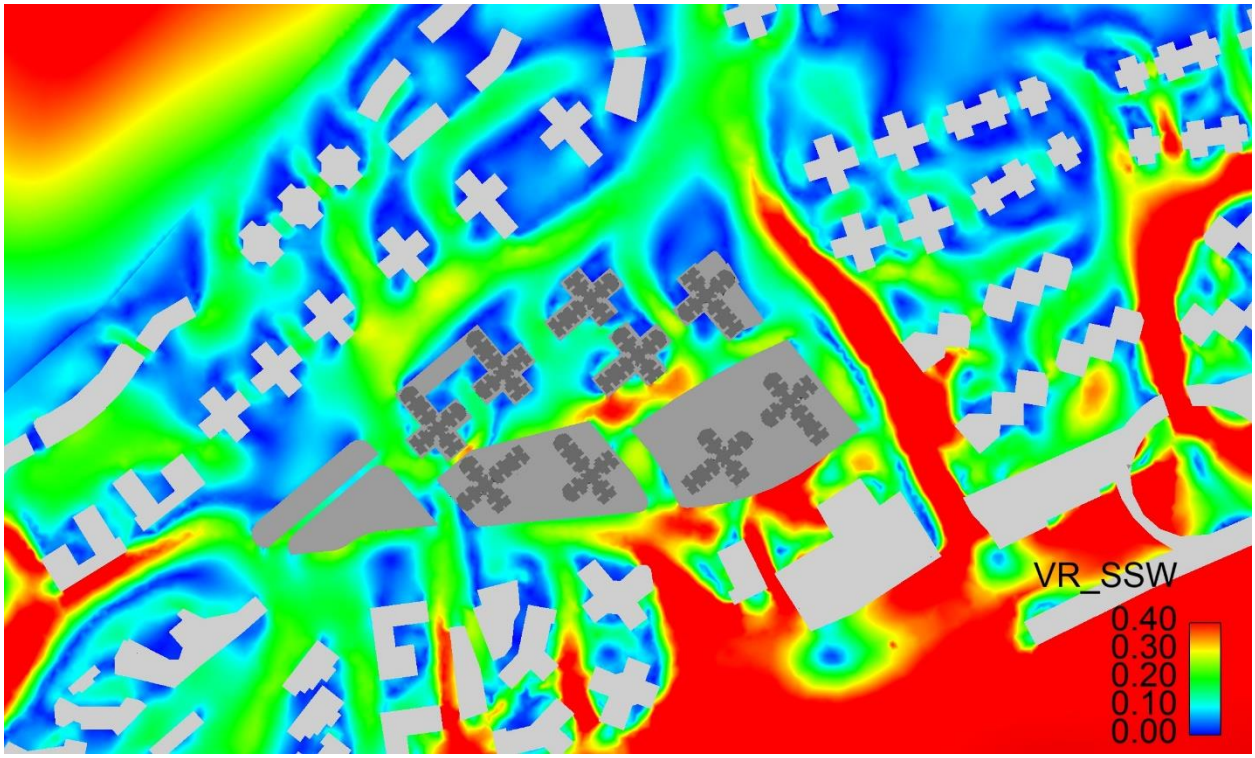

Figure B14 Contour Plot of VR under SSW Wind

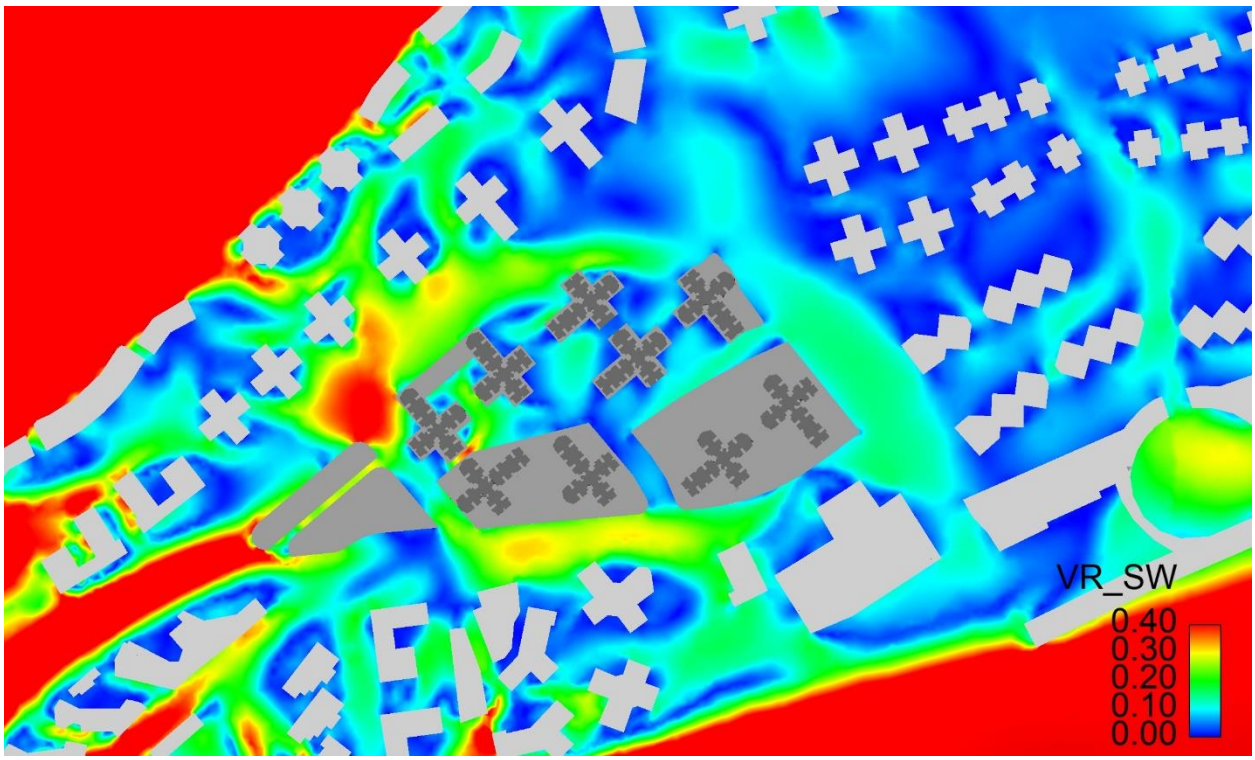

Figure B15 Contour Plot of VR under SW Wind

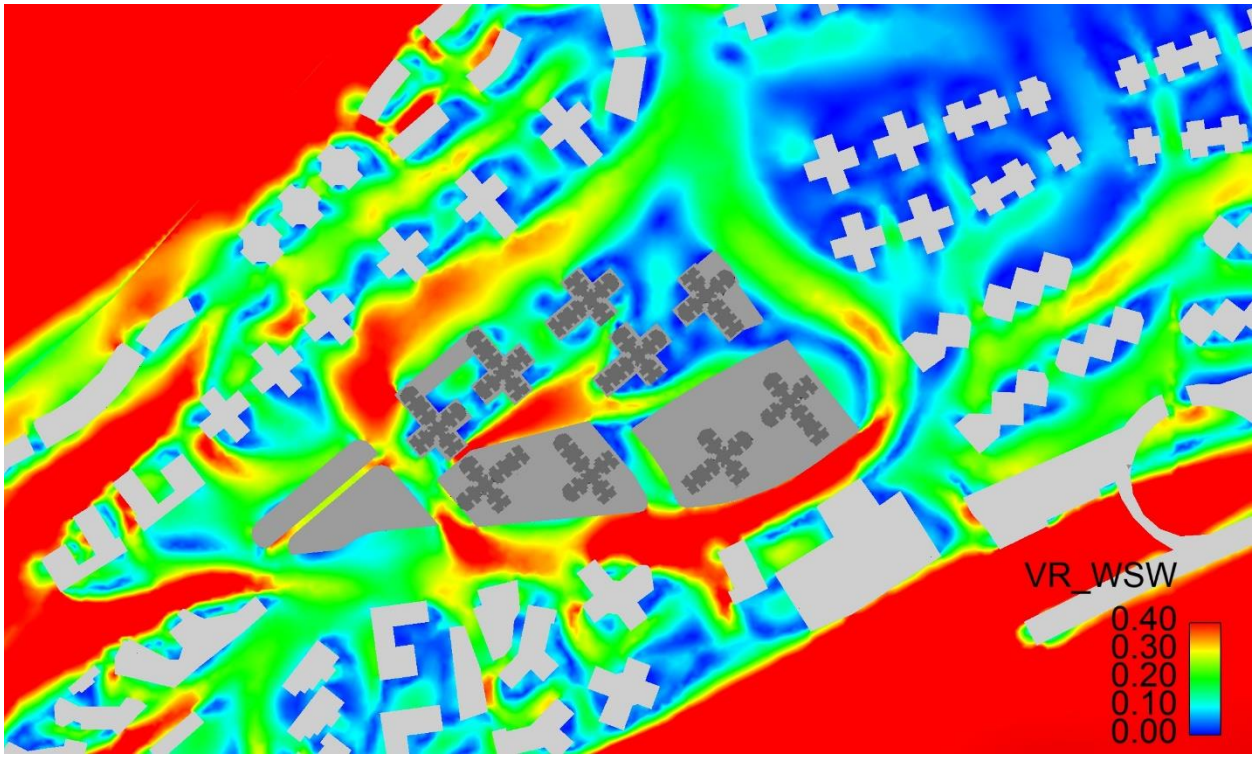

Figure B16 Contour Plot of VR under WSW Wind

D2 Proposed scheme

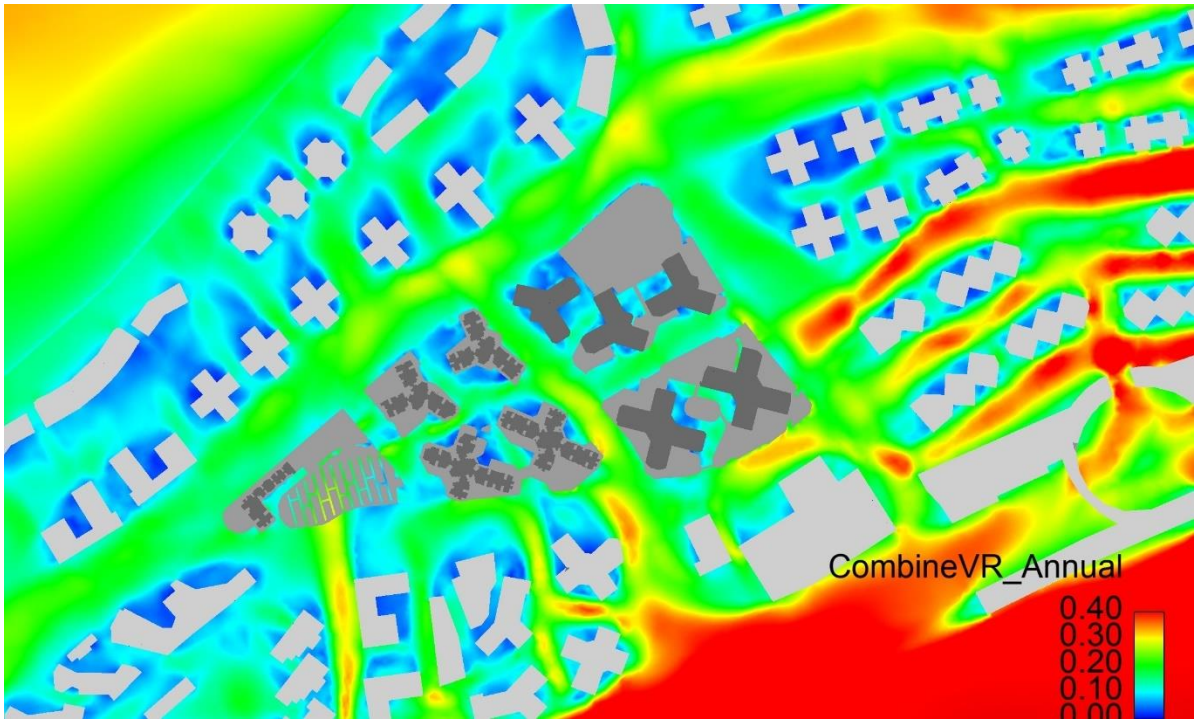

Figure B17 Contour Plot of VR under Annual Wind

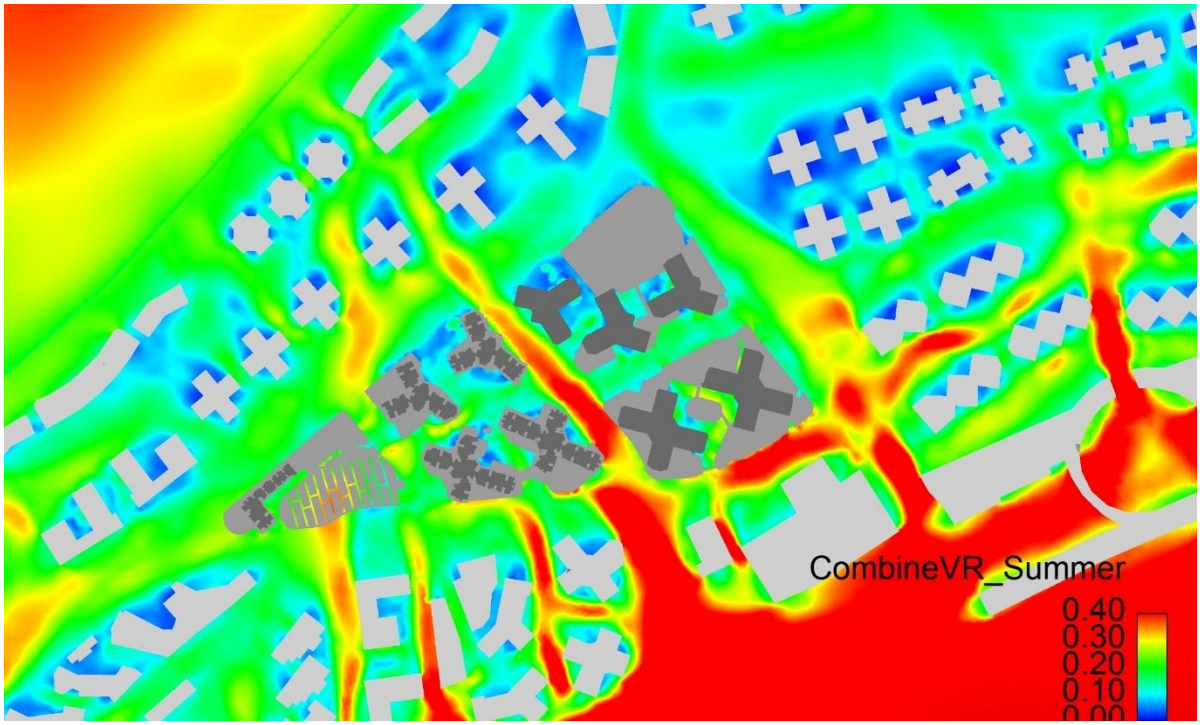

Figure B18 Contour Plot of VR under Summer Wind

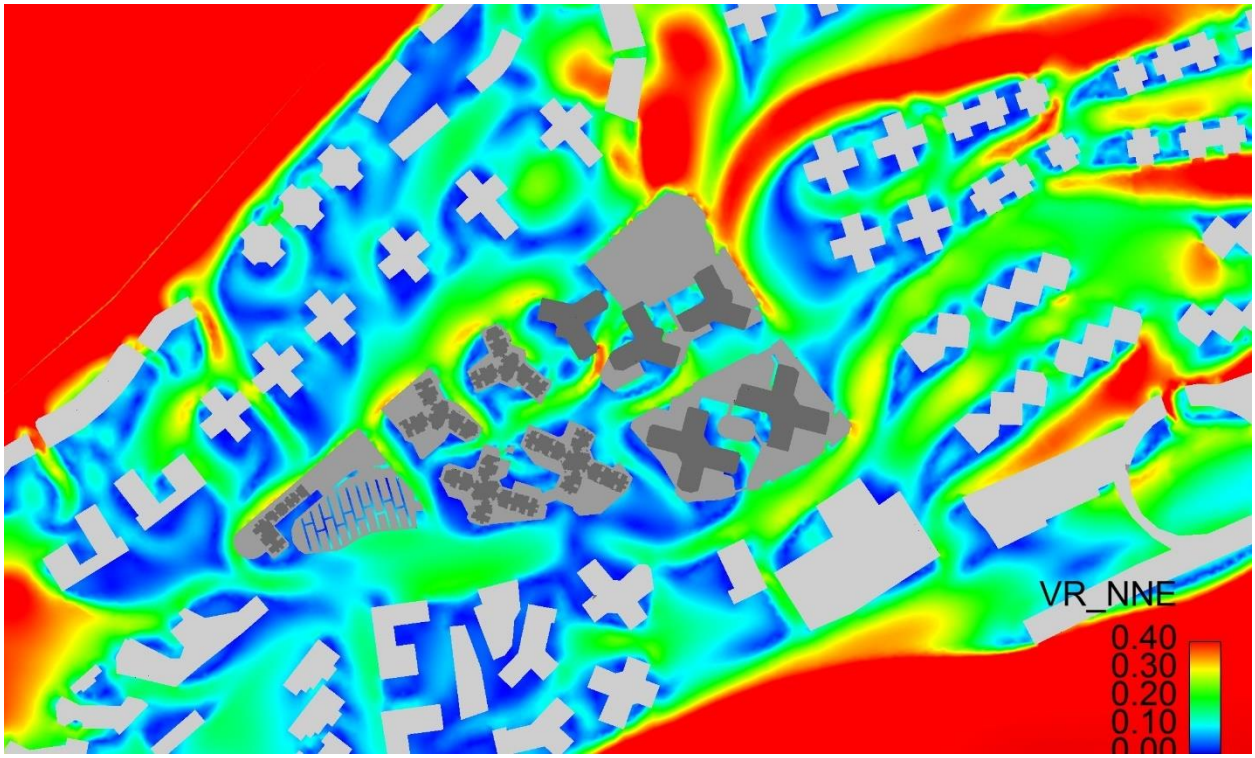

Figure B19 Contour Plot of VR under NNE Wind

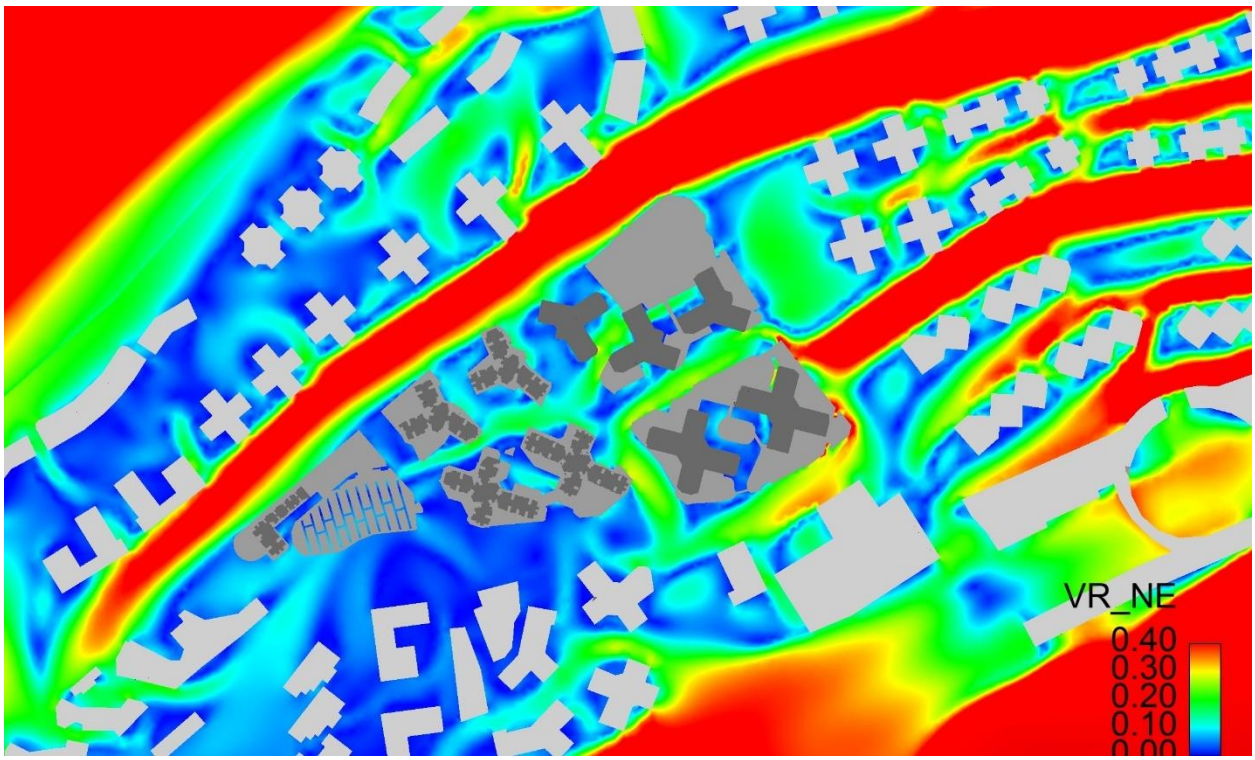

Figure B20 Contour Plot of VR under NE Wind

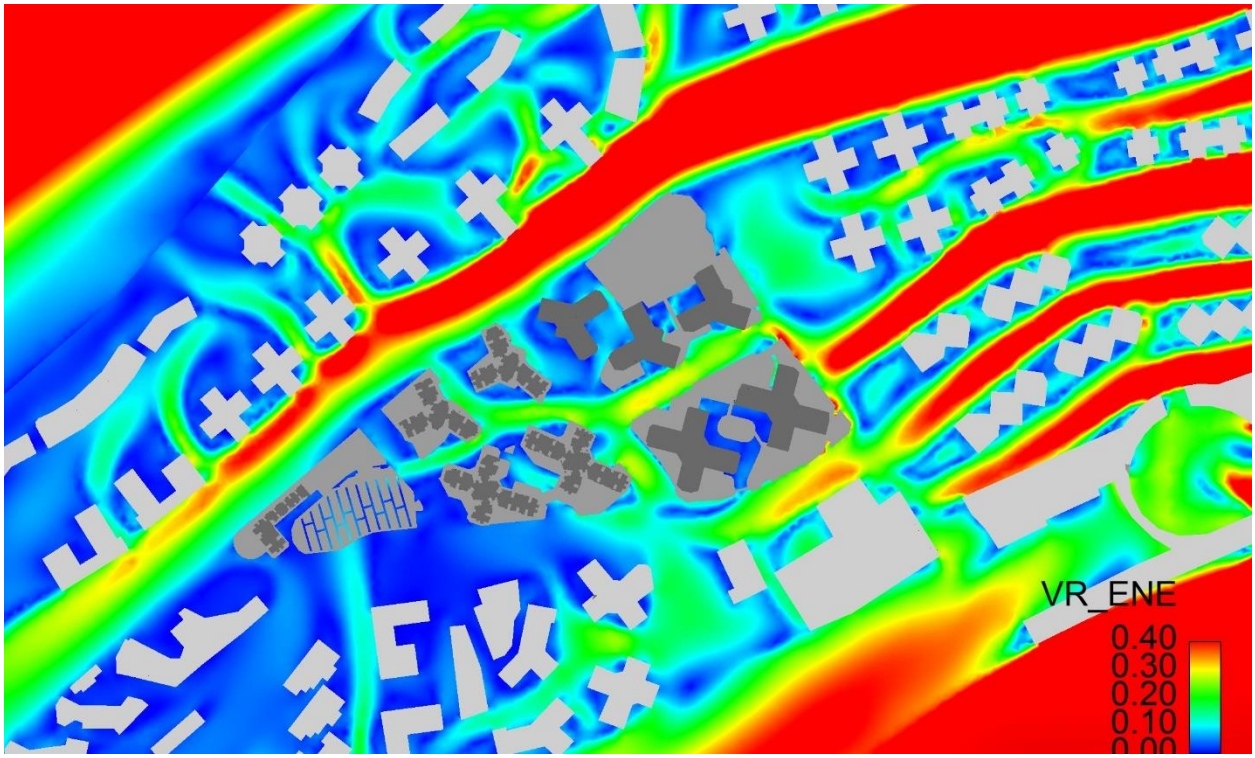

Figure B21 Contour Plot of VR under ENE Wind

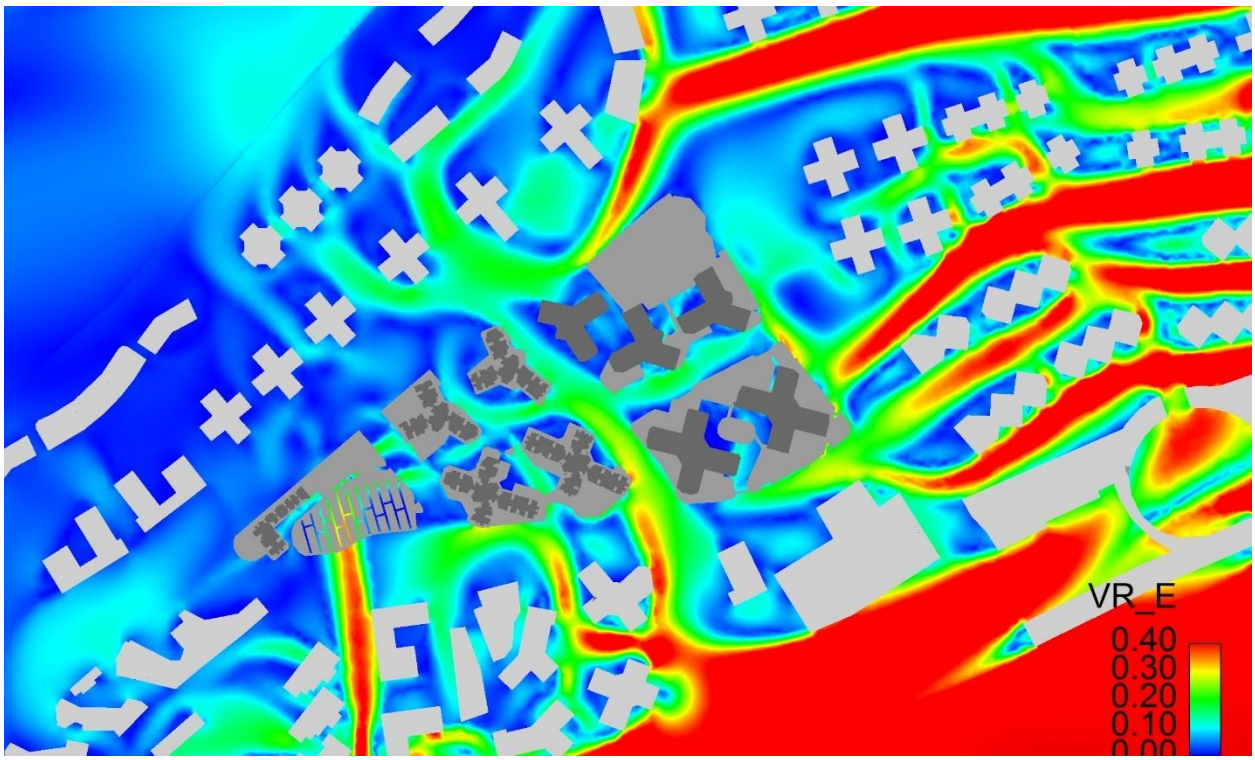

Figure B22 Contour Plot of VR under E Wind

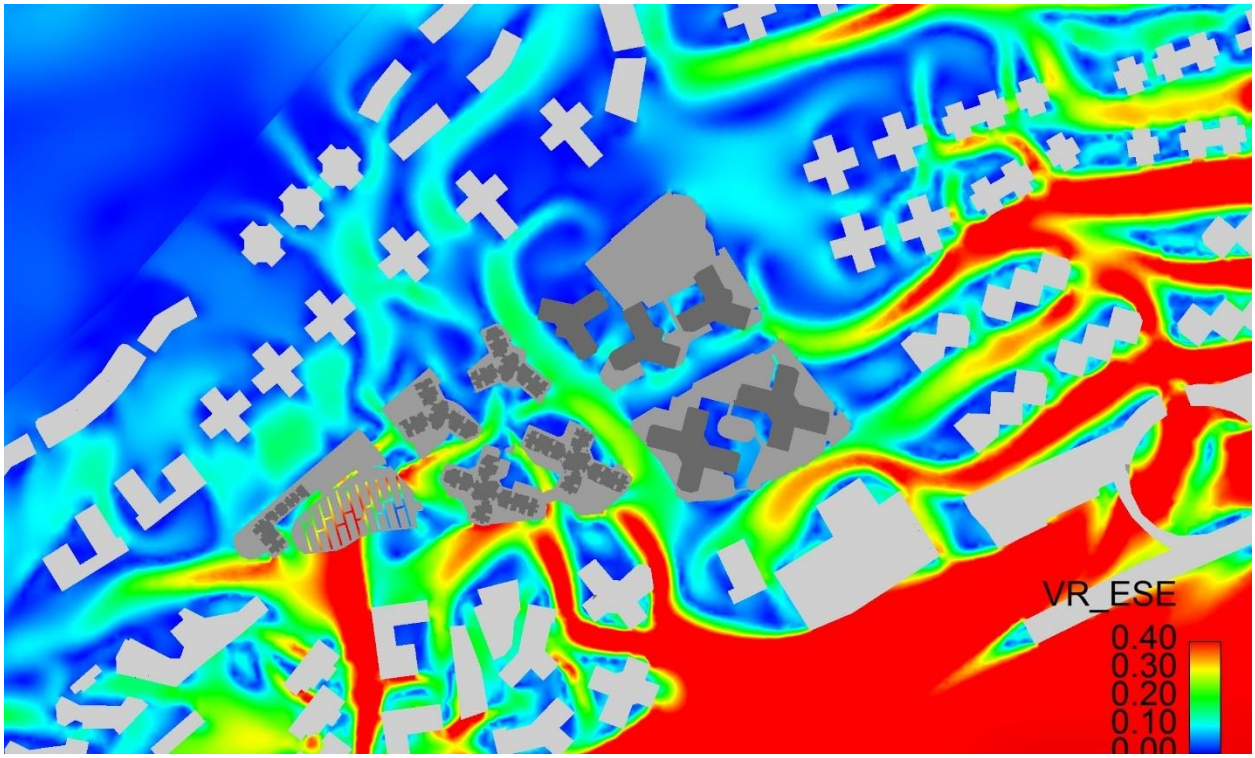

Figure B23 Contour Plot of VR under ESE Wind

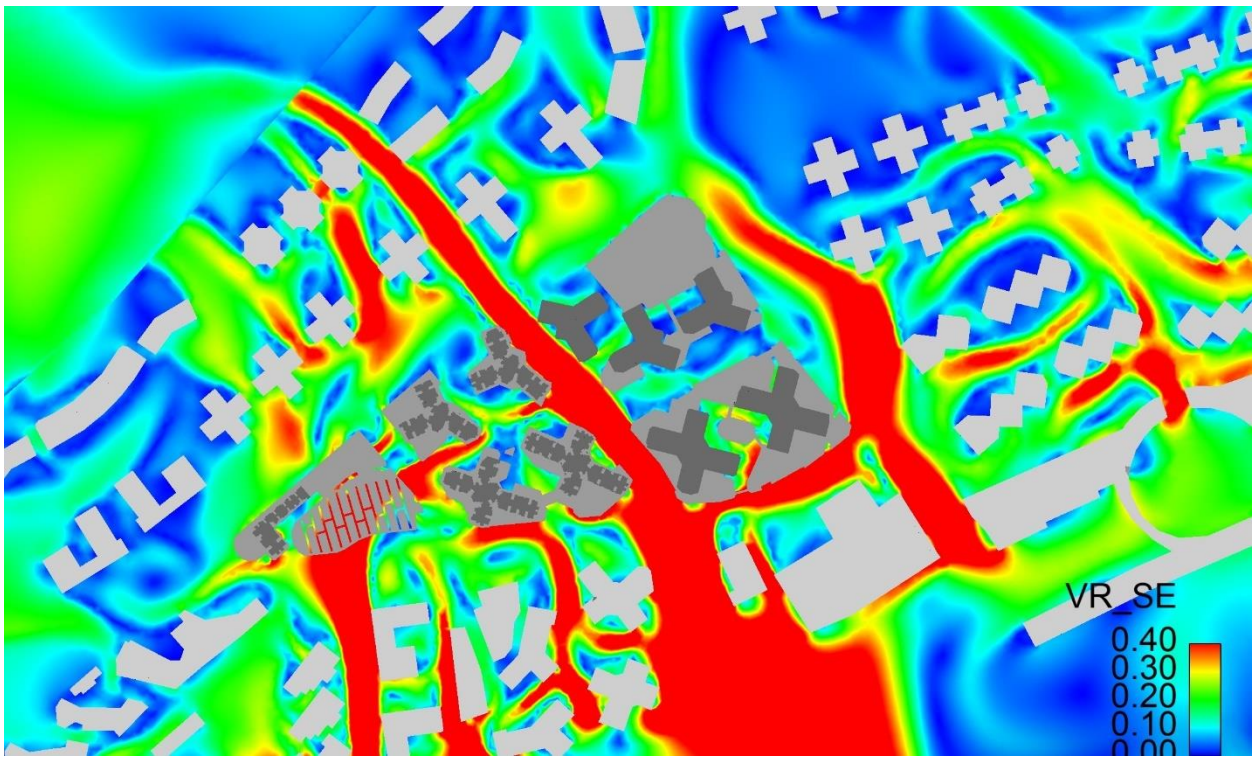

Figure B24 Contour Plot of VR under SE Wind

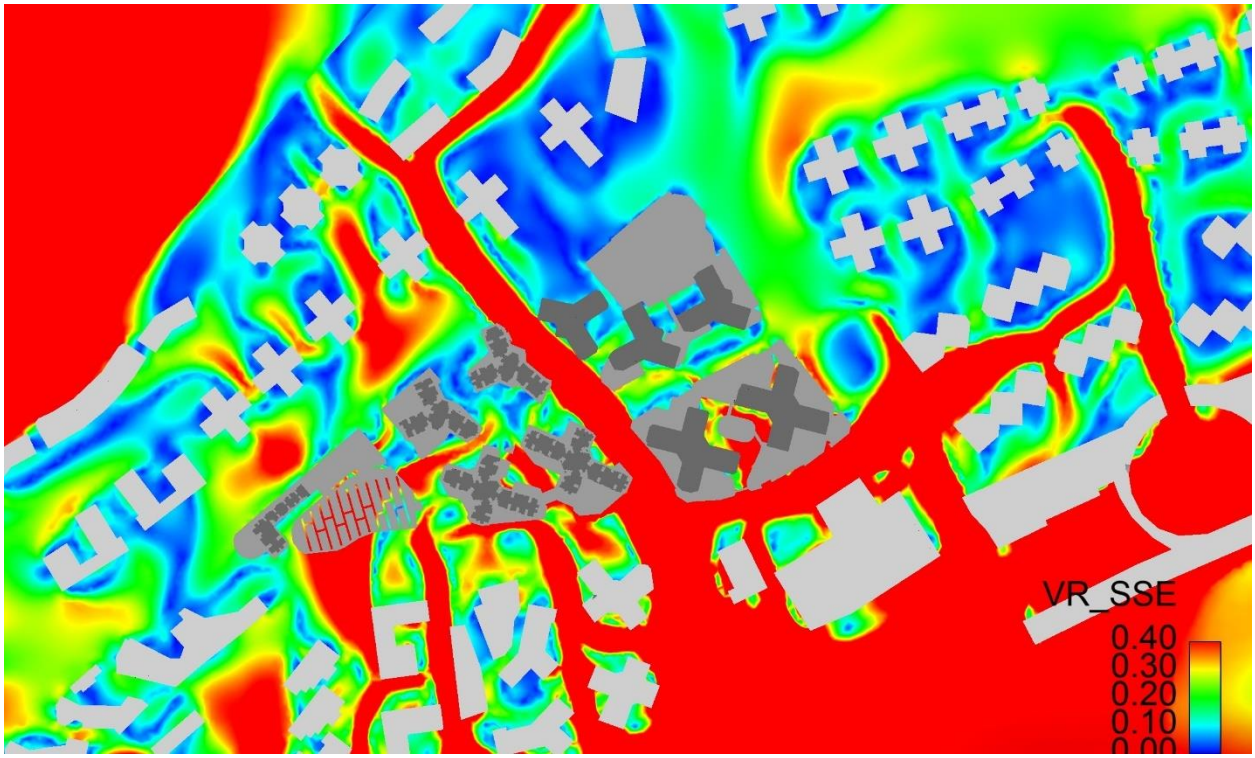

Figure B25 Contour Plot of VR under SSE Wind

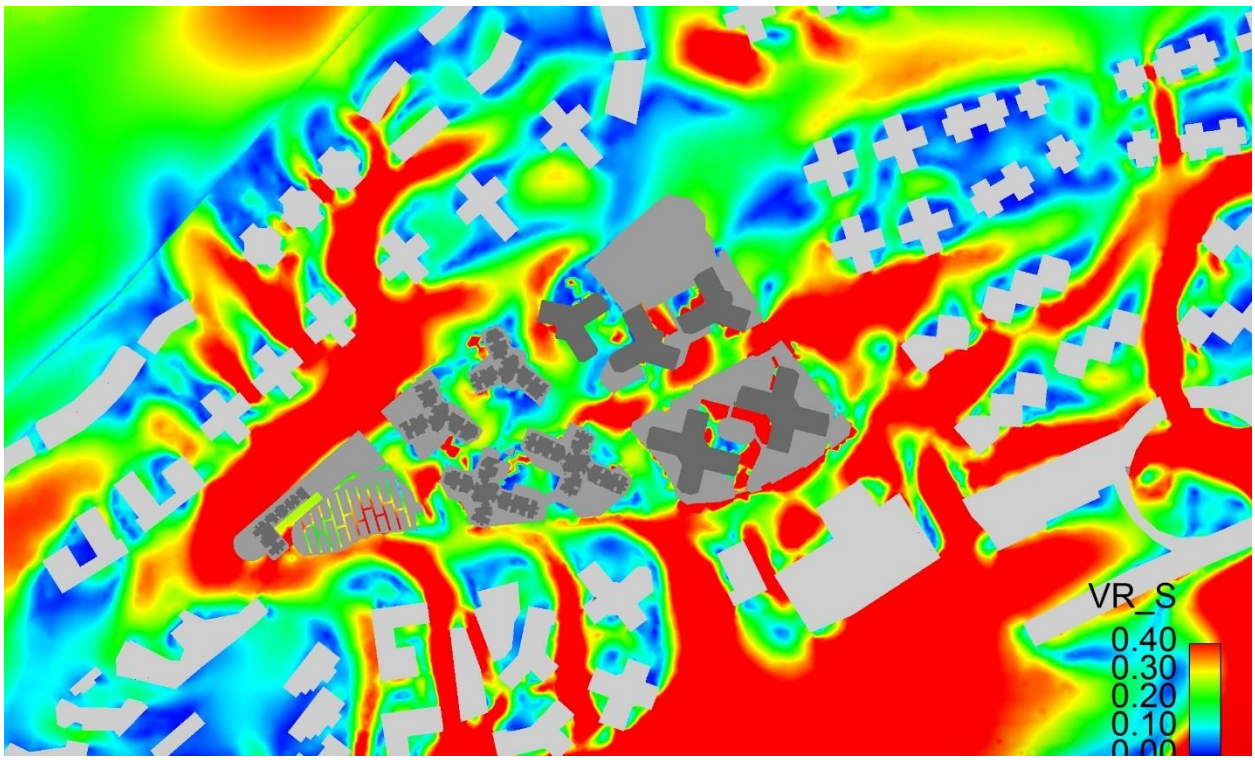

Figure B26 Contour Plot of VR under S Wind

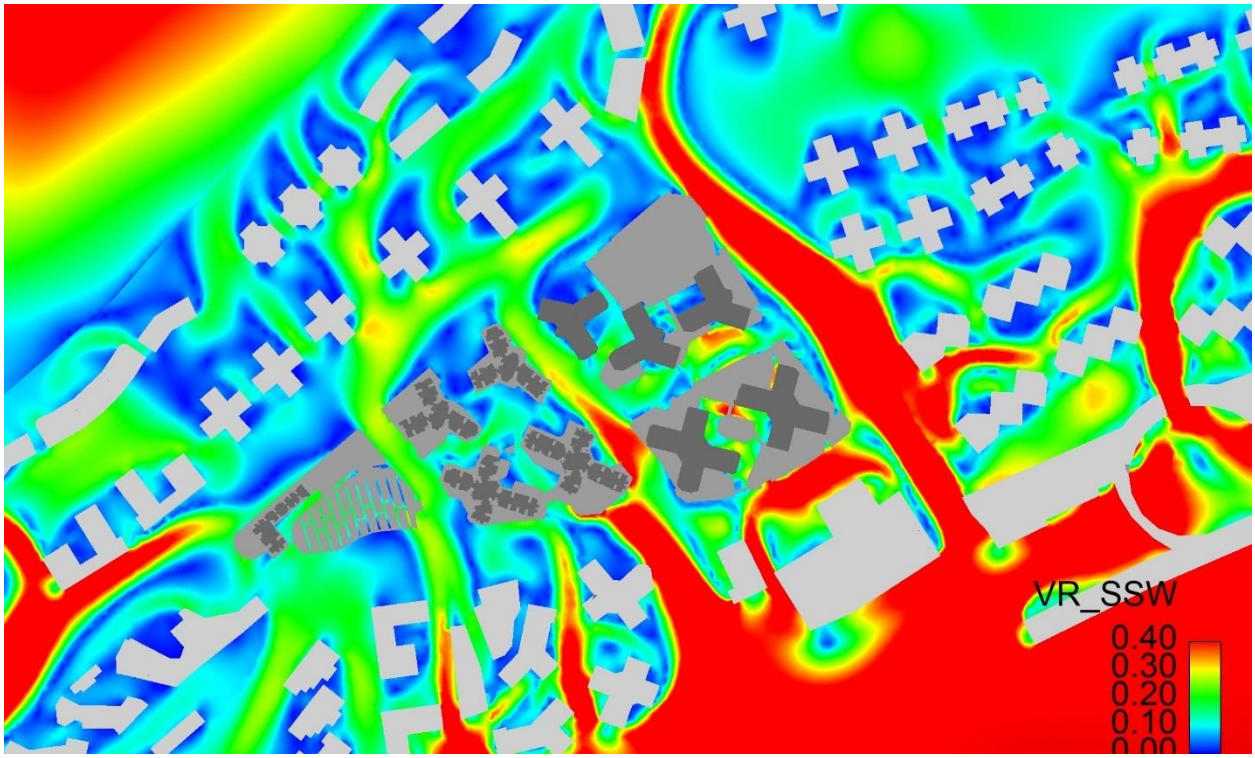

Figure B27 Contour Plot of VR under SSW Wind

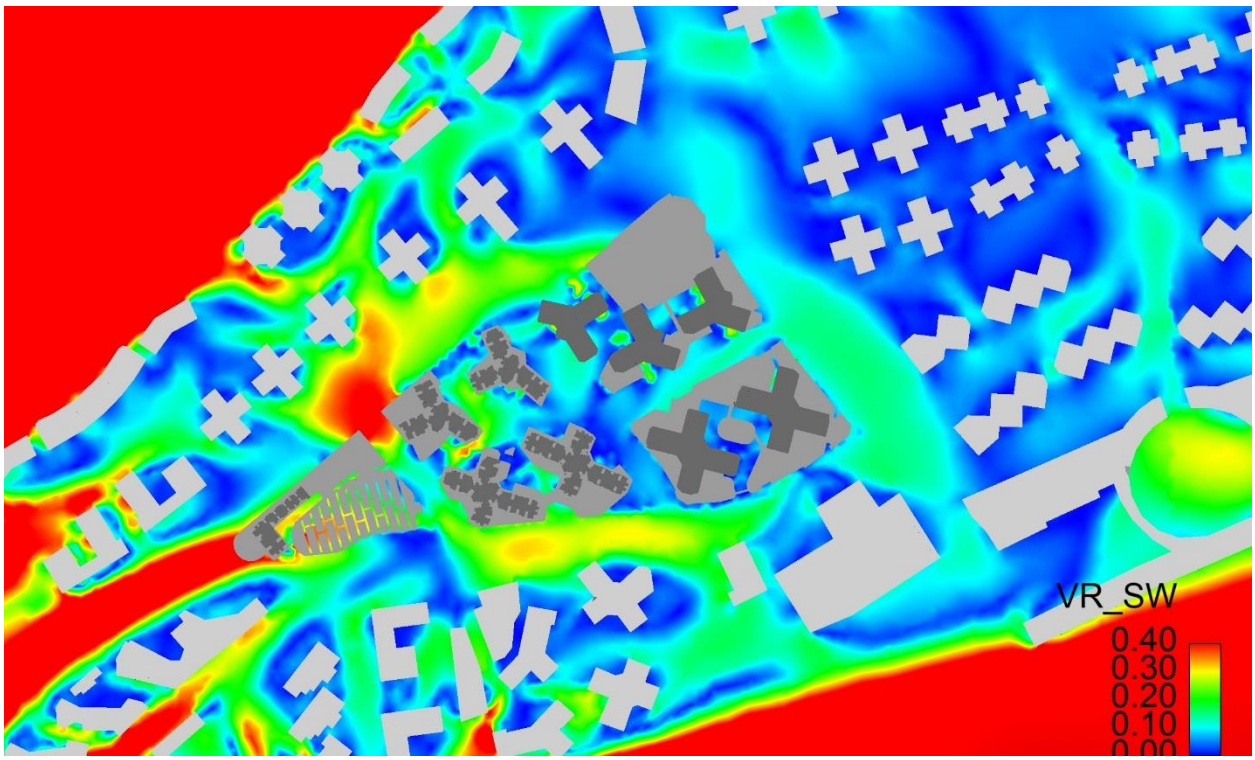

Figure B28 Contour Plot of VR under SW Wind

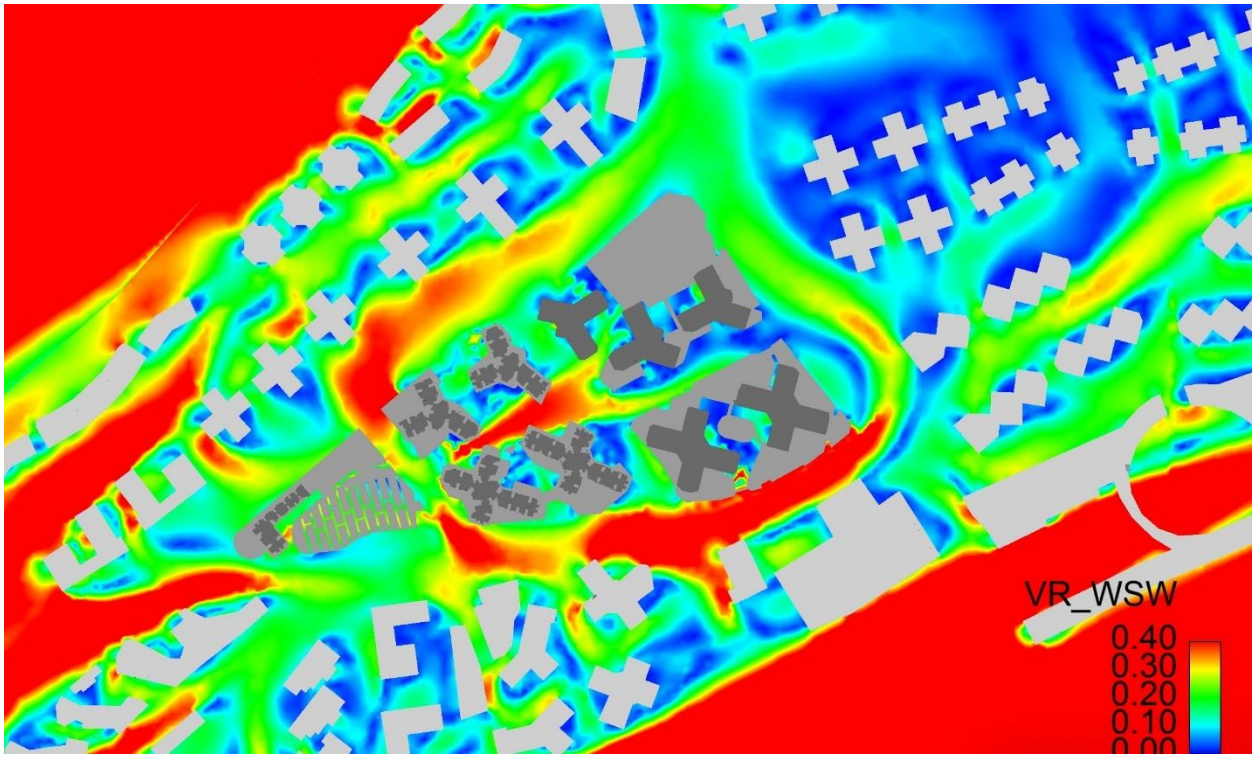

Figure B29 Contour Plot of VR under WSW Wind

Appendix C

Vector Plots of Velocity Ratio

C1 Baseline scheme

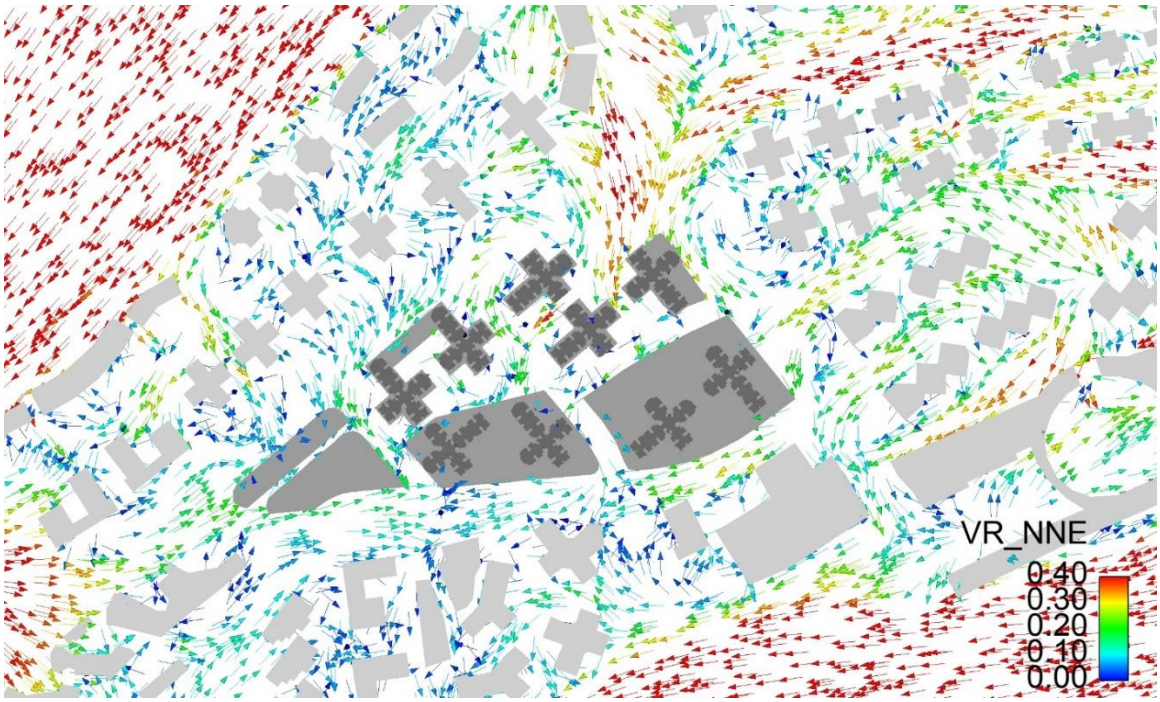

Figure C30 Vector Plot of VR under NNE Wind

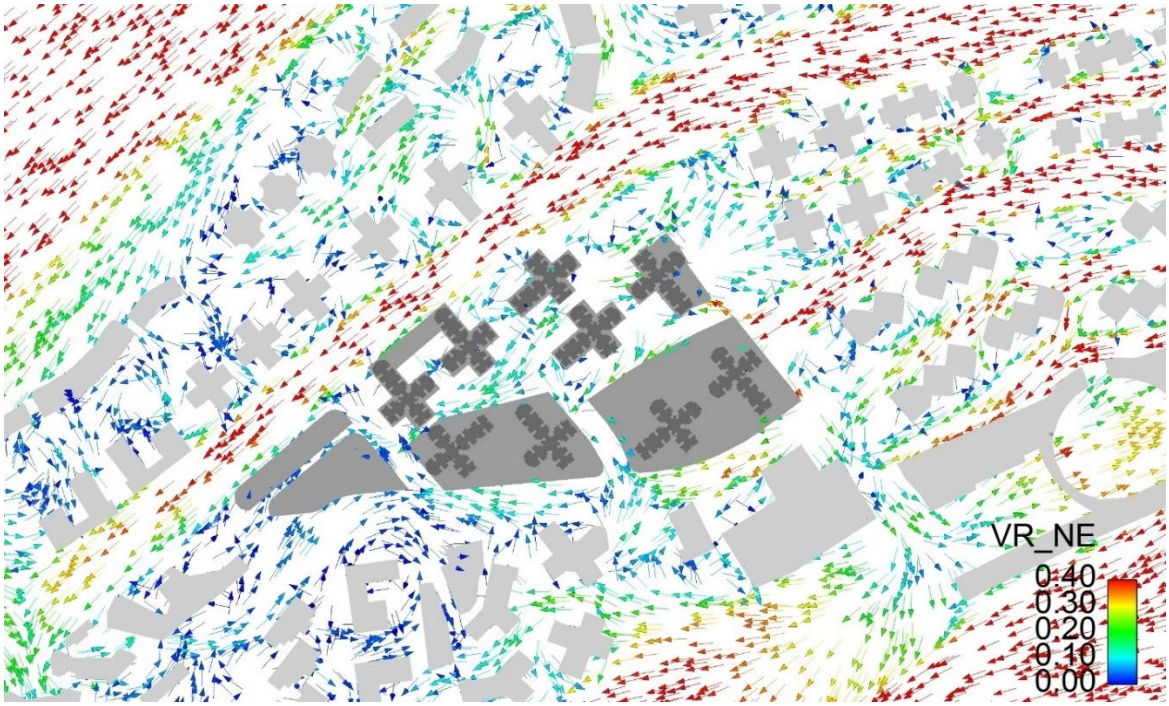

Figure C31 Vector Plot of VR under NE Wind

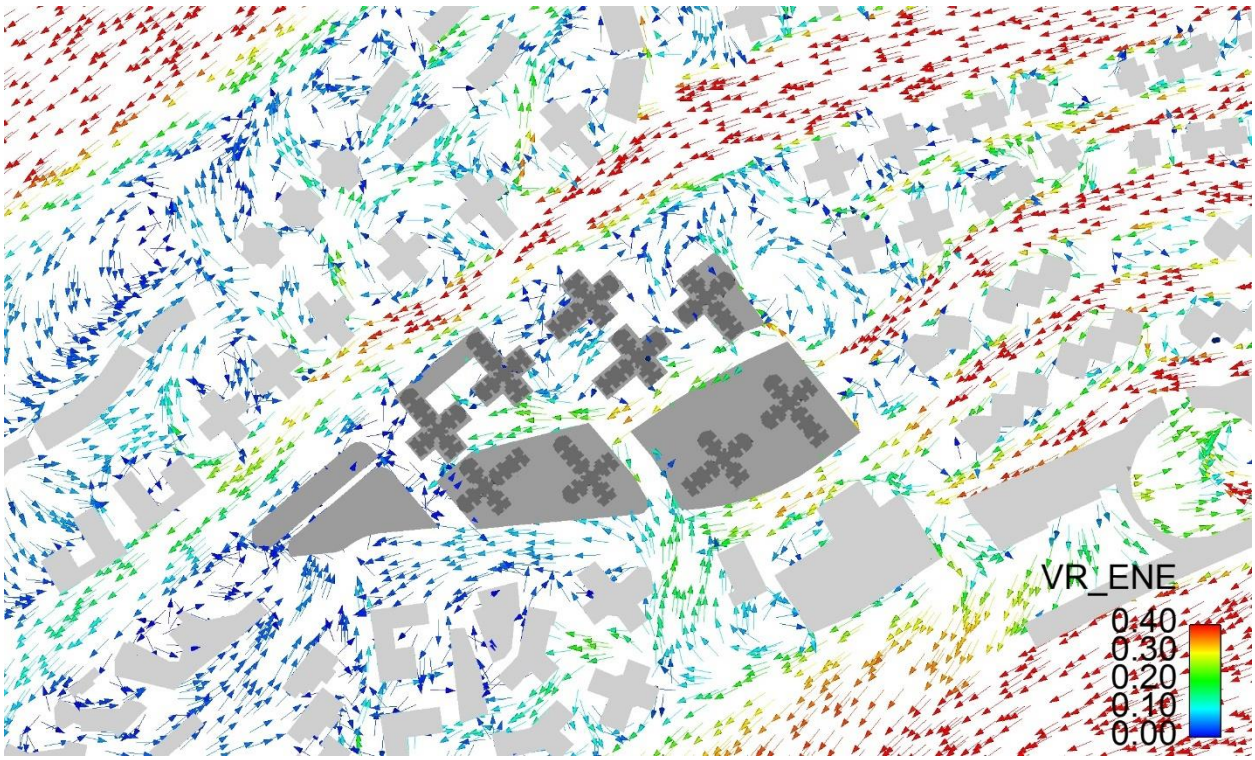

Figure C32 Vector Plot of VR under ENE Wind

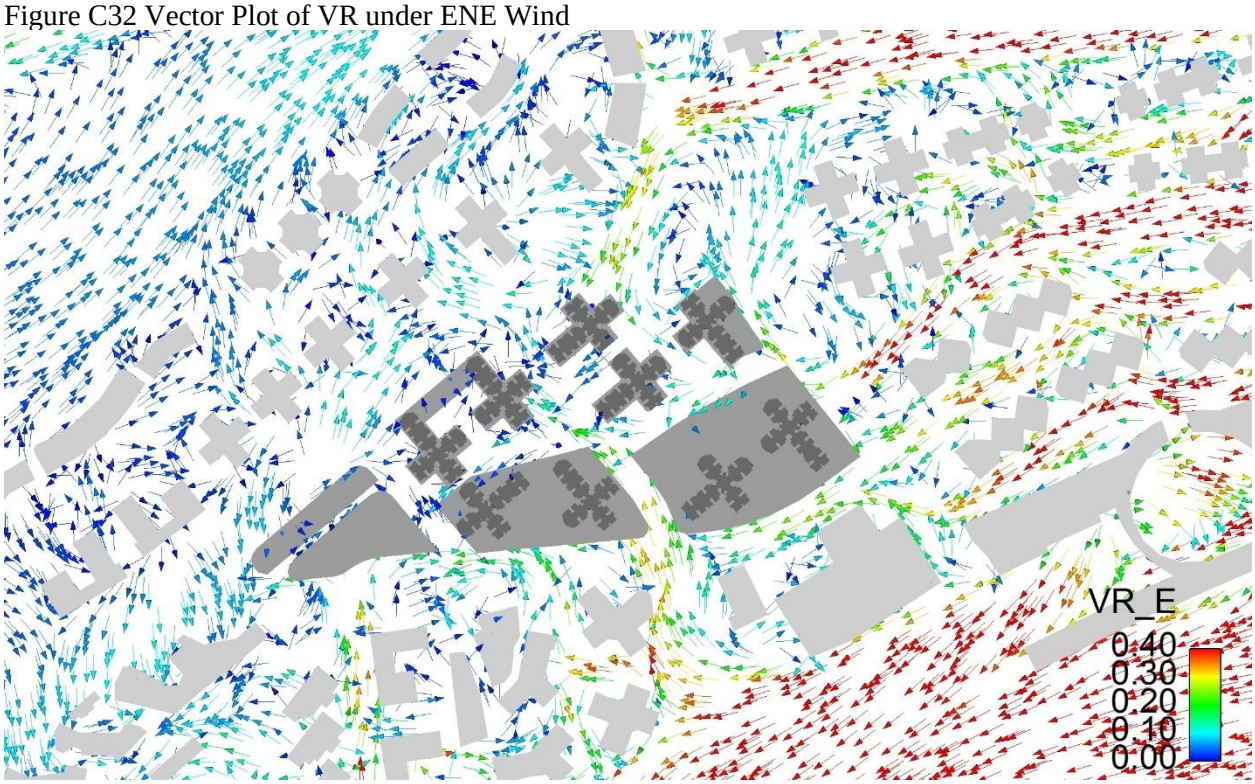

Figure C33 Vector Plot of VR under E Wind

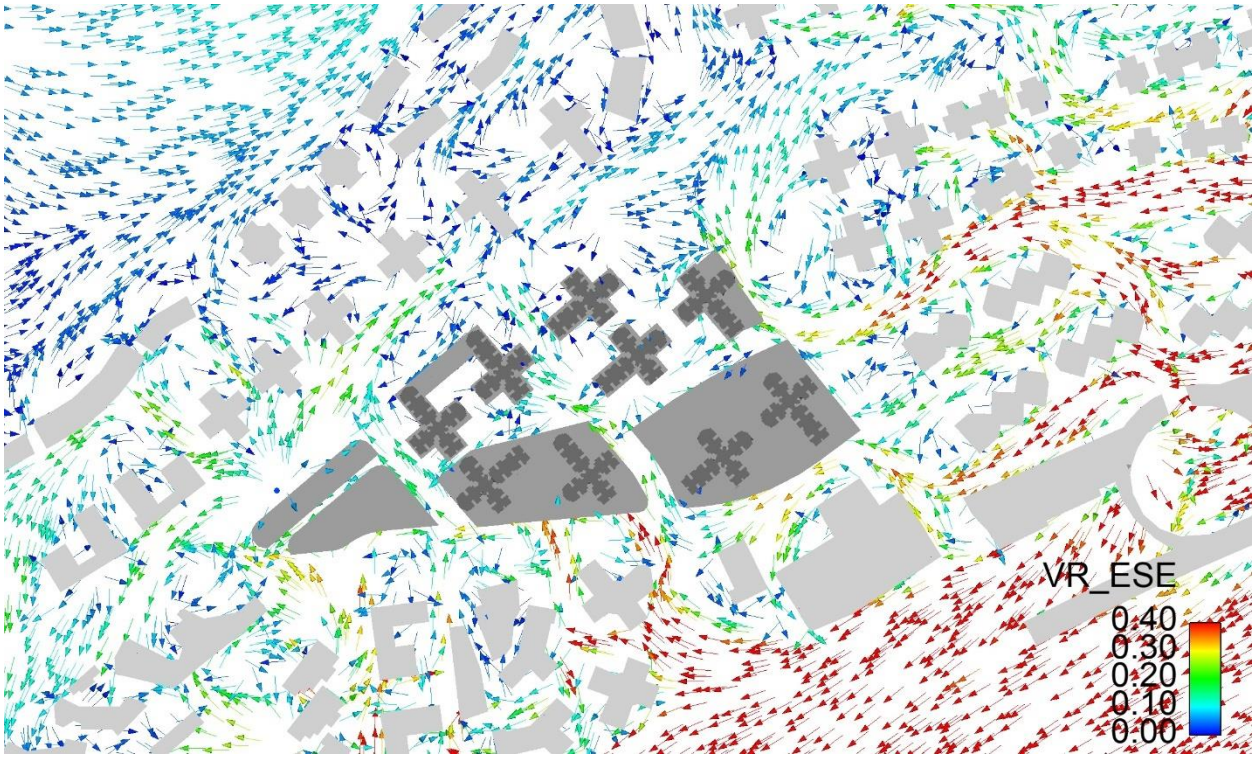

Figure C34 Vector Plot of VR under ESE Wind

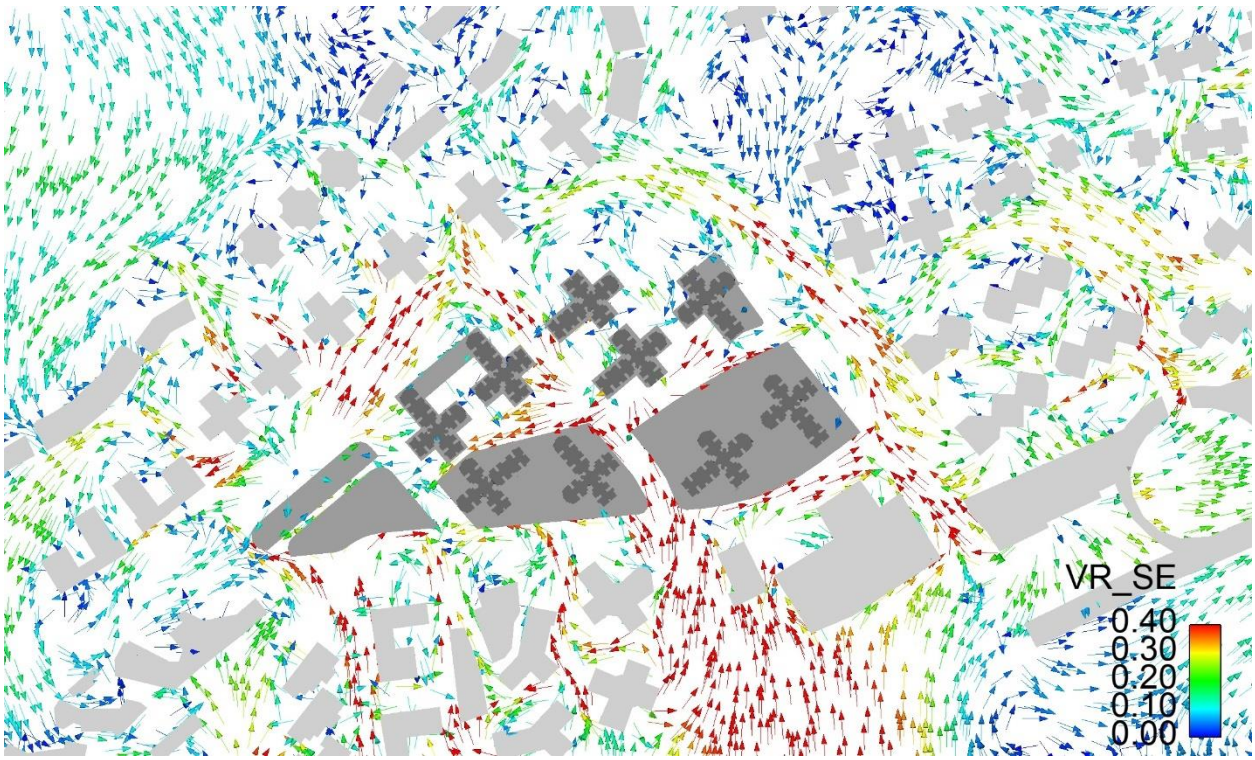

Figure C35 Vector Plot of VR under SE Wind

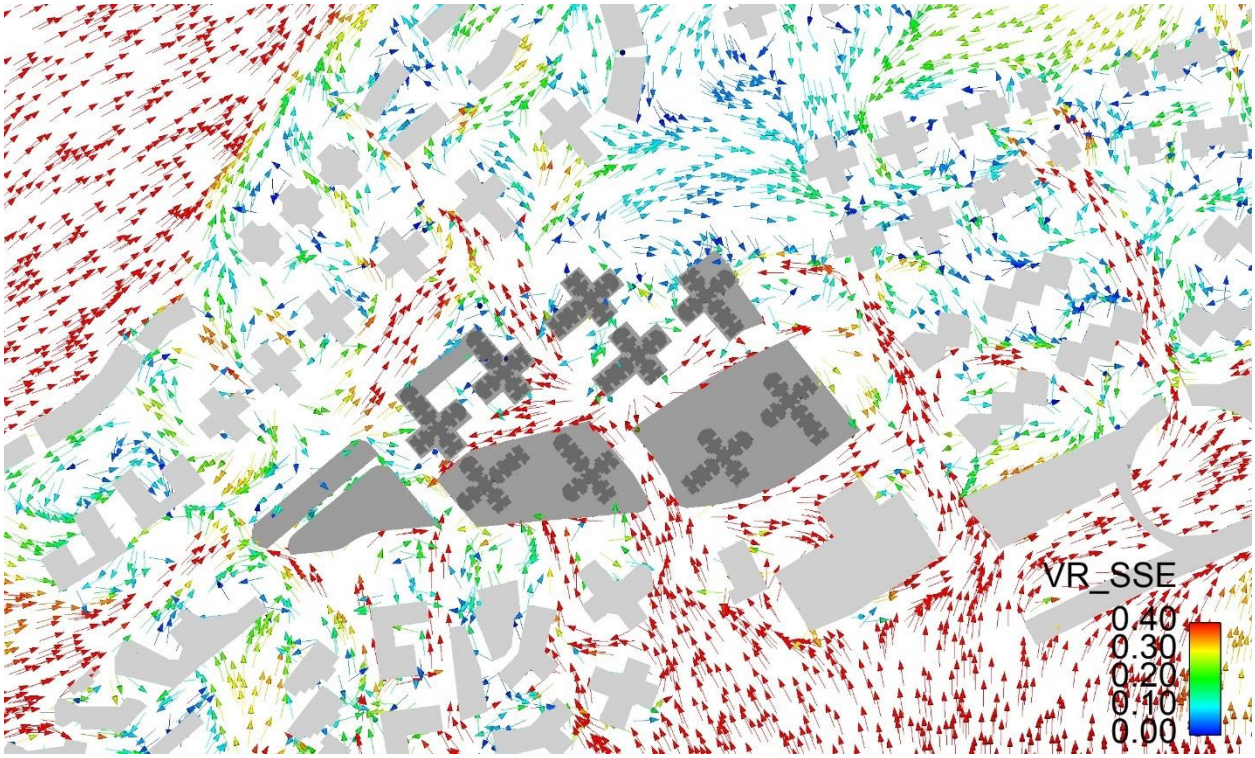

Figure C36 Vector Plot of VR under SSE Wind

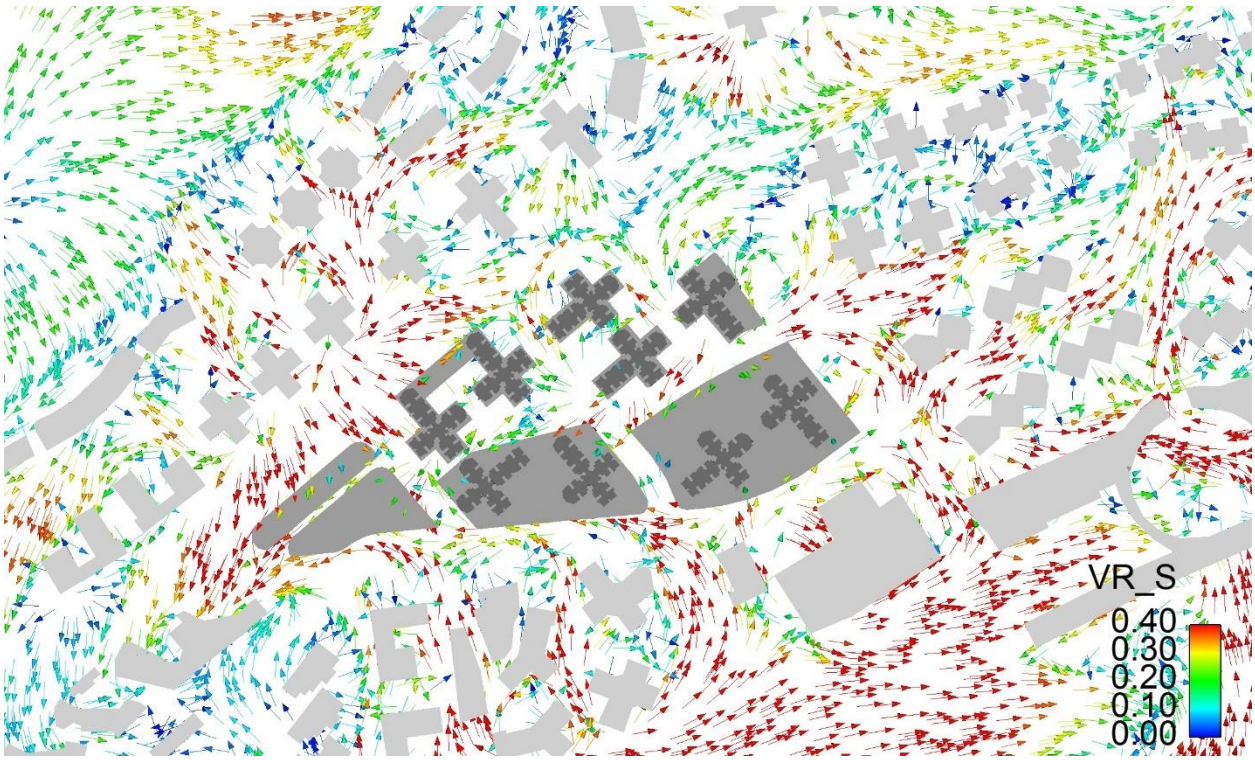

Figure C37 Vector Plot of VR under S Wind

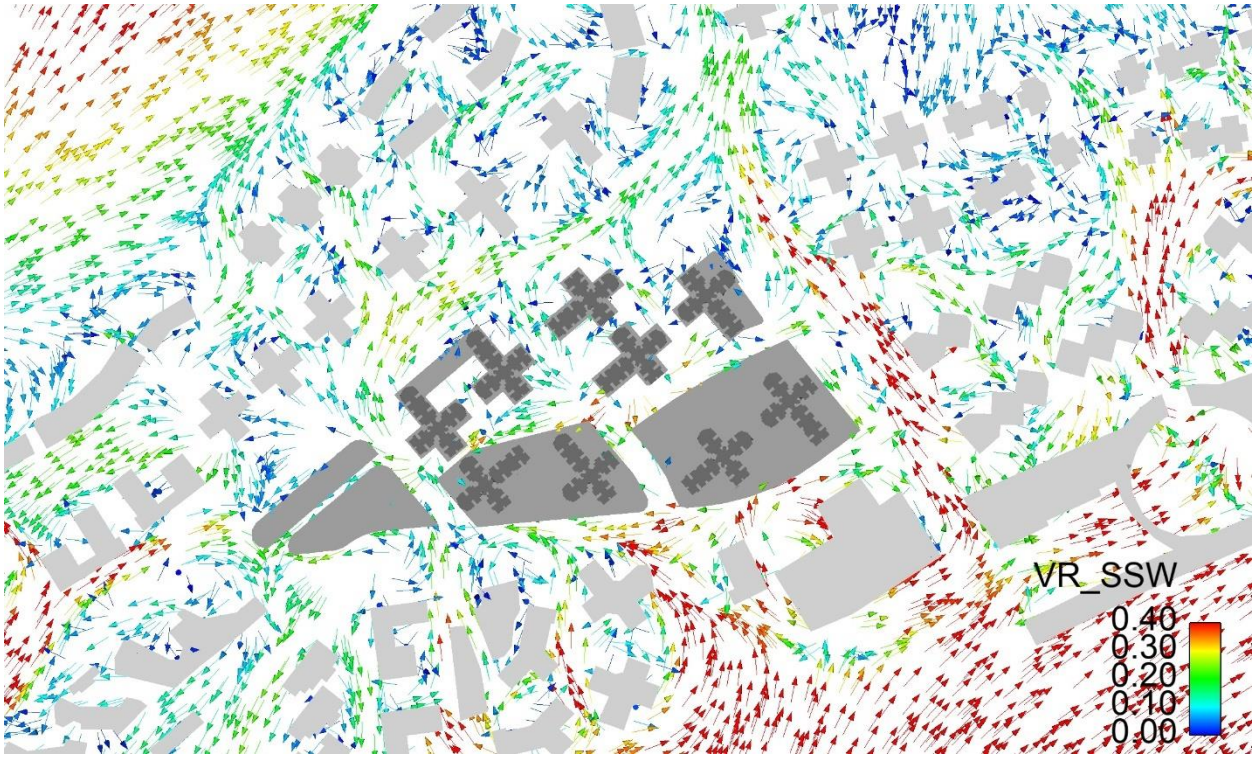

Figure C38 Vector Plot of VR under SSW Wind

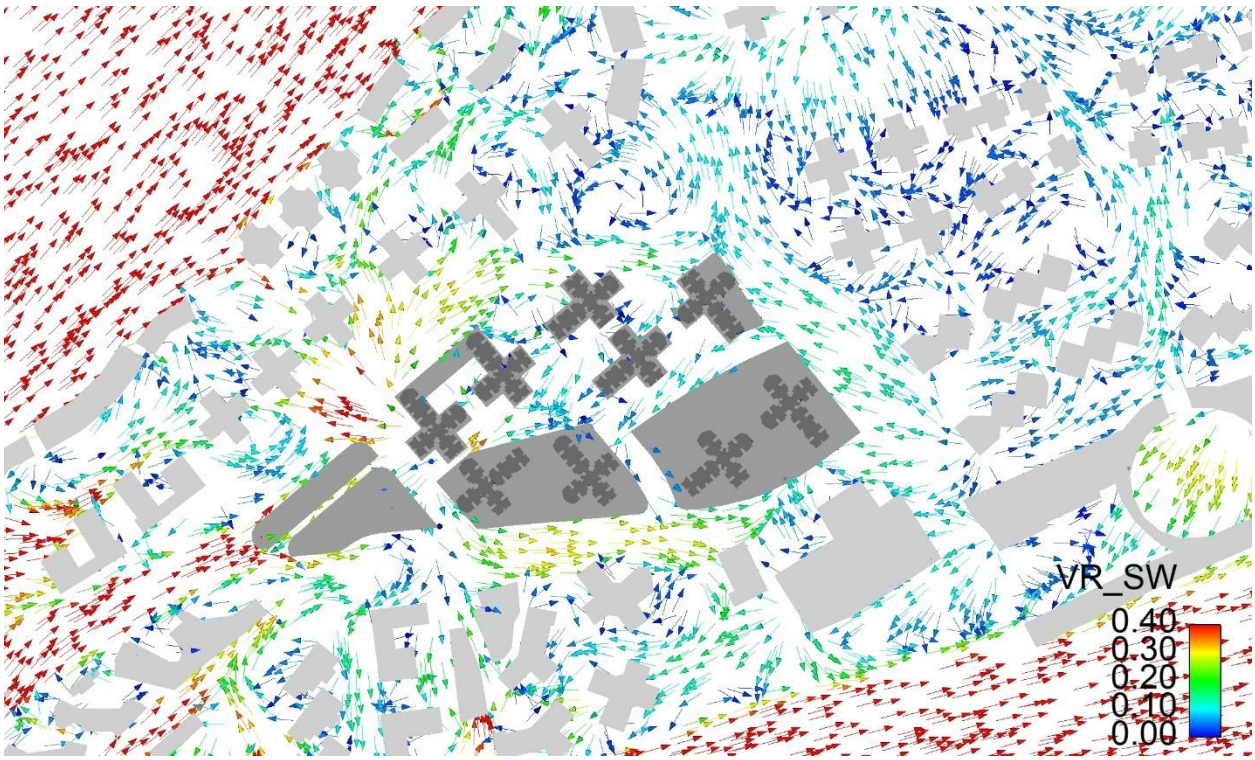

Figure C39 Vector Plot of VR under SW Wind

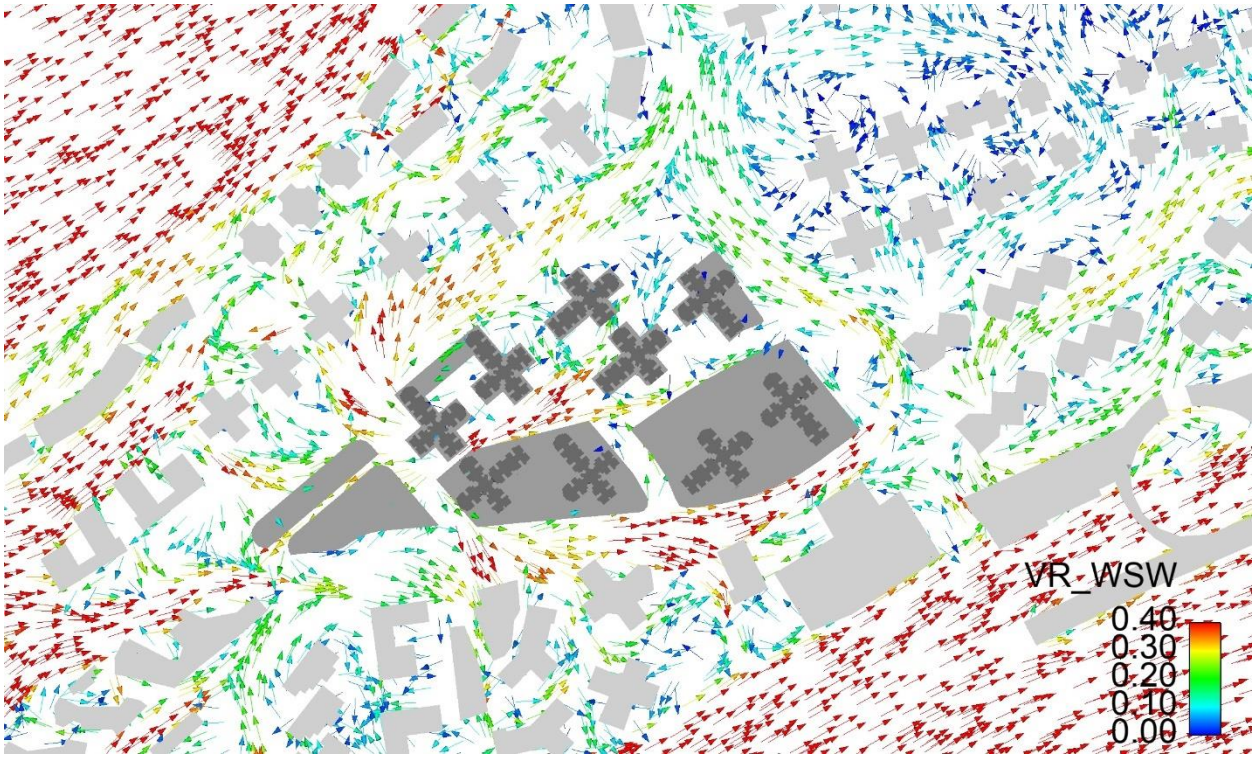

Figure C40 Vector Plot of VR under WSW Wind

C2 Proposed scheme

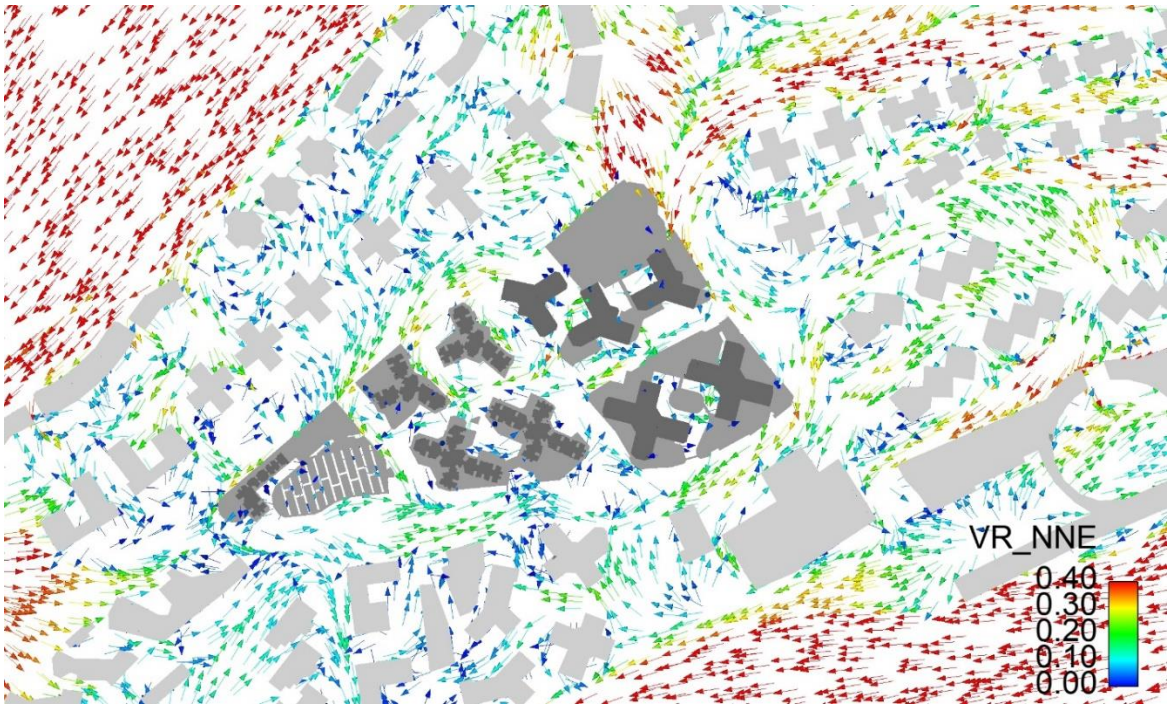

Figure C41 Vector Plot of VR under NNE Wind

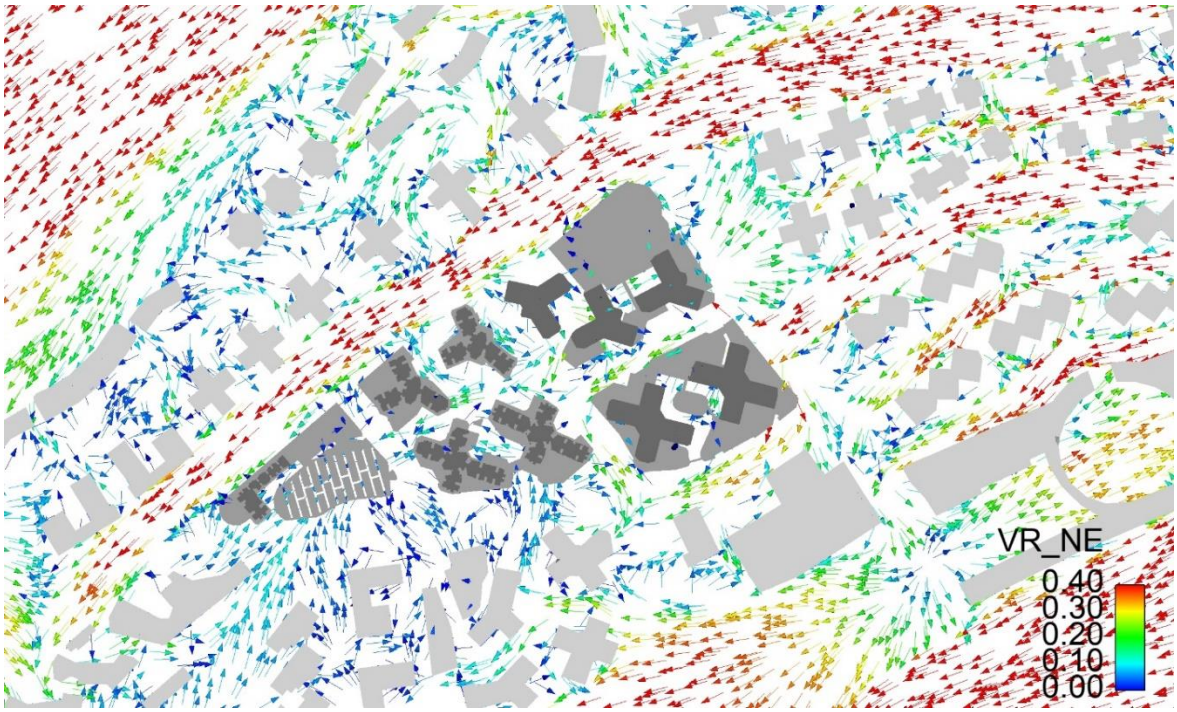

Figure C42 Vector Plot of VR under NE Wind

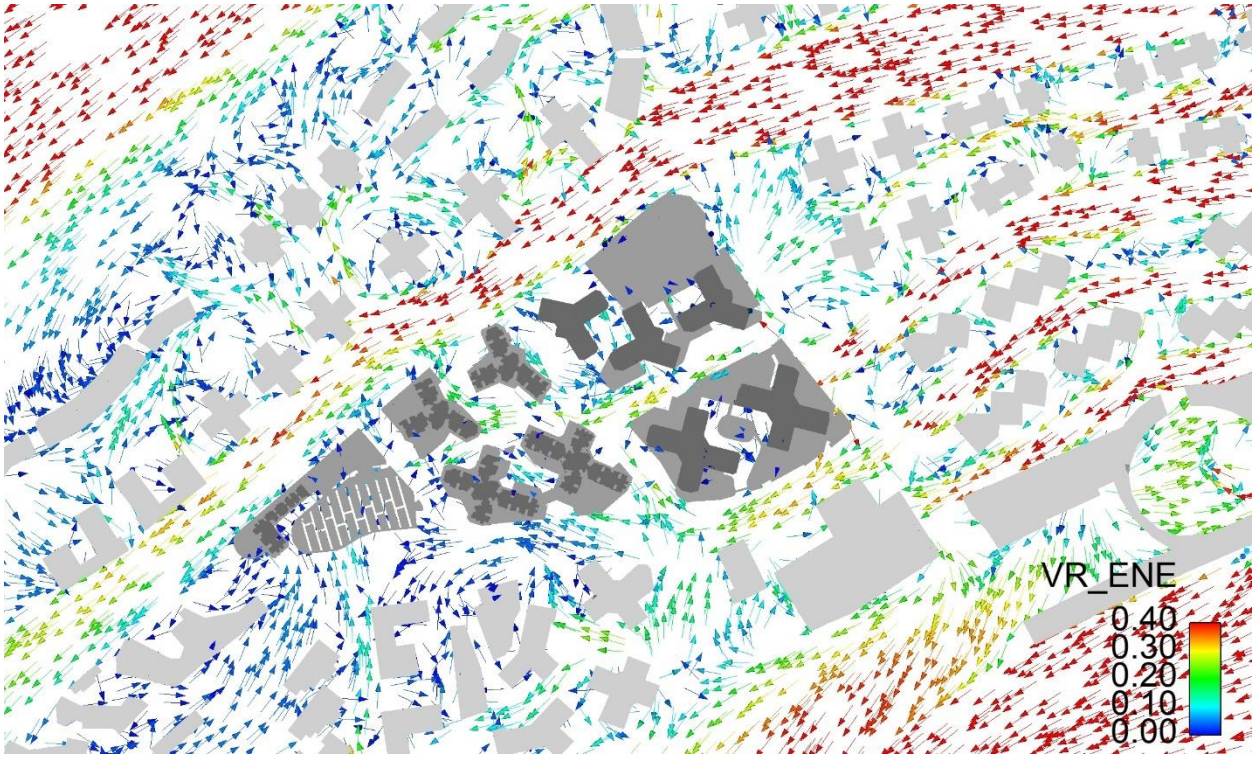

Figure C43 Vector Plot of VR under ENE Wind

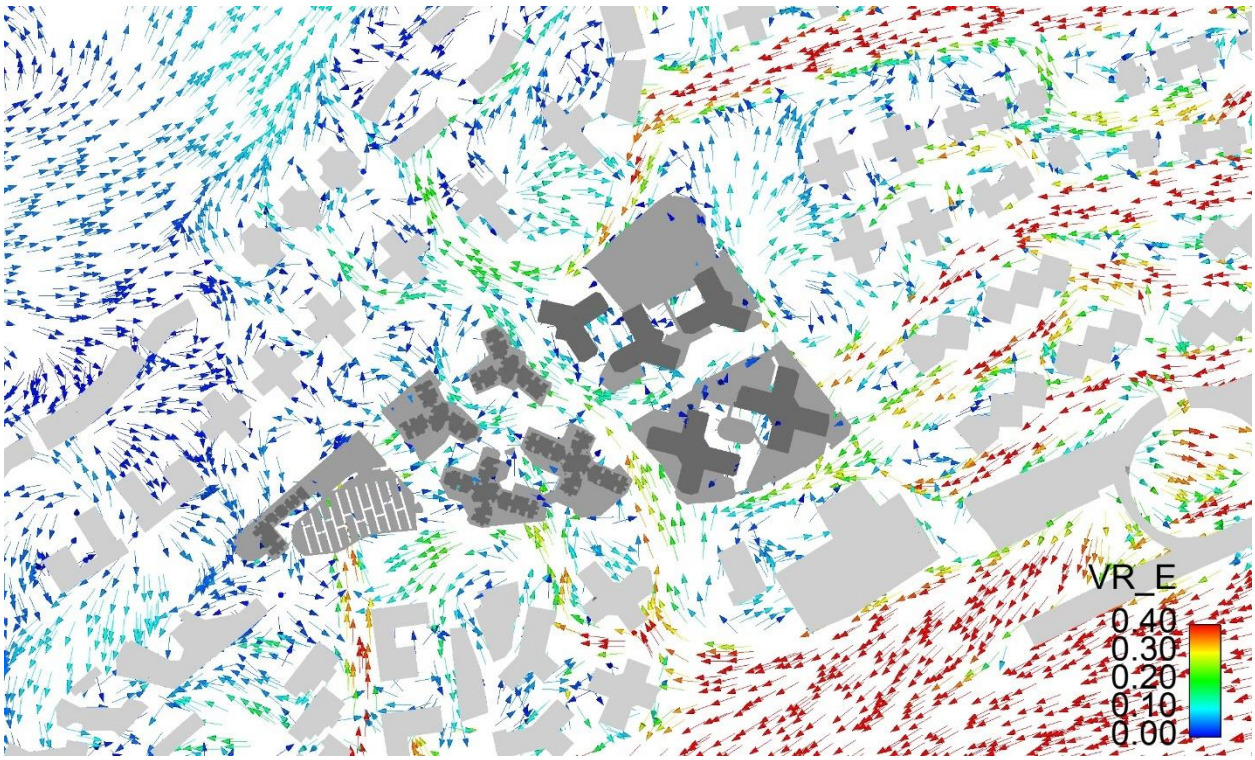

Figure C44 Vector Plot of VR under E Wind

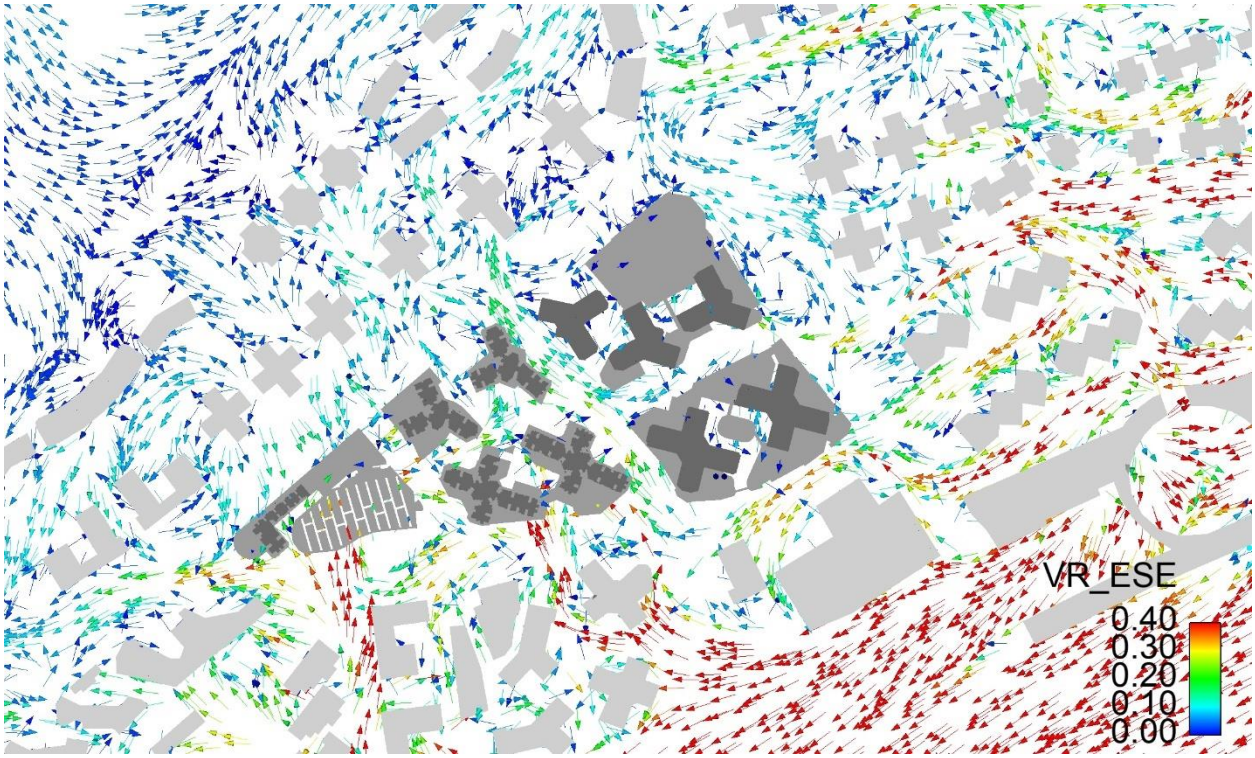

Figure C45 Vector Plot of VR under ESE Wind

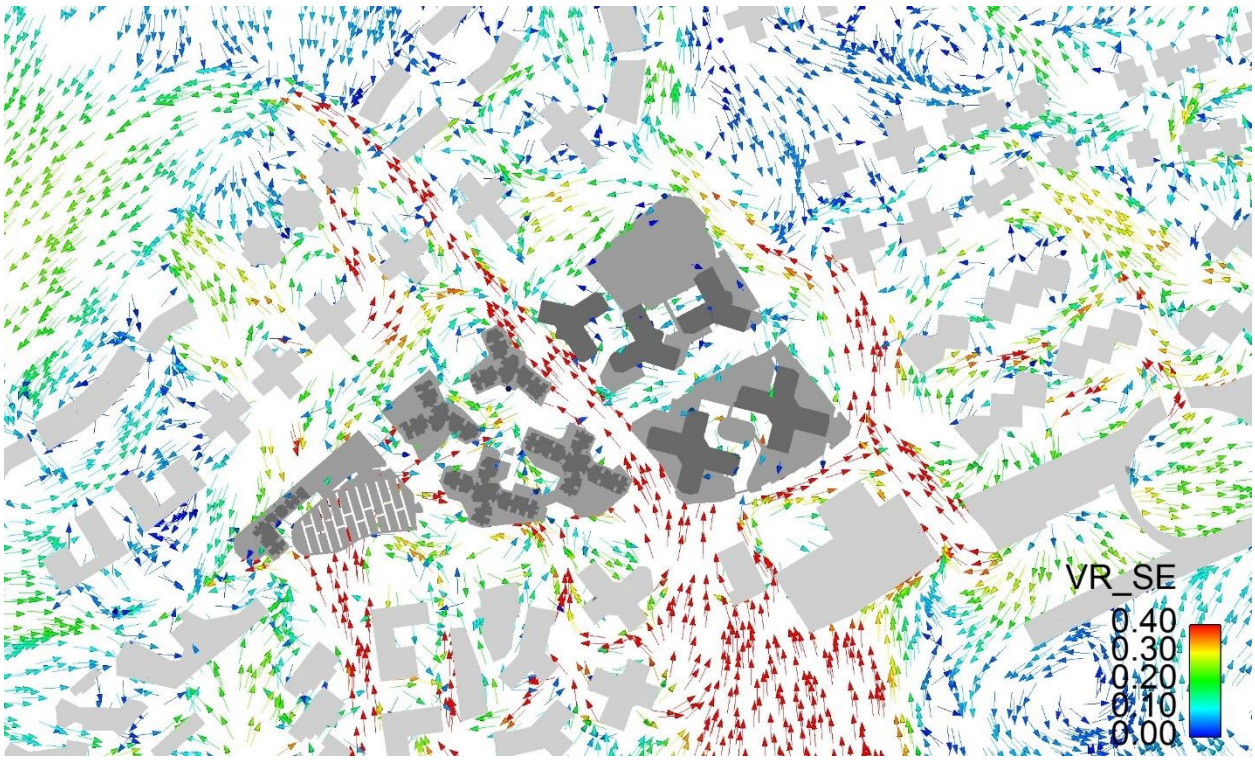

Figure C46 Vector Plot of VR under SE Wind

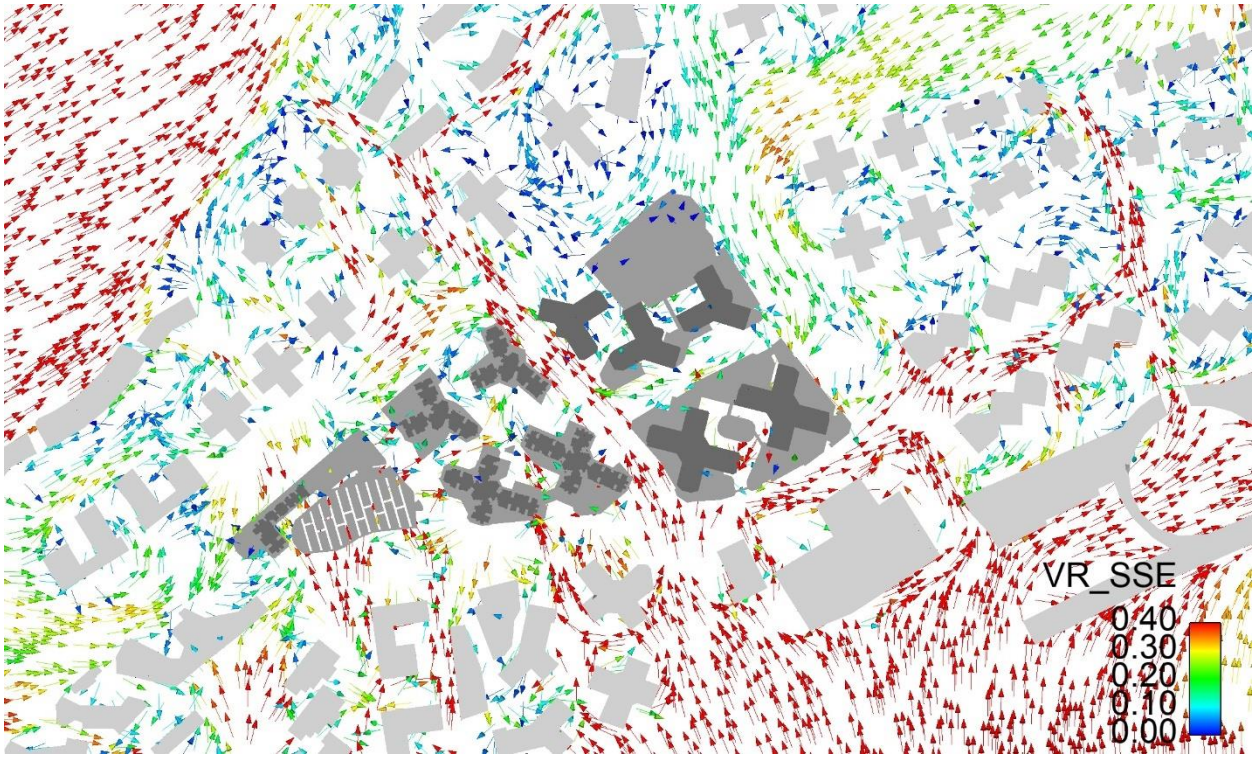

Figure C47 Vector Plot of VR under SSE Wind

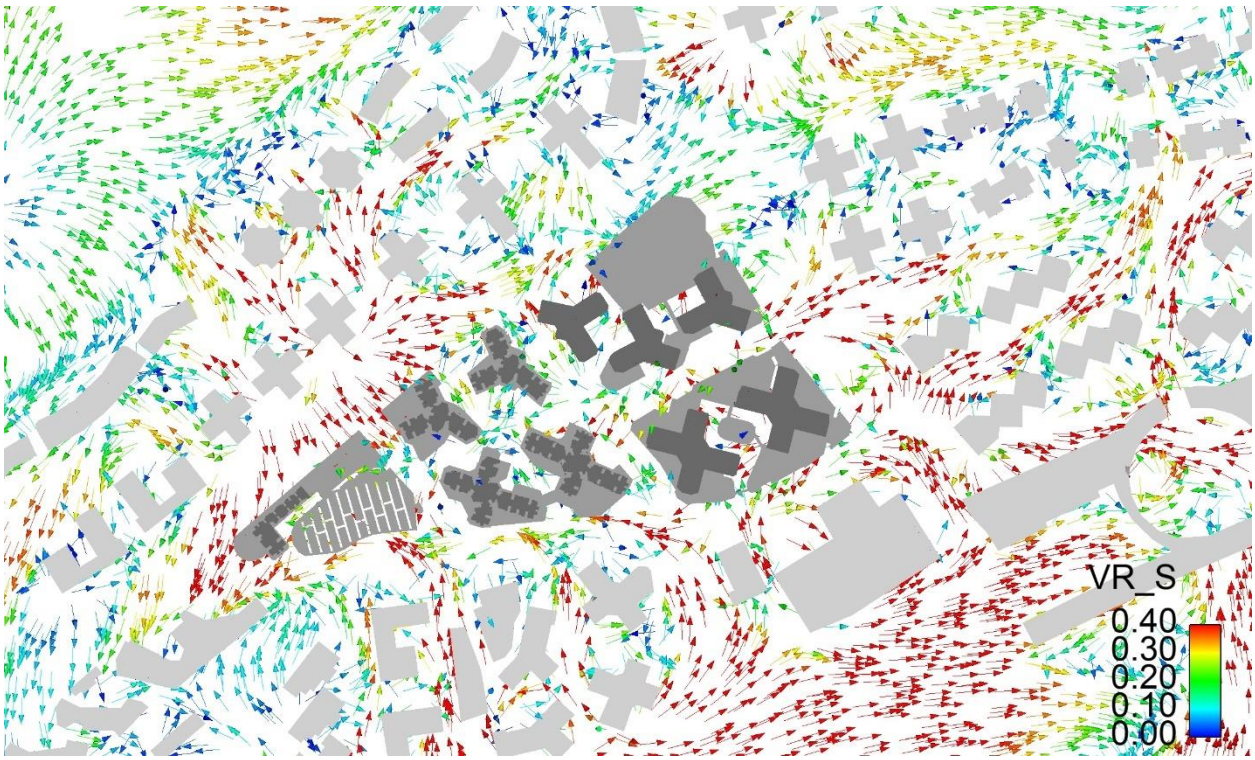

Figure C48 Vector Plot of VR under S Wind

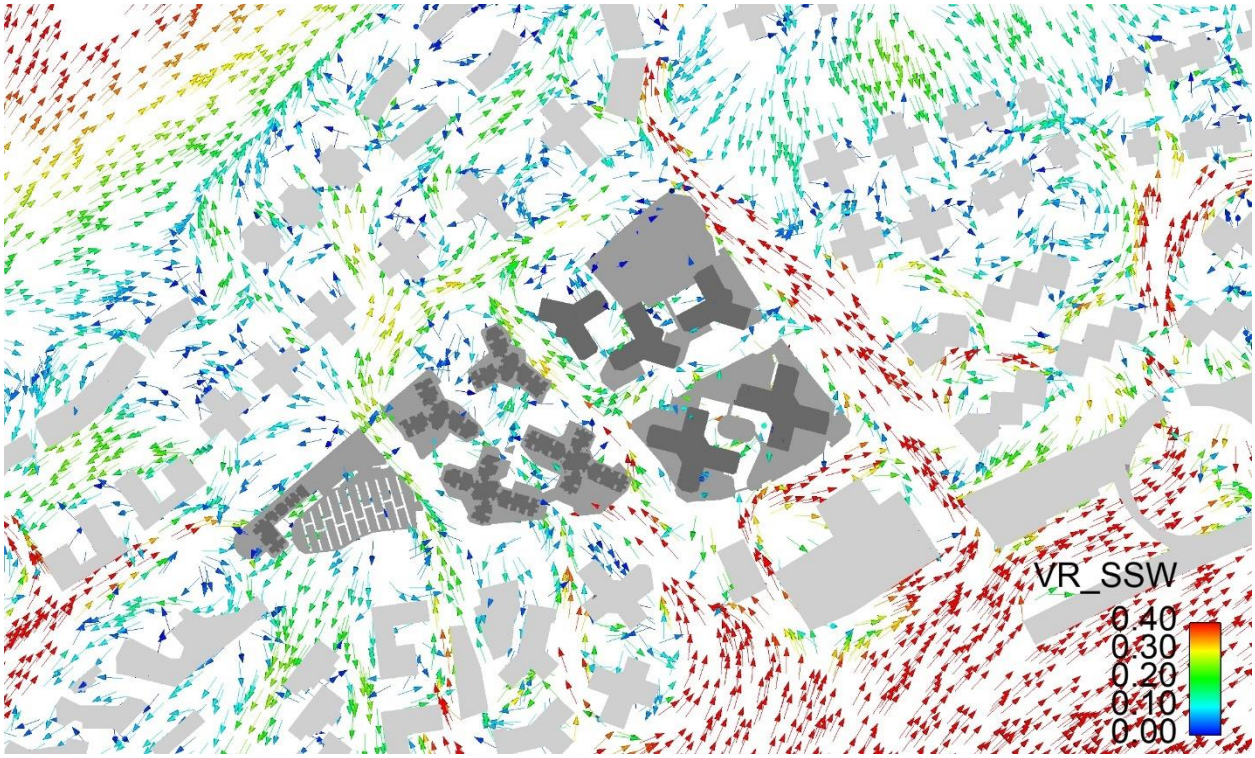

Figure C49 Vector Plot of VR under SSW Wind

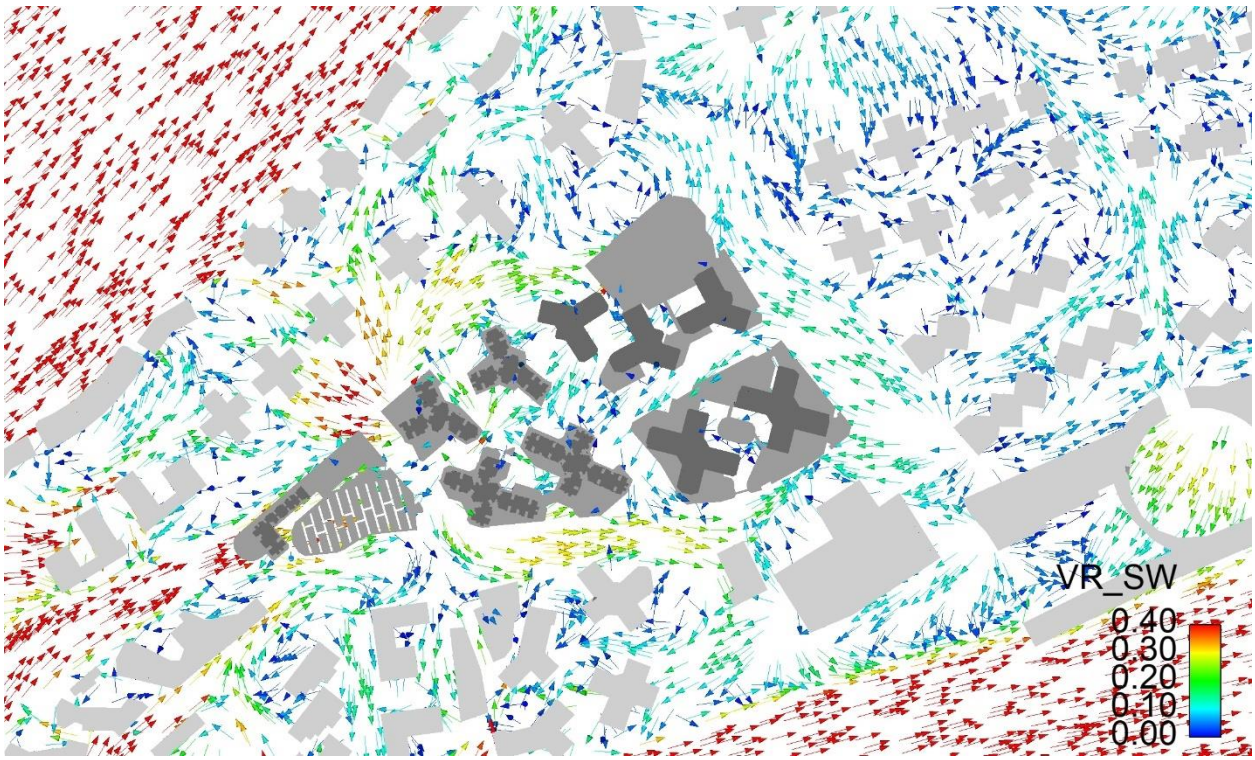

Figure C50 Vector Plot of VR under SW Wind

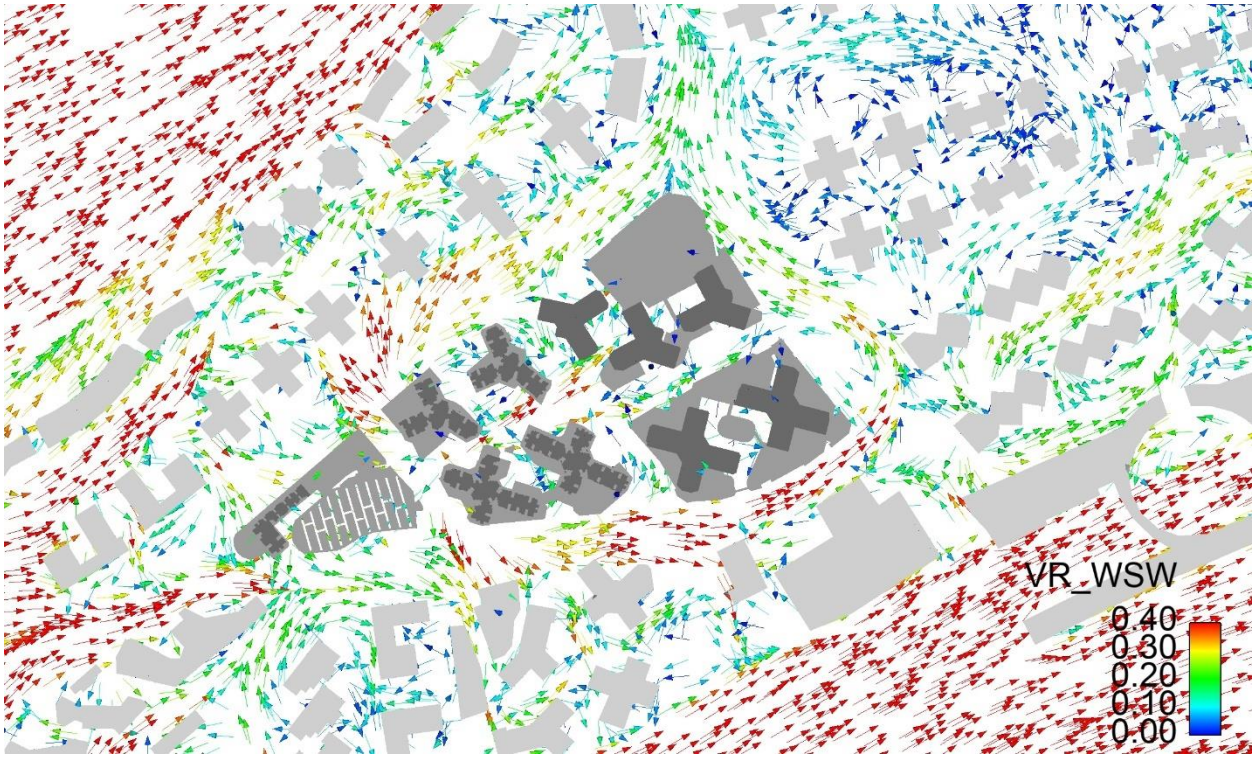

Figure C51 Vector Plot of VR under WSW Wind

Appendix D

Velocity Ratio at Test Points

D3 Baseline scheme

Table D1 Velocity Ratio of Perimeter Test Points

Baseline	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW
P1	0.18	0.15	0.05	0.08	0.13	0.12	0.18	0.50	0.20	0.47	0.11
P2	0.11	0.22	0.08	0.07	0.09	0.11	0.10	0.51	0.03	0.19	0.19
P3	0.06	0.22	0.07	0.03	0.09	0.10	0.06	0.45	0.09	0.13	0.24
P4	0.05	0.20	0.04	0.08	0.14	0.30	0.27	0.43	0.06	0.22	0.18
P5	0.19	0.21	0.06	0.06	0.10	0.34	0.43	0.59	0.19	0.41	0.43
P6	0.14	0.25	0.08	0.02	0.04	0.17	0.16	0.36	0.06	0.20	0.18
P7	0.17	0.25	0.08	0.04	0.07	0.08	0.05	0.24	0.07	0.22	0.20
P8	0.12	0.33	0.22	0.06	0.05	0.33	0.24	0.28	0.06	0.17	0.28
P9	0.21	0.17	0.07	0.03	0.06	0.34	0.68	0.16	0.10	0.09	0.13
P10	0.17	0.13	0.05	0.09	0.13	0.38	0.77	0.22	0.14	0.10	0.27
P11	0.09	0.13	0.28	0.20	0.22	0.65	1.17	0.43	0.33	0.03	0.33
P12	0.03	0.07	0.21	0.23	0.26	0.59	1.22	0.26	0.23	0.03	0.03
P13	0.15	0.14	0.15	0.28	0.21	0.60	1.22	0.17	0.16	0.07	0.16
P14	0.11	0.14	0.10	0.20	0.31	0.38	0.69	0.36	0.21	0.27	0.37
P15	0.06	0.13	0.09	0.13	0.16	0.19	0.21	0.32	0.21	0.24	0.15
P16	0.02	0.11	0.09	0.22	0.35	0.44	0.51	0.32	0.16	0.23	0.20
P17	0.10	0.07	0.05	0.08	0.20	0.23	0.22	0.27	0.11	0.25	0.43
P18	0.16	0.05	0.03	0.17	0.15	0.40	0.38	0.19	0.21	0.03	0.18
P19	0.15	0.06	0.04	0.20	0.30	0.49	0.50	0.34	0.21	0.13	0.10

Baseline	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW
P20	0.16	0.03	0.02	0.17	0.23	0.36	0.37	0.35	0.22	0.27	0.06
P21	0.17	0.04	0.01	0.09	0.29	0.28	0.09	0.41	0.18	0.33	0.16
P22	0.19	0.08	0.06	0.07	0.13	0.35	0.66	0.35	0.16	0.12	0.13
P23	0.19	0.16	0.07	0.10	0.03	0.09	0.08	0.13	0.10	0.17	0.24
P24	0.14	0.22	0.13	0.22	0.01	0.07	0.07	0.17	0.11	0.16	0.18
P25	0.24	0.35	0.27	0.24	0.05	0.12	0.09	0.10	0.17	0.03	0.15
P26	0.39	0.33	0.27	0.07	0.06	0.28	0.07	0.18	0.11	0.08	0.12
P27	0.31	0.15	0.05	0.07	0.12	0.26	0.03	0.23	0.05	0.11	0.18
P28	0.25	0.07	0.10	0.08	0.23	0.12	0.09	0.24	0.07	0.10	0.19
P29	0.24	0.06	0.13	0.20	0.23	0.06	0.15	0.14	0.09	0.09	0.08
P30	0.15	0.37	0.36	0.31	0.14	0.08	0.24	0.29	0.10	0.12	0.07
P31	0.07	0.24	0.15	0.11	0.12	0.07	0.25	0.26	0.24	0.11	0.16
P32	0.26	0.37	0.27	0.10	0.09	0.05	0.12	0.19	0.16	0.11	0.10
P33	0.19	0.23	0.27	0.22	0.31	0.59	0.78	0.28	0.33	0.11	0.42
P34	0.23	0.26	0.28	0.22	0.32	0.67	0.96	0.49	0.43	0.12	0.38
P35	0.19	0.20	0.20	0.16	0.18	0.57	1.12	0.23	0.16	0.12	0.38
P36	0.03	0.14	0.09	0.12	0.07	0.31	0.41	0.42	0.39	0.18	0.37
P37	0.11	0.11	0.06	0.21	0.15	0.59	1.05	0.11	0.17	0.07	0.24
P38	0.12	0.10	0.24	0.20	0.22	0.43	0.85	0.32	0.20	0.08	0.12
P39	0.04	0.04	0.03	0.11	0.12	0.28	0.58	0.12	0.10	0.05	0.25
P40	0.09	0.10	0.08	0.04	0.11	0.39	0.60	0.31	0.14	0.12	0.15

Table D2 Velocity Ratio of Overall Test Points

Baseline	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW
O1	0.17	0.33	0.15	0.08	0.07	0.06	0.32	0.07	0.24	0.57	0.39
O2	0.06	0.36	0.17	0.08	0.19	0.12	0.17	0.30	0.33	0.34	0.15
O3	0.14	0.38	0.19	0.06	0.20	0.10	0.16	0.29	0.31	0.17	0.08
O4	0.09	0.40	0.20	0.05	0.19	0.21	0.17	0.52	0.10	0.05	0.15
O5	0.08	0.42	0.22	0.08	0.14	0.25	0.28	0.61	0.08	0.06	0.31
O6	0.11	0.43	0.22	0.03	0.17	0.17	0.10	0.65	0.06	0.09	0.13
O7	0.08	0.43	0.16	0.12	0.22	0.43	0.28	0.64	0.11	0.36	0.18
O8	0.13	0.44	0.16	0.10	0.13	0.45	0.49	0.72	0.22	0.39	0.44
O9	0.11	0.45	0.20	0.05	0.04	0.33	0.41	0.47	0.24	0.27	0.32
O10	0.15	0.49	0.36	0.03	0.05	0.15	0.18	0.32	0.19	0.25	0.31
O11	0.12	0.45	0.39	0.10	0.05	0.42	0.45	0.31	0.16	0.23	0.30
O12	0.17	0.07	0.09	0.03	0.06	0.08	0.09	0.25	0.23	0.23	0.51
O13	0.27	0.08	0.13	0.03	0.23	0.27	0.26	0.32	0.15	0.16	0.36
O14	0.06	0.07	0.14	0.02	0.24	0.36	0.23	0.28	0.23	0.16	0.41
O15	0.20	0.08	0.10	0.05	0.17	0.19	0.21	0.26	0.07	0.16	0.20
O16	0.22	0.05	0.04	0.08	0.20	0.41	0.39	0.53	0.09	0.05	0.24
O17	0.07	0.02	0.14	0.09	0.12	0.38	0.33	0.65	0.14	0.15	0.36
O18	0.08	0.09	0.24	0.07	0.16	0.32	0.18	0.47	0.11	0.24	0.22
O19	0.09	0.05	0.17	0.02	0.02	0.08	0.08	0.54	0.07	0.20	0.22
O20	0.09	0.03	0.23	0.10	0.07	0.36	0.30	0.58	0.25	0.32	0.32
O21	0.12	0.07	0.05	0.09	0.02	0.24	0.27	0.53	0.17	0.20	0.14
O22	0.08	0.05	0.13	0.08	0.10	0.41	0.36	0.35	0.14	0.22	0.24

Baseline	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW
O23	0.08	0.08	0.08	0.04	0.02	0.07	0.10	0.13	0.05	0.05	0.18
O24	0.09	0.06	0.06	0.09	0.10	0.26	0.32	0.14	0.17	0.21	0.19
O25	0.08	0.14	0.09	0.08	0.08	0.31	0.48	0.14	0.20	0.21	0.15
O26	0.07	0.08	0.10	0.09	0.08	0.33	0.46	0.10	0.12	0.13	0.19
O27	0.08	0.20	0.19	0.04	0.03	0.14	0.11	0.15	0.04	0.08	0.15
O28	0.25	0.19	0.26	0.11	0.04	0.20	0.37	0.29	0.08	0.08	0.10
O29	0.17	0.48	0.43	0.10	0.09	0.12	0.27	0.26	0.25	0.22	0.32
O30	0.09	0.50	0.48	0.08	0.05	0.12	0.10	0.12	0.19	0.05	0.31
O31	0.15	0.52	0.53	0.15	0.07	0.22	0.14	0.12	0.16	0.03	0.28
O32	0.40	0.50	0.53	0.27	0.09	0.25	0.10	0.09	0.15	0.07	0.22
O33	0.37	0.46	0.51	0.12	0.08	0.07	0.08	0.13	0.17	0.09	0.19
O34	0.25	0.45	0.55	0.17	0.06	0.03	0.07	0.15	0.22	0.07	0.17
O35	0.15	0.46	0.57	0.32	0.03	0.04	0.05	0.34	0.18	0.09	0.09
O36	0.39	0.15	0.07	0.09	0.03	0.15	0.10	0.36	0.12	0.11	0.17
O37	0.36	0.17	0.31	0.35	0.05	0.07	0.05	0.31	0.17	0.10	0.16
O38	0.31	0.39	0.36	0.06	0.08	0.06	0.11	0.17	0.25	0.10	0.16
O39	0.16	0.08	0.06	0.11	0.16	0.21	0.11	0.06	0.35	0.08	0.14
O40	0.06	0.12	0.08	0.10	0.03	0.43	0.15	0.19	0.37	0.07	0.20
O41	0.10	0.12	0.08	0.04	0.06	0.30	0.13	0.41	0.19	0.14	0.27
O42	0.12	0.46	0.19	0.16	0.28	0.23	0.35	0.52	0.18	0.15	0.12
O43	0.20	0.10	0.11	0.09	0.06	0.27	0.34	0.36	0.19	0.15	0.08
O44	0.11	0.14	0.18	0.19	0.12	0.45	0.33	0.41	0.28	0.15	0.31
O45	0.14	0.13	0.13	0.13	0.27	0.55	0.46	0.34	0.39	0.14	0.14

Baseline	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW
O46	0.11	0.07	0.20	0.18	0.22	0.65	0.77	0.59	0.46	0.11	0.17
O47	0.16	0.19	0.19	0.08	0.13	0.57	1.07	0.60	0.55	0.12	0.14
O48	0.25	0.51	0.25	0.19	0.35	0.23	0.55	0.46	0.36	0.06	0.16
O49	0.27	0.57	0.43	0.37	0.41	0.21	0.18	0.42	0.26	0.05	0.09
O50	0.23	0.28	0.46	0.35	0.25	0.24	0.47	0.66	0.20	0.09	0.25
O51	0.25	0.18	0.37	0.30	0.19	0.21	0.39	0.63	0.27	0.06	0.14
O52	0.20	0.10	0.31	0.26	0.17	0.29	0.80	0.47	0.56	0.12	0.09
O53	0.18	0.21	0.16	0.17	0.27	0.39	0.53	0.51	0.29	0.14	0.43
O54	0.21	0.26	0.30	0.26	0.30	0.57	0.65	0.28	0.14	0.06	0.48
O55	0.28	0.33	0.32	0.24	0.32	0.51	1.01	0.34	0.44	0.09	0.46
O56	0.23	0.25	0.24	0.15	0.23	0.28	0.92	0.34	0.40	0.18	0.45
O57	0.17	0.13	0.13	0.13	0.07	0.59	0.39	0.34	0.40	0.23	0.42
O58	0.09	0.18	0.12	0.28	0.48	0.60	1.21	0.55	0.42	0.16	0.15
O59	0.05	0.10	0.18	0.16	0.22	0.62	1.25	0.61	0.56	0.07	0.12
O60	0.07	0.14	0.20	0.25	0.21	0.69	1.33	0.51	0.43	0.15	0.37
O61	0.06	0.05	0.13	0.29	0.29	0.62	1.26	0.49	0.35	0.30	0.48
O62	0.13	0.11	0.08	0.05	0.09	0.15	0.28	0.06	0.32	0.29	0.47
O63	0.12	0.13	0.07	0.12	0.33	0.27	0.51	0.23	0.19	0.29	0.31
O64	0.07	0.10	0.07	0.11	0.08	0.13	0.11	0.18	0.11	0.31	0.35
O65	0.05	0.03	0.06	0.11	0.11	0.13	0.15	0.16	0.11	0.18	0.41
O66	0.14	0.03	0.04	0.04	0.09	0.25	0.30	0.48	0.14	0.07	0.22
O67	0.10	0.01	0.03	0.02	0.06	0.19	0.18	0.18	0.07	0.12	0.18
O68	0.13	0.05	0.03	0.14	0.16	0.29	0.30	0.15	0.07	0.08	0.15

Baseline	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW
O69	0.07	0.05	0.06	0.29	0.39	0.67	0.52	0.22	0.17	0.13	0.21
O70	0.05	0.02	0.07	0.31	0.32	0.66	0.33	0.25	0.19	0.16	0.15
O71	0.06	0.02	0.09	0.34	0.33	0.68	0.40	0.30	0.22	0.15	0.08
O72	0.05	0.05	0.05	0.16	0.24	0.28	0.41	0.28	0.13	0.09	0.20
O73	0.10	0.13	0.17	0.25	0.35	0.32	0.48	0.50	0.30	0.04	0.31
O74	0.09	0.04	0.03	0.11	0.17	0.37	0.48	0.44	0.23	0.04	0.31
O75	0.08	0.02	0.03	0.02	0.23	0.42	0.90	0.49	0.33	0.17	0.09
O76	0.05	0.03	0.02	0.02	0.16	0.23	0.58	0.44	0.18	0.18	0.06
O77	0.07	0.06	0.05	0.04	0.19	0.11	0.16	0.13	0.19	0.14	0.17
O78	0.06	0.03	0.05	0.07	0.09	0.21	0.29	0.12	0.17	0.15	0.22
O79	0.12	0.08	0.04	0.07	0.14	0.23	0.26	0.09	0.15	0.21	0.17
O80	0.12	0.06	0.03	0.12	0.32	0.47	0.46	0.27	0.17	0.16	0.23
O81	0.11	0.03	0.02	0.03	0.22	0.19	0.18	0.38	0.17	0.07	0.30
O82	0.12	0.03	0.02	0.05	0.07	0.06	0.10	0.33	0.08	0.10	0.46
O83	0.22	0.08	0.02	0.08	0.07	0.13	0.29	0.28	0.11	0.33	0.57
O84	0.17	0.26	0.08	0.11	0.20	0.11	0.44	0.32	0.08	0.60	0.46

D4 Proposed scheme

Table D3 Velocity Ratio of Perimeter Test Points

Proposed	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW
P1	0.16	0.06	0.09	0.03	0.09	0.15	0.24	0.50	0.16	0.47	0.11
P2	0.27	0.21	0.12	0.03	0.07	0.21	0.23	0.51	0.12	0.19	0.19
P3	0.16	0.20	0.12	0.04	0.08	0.19	0.28	0.45	0.09	0.13	0.24
P4	0.16	0.12	0.06	0.02	0.04	0.32	0.19	0.43	0.01	0.22	0.18
P5	0.28	0.09	0.02	0.07	0.15	0.13	0.13	0.59	0.26	0.41	0.43
P6	0.27	0.19	0.11	0.04	0.06	0.07	0.09	0.36	0.04	0.20	0.18
P7	0.29	0.28	0.17	0.07	0.02	0.08	0.15	0.24	0.03	0.22	0.20
P8	0.26	0.34	0.28	0.15	0.06	0.46	0.92	0.28	0.06	0.17	0.28
P9	0.20	0.11	0.10	0.14	0.16	0.67	1.28	0.16	0.26	0.09	0.13
P10	0.12	0.07	0.08	0.16	0.18	0.75	1.39	0.22	0.32	0.10	0.27
P11	0.07	0.08	0.23	0.24	0.26	0.78	1.31	0.43	0.33	0.03	0.33
P12	0.13	0.20	0.21	0.28	0.26	0.78	1.54	0.26	0.45	0.03	0.03
P13	0.05	0.23	0.19	0.26	0.17	0.58	1.21	0.17	0.22	0.07	0.16
P14	0.05	0.07	0.14	0.04	0.23	0.29	0.14	0.36	0.38	0.27	0.37
P15	0.09	0.05	0.06	0.09	0.20	0.15	0.30	0.32	0.10	0.24	0.15
P16	0.07	0.04	0.05	0.24	0.34	0.51	0.42	0.32	0.19	0.23	0.20
P17	0.04	0.03	0.04	0.23	0.28	0.22	0.45	0.27	0.04	0.25	0.43
P18	0.15	0.04	0.03	0.08	0.06	0.11	0.33	0.19	0.16	0.03	0.18
P19	0.15	0.05	0.06	0.15	0.32	0.60	0.68	0.34	0.05	0.13	0.10
P20	0.08	0.08	0.02	0.02	0.33	0.44	0.46	0.35	0.16	0.27	0.06

Proposed	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW
P21	0.03	0.07	0.06	0.03	0.35	0.36	0.17	0.41	0.08	0.33	0.16
P22	0.03	0.05	0.03	0.02	0.08	0.24	0.28	0.35	0.14	0.12	0.13
P23	0.14	0.12	0.10	0.15	0.03	0.12	0.05	0.13	0.07	0.17	0.24
P24	0.12	0.27	0.24	0.31	0.04	0.19	0.04	0.17	0.09	0.16	0.18
P25	0.23	0.33	0.28	0.15	0.03	0.20	0.13	0.10	0.03	0.03	0.15
P26	0.35	0.31	0.16	0.02	0.08	0.20	0.09	0.18	0.20	0.08	0.12
P27	0.33	0.05	0.09	0.09	0.08	0.24	0.14	0.23	0.42	0.11	0.18
P28	0.35	0.08	0.12	0.15	0.03	0.11	0.14	0.24	0.19	0.10	0.19
P29	0.35	0.07	0.16	0.23	0.15	0.14	0.25	0.14	0.07	0.09	0.08
P30	0.12	0.37	0.33	0.30	0.22	0.15	0.29	0.29	0.07	0.12	0.07
P31	0.04	0.22	0.22	0.15	0.07	0.12	0.36	0.26	0.07	0.11	0.16
P32	0.29	0.31	0.13	0.09	0.10	0.52	0.45	0.19	0.25	0.11	0.10
P33	0.19	0.28	0.28	0.25	0.28	0.59	0.99	0.28	0.44	0.11	0.42
P34	0.19	0.24	0.25	0.23	0.30	0.67	1.09	0.49	0.51	0.12	0.38
P35	0.07	0.06	0.11	0.12	0.03	0.47	1.06	0.23	0.11	0.12	0.38
P36	0.10	0.07	0.06	0.14	0.10	0.44	0.91	0.42	0.13	0.18	0.37
P37	0.04	0.18	0.18	0.18	0.16	0.61	1.23	0.11	0.20	0.07	0.24
P38	0.06	0.23	0.20	0.23	0.24	0.83	1.55	0.32	0.38	0.08	0.12
P39	0.11	0.16	0.06	0.17	0.17	0.74	1.41	0.12	0.21	0.05	0.25
P40	0.13	0.07	0.05	0.09	0.12	0.61	1.02	0.31	0.23	0.12	0.15

Table D4 Velocity Ratio of Overall Test Points

Proposed	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW
O1	0.09	0.29	0.28	0.10	0.11	0.05	0.23	0.07	0.34	0.57	0.39
O2	0.02	0.42	0.30	0.08	0.08	0.07	0.20	0.30	0.40	0.34	0.15
O3	0.06	0.44	0.29	0.06	0.07	0.02	0.05	0.29	0.39	0.17	0.08
O4	0.04	0.47	0.28	0.04	0.06	0.14	0.24	0.52	0.09	0.05	0.15
O5	0.06	0.43	0.27	0.05	0.10	0.20	0.35	0.61	0.06	0.06	0.31
O6	0.17	0.38	0.25	0.02	0.16	0.37	0.40	0.65	0.07	0.09	0.13
O7	0.07	0.35	0.21	0.02	0.12	0.14	0.08	0.64	0.06	0.36	0.18
O8	0.17	0.38	0.23	0.05	0.09	0.26	0.35	0.72	0.25	0.39	0.44
O9	0.18	0.42	0.25	0.05	0.05	0.22	0.33	0.47	0.18	0.27	0.32
O10	0.23	0.46	0.36	0.03	0.10	0.17	0.26	0.32	0.09	0.25	0.31
O11	0.18	0.49	0.48	0.16	0.13	0.66	1.08	0.31	0.14	0.23	0.30
O12	0.16	0.06	0.02	0.01	0.08	0.08	0.11	0.25	0.23	0.23	0.51
O13	0.28	0.10	0.24	0.01	0.09	0.04	0.09	0.32	0.13	0.16	0.36
O14	0.11	0.05	0.11	0.03	0.09	0.06	0.22	0.28	0.21	0.16	0.41
O15	0.23	0.06	0.07	0.03	0.08	0.29	0.10	0.26	0.06	0.16	0.20
O16	0.23	0.07	0.04	0.03	0.06	0.28	0.40	0.53	0.09	0.05	0.24
O17	0.05	0.12	0.21	0.09	0.06	0.36	0.33	0.65	0.19	0.15	0.36
O18	0.09	0.16	0.25	0.07	0.11	0.36	0.19	0.47	0.09	0.24	0.22
O19	0.04	0.04	0.30	0.11	0.09	0.08	0.10	0.54	0.08	0.20	0.22
O20	0.08	0.07	0.30	0.06	0.12	0.47	0.44	0.58	0.28	0.32	0.32
O21	0.15	0.03	0.05	0.03	0.13	0.33	0.36	0.53	0.26	0.20	0.14
O22	0.05	0.08	0.18	0.18	0.12	0.22	0.16	0.35	0.15	0.22	0.24

Proposed	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW
O23	0.09	0.07	0.09	0.05	0.05	0.25	0.19	0.13	0.04	0.05	0.18
O24	0.11	0.06	0.03	0.11	0.09	0.29	0.49	0.14	0.12	0.21	0.19
O25	0.12	0.16	0.13	0.18	0.12	0.35	0.74	0.14	0.23	0.21	0.15
O26	0.08	0.08	0.10	0.17	0.07	0.39	0.51	0.10	0.12	0.13	0.19
O27	0.10	0.13	0.05	0.07	0.01	0.09	0.06	0.15	0.04	0.08	0.15
O28	0.24	0.17	0.11	0.15	0.02	0.27	0.09	0.29	0.03	0.08	0.10
O29	0.08	0.48	0.49	0.13	0.02	0.27	0.11	0.26	0.29	0.22	0.32
O30	0.06	0.52	0.54	0.11	0.02	0.26	0.05	0.12	0.27	0.05	0.31
O31	0.16	0.56	0.57	0.14	0.02	0.24	0.11	0.12	0.12	0.03	0.28
O32	0.45	0.56	0.58	0.33	0.04	0.11	0.10	0.09	0.09	0.07	0.22
O33	0.41	0.56	0.59	0.12	0.07	0.14	0.14	0.13	0.13	0.09	0.19
O34	0.27	0.57	0.62	0.20	0.05	0.02	0.17	0.15	0.11	0.07	0.17
O35	0.06	0.53	0.61	0.41	0.11	0.05	0.14	0.34	0.11	0.09	0.09
O36	0.41	0.14	0.05	0.04	0.05	0.10	0.13	0.36	0.11	0.11	0.17
O37	0.39	0.06	0.25	0.45	0.20	0.03	0.15	0.31	0.09	0.10	0.16
O38	0.32	0.46	0.34	0.07	0.09	0.02	0.16	0.17	0.10	0.10	0.16
O39	0.20	0.15	0.12	0.10	0.10	0.11	0.23	0.06	0.10	0.08	0.14
O40	0.07	0.19	0.16	0.13	0.07	0.43	0.20	0.19	0.55	0.07	0.20
O41	0.09	0.18	0.10	0.02	0.04	0.23	0.18	0.41	0.55	0.14	0.27
O42	0.10	0.49	0.23	0.12	0.25	0.24	0.11	0.52	0.60	0.15	0.12
O43	0.28	0.06	0.06	0.06	0.06	0.57	0.07	0.36	0.65	0.15	0.08
O44	0.12	0.06	0.20	0.24	0.18	0.42	0.92	0.41	0.61	0.15	0.31
O45	0.17	0.15	0.14	0.07	0.26	0.57	0.32	0.34	0.70	0.14	0.14

Proposed	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW
O46	0.08	0.05	0.26	0.14	0.17	0.67	0.91	0.59	0.64	0.11	0.17
O47	0.13	0.21	0.22	0.07	0.07	0.66	1.34	0.60	0.67	0.12	0.14
O48	0.09	0.56	0.24	0.13	0.14	0.54	0.19	0.46	0.44	0.06	0.16
O49	0.25	0.61	0.52	0.39	0.37	0.21	0.05	0.42	0.24	0.05	0.09
O50	0.24	0.30	0.51	0.39	0.32	0.40	1.02	0.66	0.37	0.09	0.25
O51	0.28	0.20	0.41	0.33	0.27	0.26	0.87	0.63	0.37	0.06	0.14
O52	0.22	0.12	0.33	0.30	0.24	0.14	1.04	0.47	0.40	0.12	0.09
O53	0.21	0.22	0.20	0.21	0.24	0.18	1.14	0.51	0.23	0.14	0.43
O54	0.27	0.30	0.33	0.29	0.35	0.57	1.11	0.28	0.48	0.06	0.48
O55	0.25	0.30	0.31	0.15	0.34	0.42	1.29	0.34	0.50	0.09	0.46
O56	0.22	0.25	0.26	0.04	0.24	0.28	0.54	0.34	0.42	0.18	0.45
O57	0.07	0.15	0.18	0.12	0.06	0.64	0.77	0.34	0.24	0.23	0.42
O58	0.09	0.17	0.10	0.35	0.61	0.63	1.32	0.55	0.42	0.16	0.15
O59	0.11	0.09	0.17	0.11	0.09	0.63	1.38	0.61	0.58	0.07	0.12
O60	0.08	0.08	0.16	0.22	0.11	0.73	1.47	0.51	0.65	0.15	0.37
O61	0.03	0.13	0.12	0.31	0.27	0.68	1.39	0.49	0.54	0.30	0.48
O62	0.11	0.03	0.09	0.09	0.08	0.12	0.35	0.06	0.05	0.29	0.47
O63	0.08	0.07	0.04	0.22	0.28	0.42	0.62	0.23	0.29	0.29	0.31
O64	0.16	0.03	0.05	0.07	0.10	0.10	0.16	0.18	0.09	0.31	0.35
O65	0.17	0.06	0.03	0.15	0.34	0.23	0.26	0.16	0.05	0.18	0.41
O66	0.16	0.02	0.01	0.14	0.22	0.27	0.34	0.48	0.11	0.07	0.22
O67	0.16	0.02	0.01	0.11	0.17	0.20	0.30	0.18	0.07	0.12	0.18
O68	0.12	0.04	0.02	0.06	0.16	0.16	0.25	0.15	0.10	0.08	0.15

Proposed	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW
O69	0.10	0.06	0.11	0.37	0.50	0.80	0.64	0.22	0.18	0.13	0.21
O70	0.14	0.06	0.11	0.39	0.49	0.78	0.37	0.25	0.20	0.16	0.15
O71	0.11	0.02	0.14	0.41	0.46	0.83	0.37	0.30	0.25	0.15	0.08
O72	0.05	0.03	0.08	0.18	0.30	0.20	0.47	0.28	0.09	0.09	0.20
O73	0.14	0.10	0.19	0.33	0.55	0.29	0.67	0.50	0.37	0.04	0.31
O74	0.19	0.02	0.02	0.13	0.25	0.20	0.37	0.44	0.20	0.04	0.31
O75	0.05	0.02	0.01	0.15	0.26	0.24	0.92	0.49	0.27	0.17	0.09
O76	0.06	0.04	0.03	0.04	0.12	0.24	0.63	0.44	0.17	0.18	0.06
O77	0.06	0.10	0.05	0.05	0.24	0.09	0.08	0.13	0.19	0.14	0.17
O78	0.11	0.10	0.05	0.09	0.13	0.20	0.30	0.12	0.11	0.15	0.22
O79	0.12	0.09	0.04	0.07	0.15	0.22	0.36	0.09	0.10	0.21	0.17
O80	0.09	0.08	0.04	0.06	0.39	0.52	0.51	0.27	0.15	0.16	0.23
O81	0.16	0.07	0.04	0.02	0.30	0.19	0.11	0.38	0.13	0.07	0.30
O82	0.10	0.09	0.02	0.04	0.19	0.09	0.08	0.33	0.10	0.10	0.46
O83	0.18	0.03	0.04	0.06	0.16	0.15	0.07	0.28	0.13	0.33	0.57
O84	0.08	0.32	0.18	0.11	0.14	0.11	0.25	0.32	0.10	0.60	0.46