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Simulation-Informed Urban Design: Improving Urban Microclimate in Real-World Practice in a High Density City.

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Abstract. In many dense cities, urban heat and the interaction of buildings with their immediate urban environment emerges as a pressing issue due to growing urban heat island effect and climate change. Informed evidence based design decisions to mitigate heat stress becomes a priority for urban planning and design practitioners. The aim of the study is to develop informed design and development decisions using computer simulation tools concerning urban microclimate performance. In this study, academic researchers have worked with industrial partners in an urban renewal project in Hong Kong's high density urban area. In-house developed simulation software such as CityComfort+ and HTB2-Virvil were applied to assess urban microclimate conditions and risks of pedestrian thermal stress throughout key seasons. Simulation results were provided as feedback to project designers and managers at early stage, allowing timely design modification to improve performance while maintaining code compliance and design and fiscal priorities. The procedure is iterative until performance attributes converge. Preliminary results show that the informed design can deliver significant microclimate benefits compared with "business-as-usual scenarios". By shaping building mass, orientation, and strategic placement of shading and vegetation, the improved design is expected to reduce summer-time outdoor heat stress by 1°C measured in UTCI equivalent temperature, thus bringing the average conditions for the hot season into the "comfort zone" for the local community. Energy simulation can predict overall energy demand and the potential for renewable energy supply at an urban scale. The simulation-designer workflow shows promising potentials to improve urban microclimate performance of design outcomes and the potential for zero carbon urban blocks. The early-stage action, forward-looking partnership, and computing efficiency of the simulation tools are the keys.

1. Introduction

The study consists of computer simulation of environmental qualities of the development of urban form for the KC-AA1 site in To Kwa Wan, optimising for external environmental comfort conditions. Simulated data were provided as feedback to project designers and managers at early stage, allowing timely design modification to improve performance while maintaining code compliance and the Authority's development priorities.

The Sustainable High Density Cities Lab (SHDC) of the HKUrbanLab, Faculty of Architecture has developed a framework software and hardware to conduct computer-based urban environment

assessment. The team has a number of in-house developed software tools. CityComfort+, a computer simulation tool that is uniquely equipped to assess urban climate and human responses at micro-scale. It has collaborated with the Cardiff University in the further development of HTB2 and VIRVIL, to model urban scale thermal and energy performance.

The modelling framework has been engaged by the URA (Urban Renewal Authority) Hong Kong to provide quick computer simulation tools that can be more readily applied for environmental analysis to enhance planning and design works at early design stage, particularly for the district-based redevelopment project in To Kwa Wan, namely KC-AA1. The overall aim is to apply a holistic planning approach. The objectives include creating a smart, sustainable and walkable neighbourhood and to enhance amenity value of public open space within the high density urban context of Hong Kong. The existing site to be redeveloped has an area of 57,800 ㎡ is shown in Figure 1. It mainly consists of residential dwellings of 10 floors or below, mostly built at the middle of 20th century. The initial scheme as proposed by the design team features a high-rise (100m), high-density (FAR=9.0), mixed use development as illustrated in Figure 2.

Figure 1. Existing condition of the To Kwa Wan site in Hong Kong
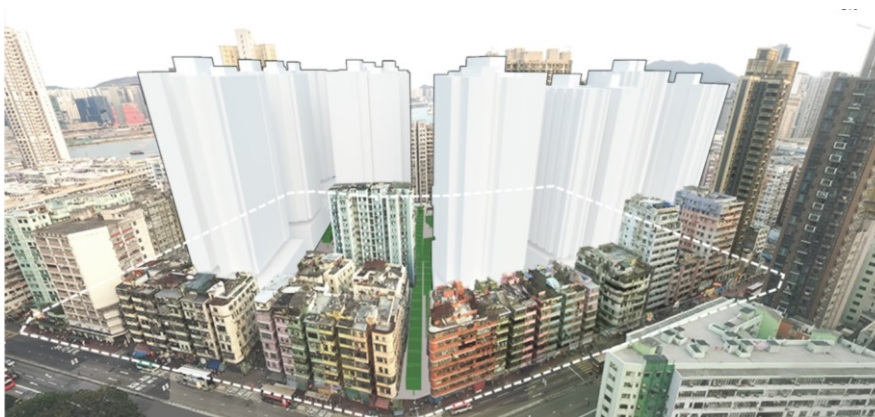

Figure 2. Initial scheme proposed by the design team.

The research aimed to investigate:
(i)   How simulation tools can inform measurable urban environmental performance instead of merely adding a "green label?
(ii)   How much can a passive design strategy improve key environmental indicators for an urban redevelopment project in Hong Kong's high-density neighbourhoods?
(iii)   To what extent can a high density urban block generate energy using building integrated renewables?
        This paper presents some preliminary findings.

2. Method

The primary method employed is computer simulation using software tools such as CityComfort+, FlowDesigner and DIVA-for-Rhino, together with HTB2-VIRVIL for energy simulation. Performance criteria for pedestrian thermal comfort, wind speed, daylighting, and visual comfort (glare) were established for key open spaces. Simulation runs were conducted for the existing condition and a range of design options. The software used is summarised below.

CityComfort+ Rhino Software Plugin is a design and planning tool jointly developed at the University of Hong Kong and Harvard University [3], [2]. To model micro-scale environmental parameters, including human perception of thermal comfort, day-lighting, wind speed, solar radiation, air temperature, air quality, and noise, etc. [1].

FlowDesigner is a 3D simulation software for air flow and thermal/contamination distribution developed by Advanced Knowledge Laboratory (AKL). The software uses Computational Fluid Dynamic (CFD) models developed to assess airflow in urban areas. FlowDesigner is user-friendly, adaptable, and practical CFD software with a high-precision and high-performance algorithm based on SIMPLE-C with automatic mesh generation, which allows designers to rapidly simulate, achieve high-accuracy result and visualize wind flow / temperature distribution in urban areas.

HTB2 – VIRVIL is a building energy model, HTB2 [5], which is able to simulate the annual hourly thermal performance of the building, using local weather data, building construction details and occupancy profiles. HTB2 has been developed at Cardiff University over a period of nearly 40 years, and has undergone extensive testing, validation, including the IEA Annex 1 [8], IEA task 12 [6] and the IEA BESTEST [7]. HTB2 – VIRVIL is an extension of single building energy modelling to apply to multi-building scale developments, typically up to a few hundred buildings, which could be a new or existing development, or a mix [4].
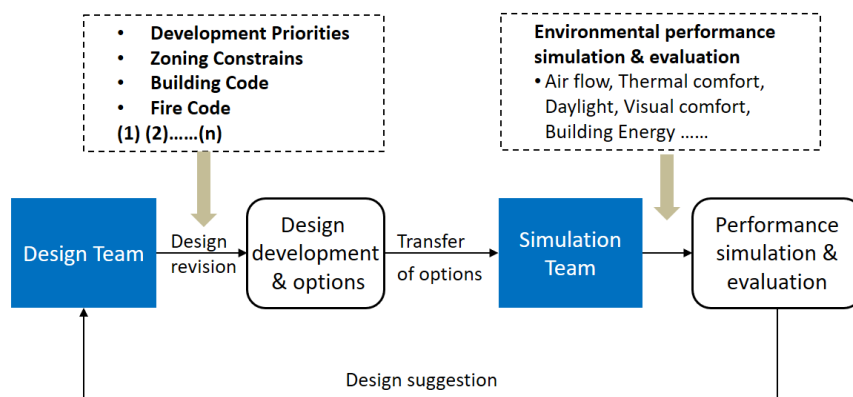

Figure 3. Simulation interaction between the design and simulation team

3. Results

Pedestrian Simulation software were applied to predict performance indicators, i.e. urban microclimate, pedestrian thermal comfort, and building energy use, for various design options. Results were provided as feedback to project designers, allowing timely modification. The procedure repeats itself until performance gains converge. A summary of the iterative design revision informed by simulation results is provided in Figure 4 below.
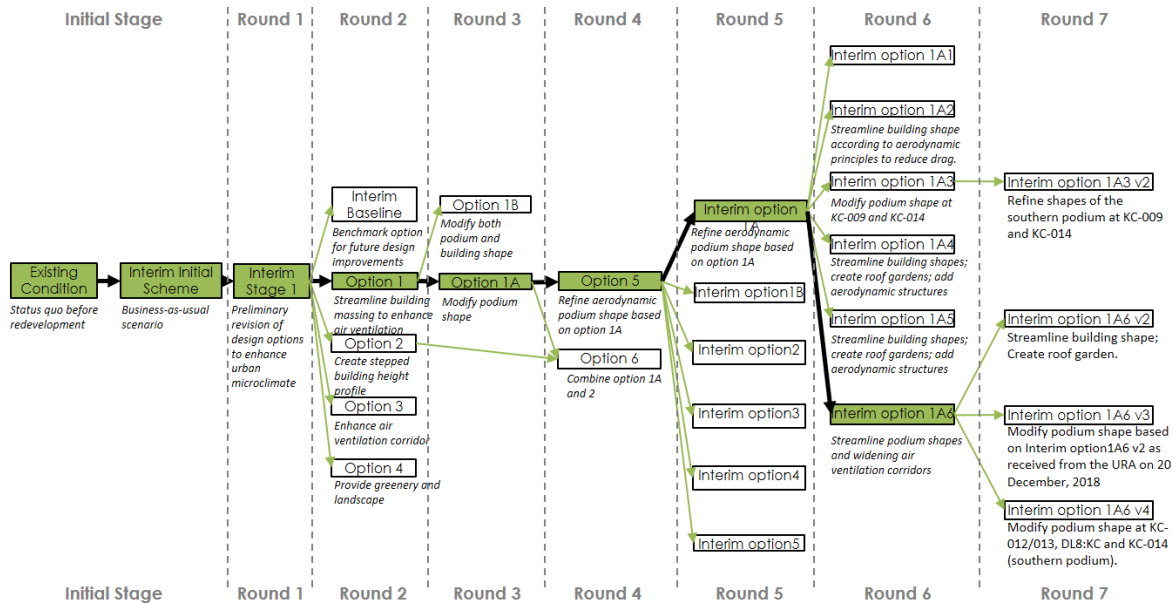
Figure 4. Roadmap for applying the simulation-design workflow to evaluate and revise intermediate options

3.1. Pedestrian-level wind assessment

Figure 5 shows the pedestrian-level (1.5m) wind speed by open space and streets are for the Existing Condition, Initial Scheme and Interim Baseline Scheme.

Table 1 shows significant improvements of pedestrian-level wind speed are expected for the Interim Baseline Scheme in comparison with the Initial Scheme and the Existing Condition.

- On-site mean wind speed is 1.07 m/s for the Interim Baseline Scheme, a nearly 70% improvement compared with those of the Existing Condition (0.63 m/s) and 40% increase compared with those of the Initial Scheme (0.89 m/s)
- The percentage of site area with wind speed above 1.1 m/s, the acceptable threshold for hot season, is 41% for the Interim Baseline Scheme. This is a significant improvement compared with those of the Initial Scheme (35%) and the Existing Condition (19%)

Table 1. Statistics of simulated wind speed results for existing, initial and interim baseline scenario

Scenarios	Mean wind speed on-site (m/s)	% of area of wind speed above 1.1 m/s	Mean wind speed at Urban Square (m/s)*	% of area of wind speed above 1.1m/s at urban square *	Size of Urban Square (m^2)	Building Footprint Area(m^2)
Interim baseline	1.07	41%	1.19	65%	2,092	31,656
Initial scheme	0.89	35%	1.45	98%	388	35,192
Existing condition	0.63	19%	N/A	N/A	0	34,380

* The size of Urban Square varies by schemes, therefore the mean wind speed and area percentage of wind speed >1.1 m/s cannot be simply compared across the board.

Table 2. Statistics of simulated outdoor thermal comfort results for existing, initial and interim baseline scenario

Scenarios	Yearly	Spring	Summer	Autumn	Winter	On-Site Mean UTCI during hot season (May-Oct.)
Interim Baseline Scheme	50.96%	59.46%	6.46%	39.00%	98.90%	28.8°C
Initial scheme	51.83%	61.04%	6.13%	40.63%	99.50%	29.3°C
Existing Condition	50.56%	55.22%	5.05%	42.14%	99.83%	29.7°C

A main contributor to pedestrian-level wind improvement is the reduced building ground coverage in the Initial Scheme and the Interim Baseline Scheme compared with the Existing Conditions, despite the fact that the former two features more building floor area than the later. The dense, medium-height building fabrics of the Existing Condition blocked wind from penetrating the neighbourhood. Figure 6a to b shows the percentage of comfortable hours that falls into acceptable thermal conditions (UTCI 15.2-28.8°C) for spring, summer, autumn and winter, for the Existing Condition, the Initial Scheme and the Interim Baseline Scheme. Table 2 shows that the Interim Baseline Scheme is expected to reduce summer time heat stress compared with the other two On-site Mean UTCI equivalent temperature during the hot season (May.-Oct.) is expected to be 28.8 °C, which is 0.9 °C cooler from those of the existing condition.
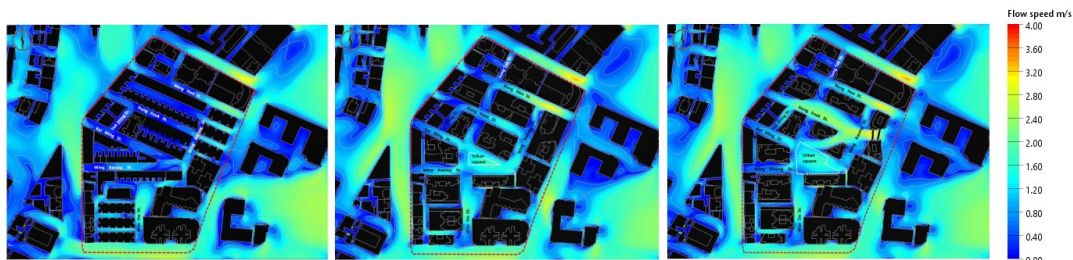

Figure 5. Simulated wind speed contours for Existing Condition, Initial Scheme and Interim Baseline Scheme
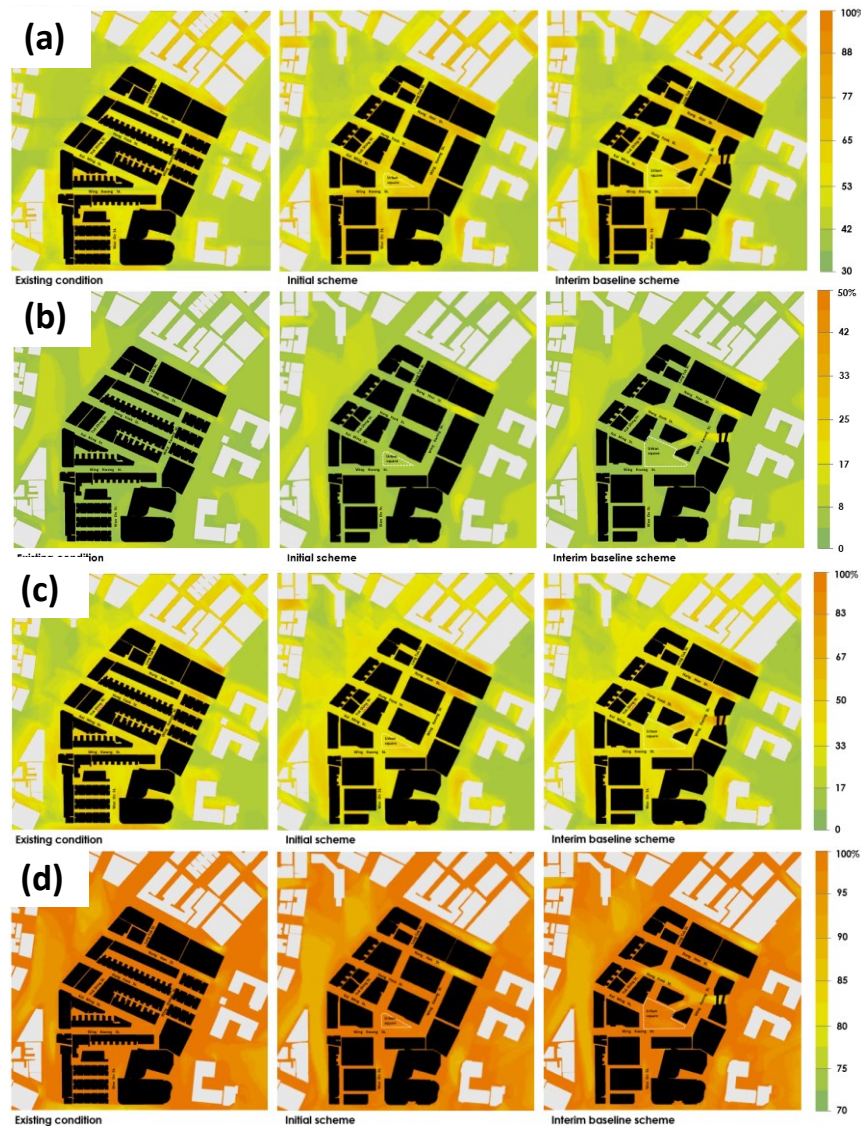
Figure 6. Simulated outdoor thermal comfort contours (%) for (a)Spring, (b)Summer, (c)Autumn, (d)Winter for Existing Condition, Initial Scheme and Interim Baseline Scheme

3.2. Passive design principles

A comparison of the mean thermal comfort conditions aggregated across the core KC-AA1 site shows a varied performance level across a range of building form and layout options (Figure 7). The options are: existing condition, initial scheme, interim baseline, interim option 2, interim option 3, and interim option 1A6.

While the existing condition features a challenging mean UTCI equivalent temperature of 29.7 ℃, the Interim Option 1A6 is expected to be 28.7 ℃, a one-degree reduction from the status quo (in line with the benchmark set previously). The improvement is largely due to the acceleration of on- site wind, with Option 1A6 being the only option with a satisfactory on-site mean wind speed above 1.1 m/s.
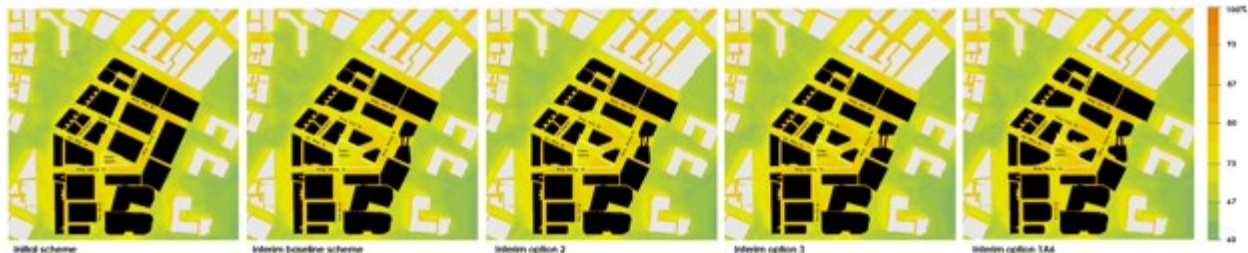### 3.3.

Figure 7. Simulated thermal comfort conditions across design options

Thermal comfort performances by option (Figure 8) show improvements from the interim baseline scheme in hot season. This suggested that streamlined podium shapes and reduced building footprints have marked effects on moderate thermal heat stress. Compared with other options, interim option 1A6 achieved the best performances in relation to thermal comfort. The second best is option 2. The increment, although small in absolute percentages, is statistically significant and is expected to deliver sizable impact at block-scale.
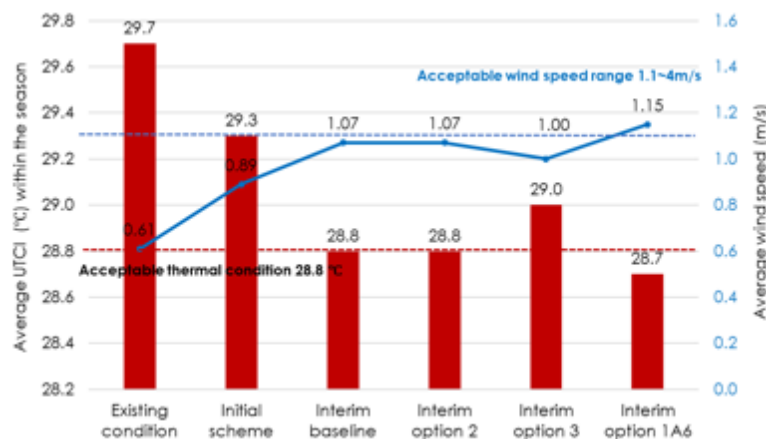

Figure 8. Summary of on-site average wind speed and equivalent temperature during hot season across design options.

Wind ventilation corridor is an effective approach to introduce cooler wind into built areas. Suitable disposition of building blocks could help effective air flows around buildings in desirable directions. To minimize obstruction of airflow, the axis of the building blocks should be parallel to the prevailing wind.
1. Wind speed at 50% of the site area falls within 1.1~ 4.0 m/s under site prevailing wind conditions.
2. 80% of the areas within key open spaces, i.e. the Urban Square, has wind speed within 1.1~ 4.0 m/s under annual prevailing wind conditions.
3. Reduction of the site-wise mean UTCI equivalent temperature in hot season by 1.0 °C, from 29.8 °C of the existing condition to 28.8 °C, within the range acceptable by Hong Kong's local communities.

4. Energy use and renewable energy generation

Future urban blocks may be required to generate renewable energy, which for solar energy, will be affected by overshadowing. Computer simulations of building energy use for the KC-AA1 development was conducted using Virvil-HTB2 software (Figure 9). The hourly values of solar energy generated from the roof top and wall surfaces of buildings on-site were predicted on an annual basis. The results indicate that the renewable energy generation is sufficient to cover the buildings cooling demand, but not small power appliances (lighting, computers, refrigerators, etc.) which dominates building energy use (Table 3). Despite relative small roof-to-volume ratio in tall buildings which tend to limit the application of on-site renewal energy in high-rise high-density cities, the findings indicate the potential for low-carbon high-rise communities.
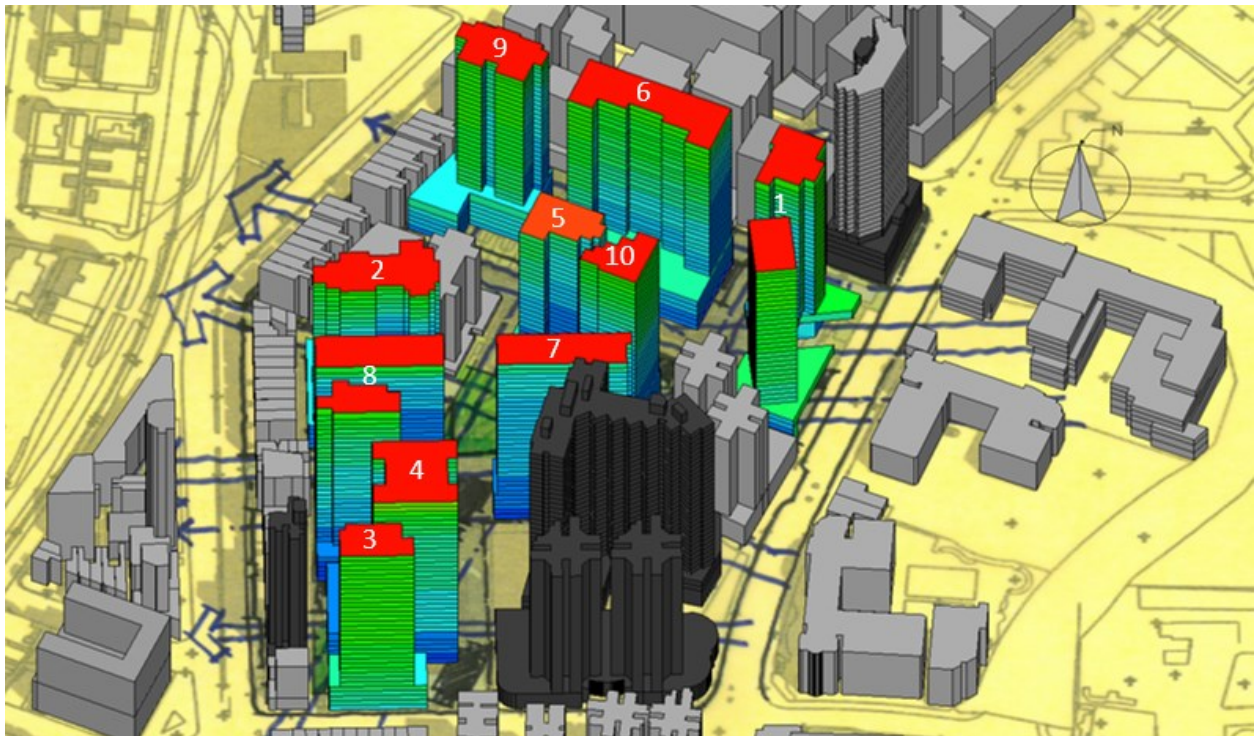
Figure 9. Visualization of building energy model using Virvil-HTB2. Solar energy potentials are color-coded for building façade and roof surfaces.

Table 3. Simulated building annual energy demand and building integrated renewable energy generation for the interim stage 1 option

Buildings	Floor area (m2)	PV generation on all the walls and roof (kWh/floor area/year)	Heating load (kWh/floor area/year)	Cooling load (kWh/floor area/year)	Small power load (kWh/floor area/year)
1	161,000	18.7	0.6	-23.7	43.7
2	31,100	26.3	1.0	-25.0	43.7
3	13,600	37.4	1.1	-27.7	43.7
4	33,500	22.0	0.8	-24.2	43.7
5	13,000	32.1	1.4	-25.0	43.7
6	36,400	25.0	0.8	-25.5	43.7
7	25,000	22.5	1.1	-24.4	43.7
8	39,400	17.2	1.1	-24.0	43.7
9	21,700	32.2	1.0	-26.6	43.7
10	12,700	27.4	1.7	-27.0	43.7

5. Conclusion

Several key findings can be drawn from the verification of design refinements:

- Simulation results show that the informed design can deliver significant microclimate benefits compared with "business-as-usual" scenarios. The improved pedestrian-level wind speed due to streamlined podium shapes and reduced building footprint has marked effects on UTCI reduction and moderate thermal heat stress in hot season;
- Greenery benefits the outdoor thermal comfort but limits in the magnitude of improvements in the thermal condition in hottest summer season;
- Artificial shading canopies are effective in in reducing UTCI and mitigating thermal heat stress in hottest summer season;

- Passive measures and devices cannot guarantee the thermal conditions stay 100% within the acceptable range during extreme hot days. Therefore, there is a need for active device such as evaporative cooling or mechanical ventilation to mitigate thermal heat stress.
- Computer simulation, if integrated in early stage planning and design, shows potentials to enhance urban microclimate performance of design schemes. It can be integrated with energy simulation and the potential for generating renewable energy on the building facades. The early-stage action, forward-looking partnership, and computing efficiency of the simulation tools are the keys.

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