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BUILDING A CLIMATE RESPONSIVE AGENT-BASED MODELING SIMULATION FOR THE WALKABILITY OF THE TROPICAL HOT AND HUMID ENVIRONMENT

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ABSTRACT

Climate change affects thermal comfort and wellness by restricting walkability potential of the built environment. This is especially in the outdoors under the harsh solar radiation exposure of the tropical hot and humid climate. Passive shading strategy plays the most significant role in the walkability potential. Vegetation and man-made structures such as pavements provide shade for comfortable navigation, with the latter being a more sustainable and wellbeing friendly solution. The walkability potential can be simulated using agent-based modelling (ABM) technique. As a heat mitigation strategy to improve the walkability, the most direct intervention is to improve the connectivity of the shading zone along the shortest path between strategic locations. People tend to walk faster and choose the shortest path when dealing with direct sun exposure while avoiding it totally if it gets unbearably hot. The ABM simulation is useful for efficient urban planning of walkability potential in campus.

1 INTRODUCTION

As part of the Singapore Green Plan 2030 (SGP2030 2025). The National University of Singapore Campus Sustainability Roadmap 2030 (NUS 2025) is an initiative comprising of Carbon Neutral NUS, Cool NUS, Zero Waste NUS, and Campus in a Tropical Rainforest. The roadmap covers climate mitigation, adaptation, resource efficiency and behavioral change for sustainability. The CoolNUS – BEAM (Baseline-Evaluating-Action-Monitoring) (BEAM 2025) plays the role through climate sensing to monitor the current condition so mitigation strategies can be administered effectively till 2030. Climate simulations are done to validate with the measured data so that the same method can be applied for future masterplans with new and refurbished buildings. Walkability is part of the strategy under the Carbon Neutral NUS scheme to minimize the reliance of transportation in the campus. Hence, the pilot study of Thermal Walk is done to ascertain the thermal comfort profiles of the walking paths available with the contribution from the surrounding urban climate.

2 NUS KENT RIDGE

The research site is located at southwest Singapore with the highest point about 60m above mean sea level. It is very near the sea with the port at the southwest direction. Figure 1 shows the 3D model of the campus with the reference of the site images. The UTown, at the north edge of the campus, is the focus of the walkability study with the impact from urban climate. It has about 10,000 people moving around the area which is around 10% of the total daily count in campus. It has a large turf courtyard square in the middle which acts as a good social interaction and leisure space.

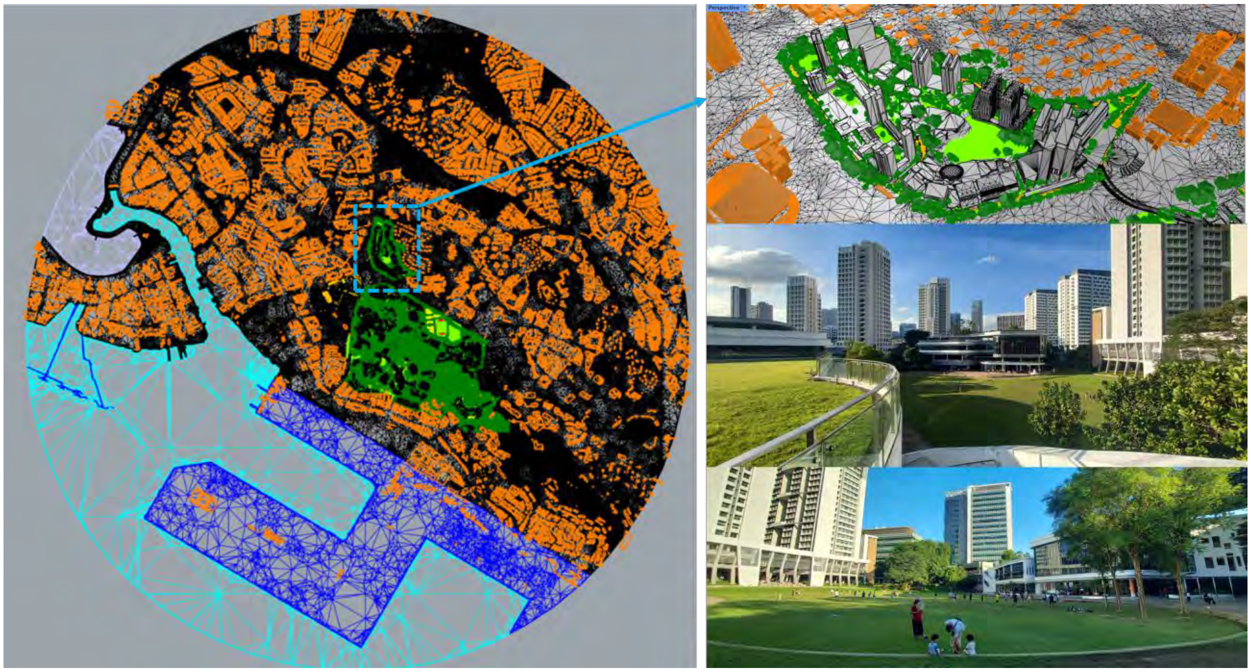


Figure 1: The NUS campus location in southwest Singapore (left) with the highlighted UTown site (right).

Figure 2 shows the vegetation layer highlighted in yellow around UTown. The walkability potential study using the ABM technique can be used to compare the impact of tree positions around the courtyard square space. As planting more trees in campus is part of the strategy to mitigate urban heat, the strategic locations to pick helps to maximize the thermal comfort and wellbeing impact. The investment is worthwhile to improve the connectivity of the human flow around the site by providing strategic shading coverage.

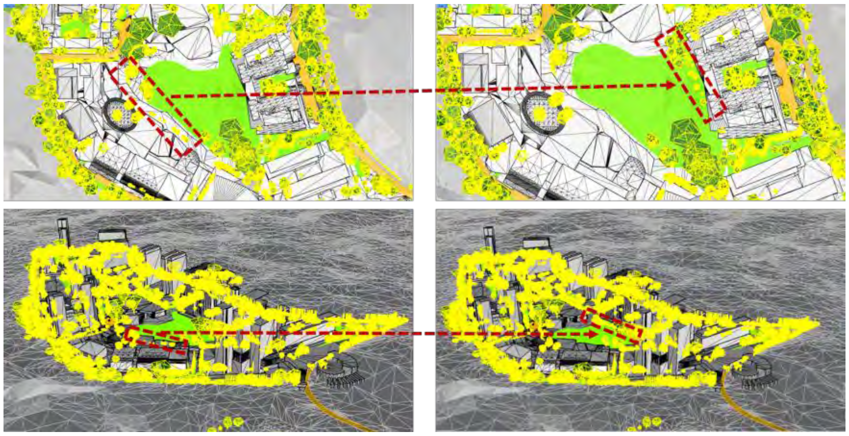


Figure 2: Potential trees addition in strategic positions: NUS is growing 10,000 more trees to achieve lower temperature with the control (left) and adjusted tree positions to shade the afternoon sun radiation (right).

3 ENVIRONMENTAL SIMULATION

ANSYS CFD, Autodesk CFD, CitySim Pro, ENVI-met, Honeybee, Ladybug, Meteodyn, Rayman, and TAS are the most common microclimate simulation tools for thermal climate indices, meteorological parameters, and outdoor design strategies (Albdour and Baranyai 2019). There were more attempts to use ENVI-met results for ABM platforms simulation. AnyLogic (Jia and Wang 2021; Ma et al 2023), GAMA (Estacio et al. 2022) and Quelea (Khan 2022) are some of the examples which investigates the urban climate impact on ideal trees spacing, walkability, walking speed and walking routes.

The Computational Fluid Dynamics (CFD) is the ideal environmental simulation software at urban district, microscale and building scales. The workflow is crafted to be robust and sustainable as shown in Figure 3. The reason is to not restrict the workflow to a certain mesher or solver. However, to kickstart the research, a mesher under HELYX (ENGYS 2025) is used. The reason is because the mesh as a foundation for CFD simulation is critical to be stable and robust. This ensures that the mesh quality will not contribute to the instability of the solver later down the road. Unfortunately, the HELYX mesher is not open-source and therefore, there is a validation with other meshers in the market, including those under the OpenFOAM family, which it originates from as well. Users can approach using both the openFOAM.org (OpenFOAM.org. 2025) and openFOAM.com (OpenFOAM.com. 2025) for the equivalent meshers, including the robust open source mesher, cfMesh (Creative Fields. 2025), that HELYX is using too.

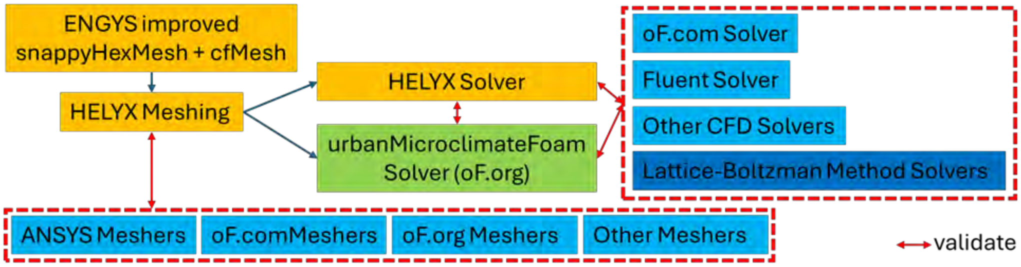


Figure 3: CFD workflow overview.

Carmeliet 2025 first developed the urban microclimate model using CFD model with the heat and moisture transport in urban materials together with thermal and radiation models. Subsequently, the vegetation model was added as well to become the more comprehensive and integrated urbanMicroclimateFoam solver (Kubilay 2025). It is the most validated urban climate CFD solver in the market. Therefore, the goal is to validate it with the HELYX solver which also has its own equivalent functions for radiation solver and vegetation model. Hatton 2025 had demonstrated the urban heat simulation for better thermal comfort in London.

Further validations can be done with other CFD solvers in the market, such as openFOAM.com version and even ANSYS Fluent solver. Once the workflow is well established, there is freedom to choose any mesher and solver to run the simulations without restrictions. That is the gist of the workflow creation which is to make it more sustainable in a flexible and versatile way for easy users' adoption based on their preferences and budget. The goal is to enable more options for solar radiation simulation to tackle urban heat and climate change.

Figure 4 shows the HELYX CFD simulation results of solar radiation ground exposure of UTown. This helps to identify the shaded and unshaded zones because of the surrounding buildings and vegetations on site. This can help identify the hotspots which affect walkability, especially during the hottest part of the day during the afternoon hours, especially between 12pm – 3pm.

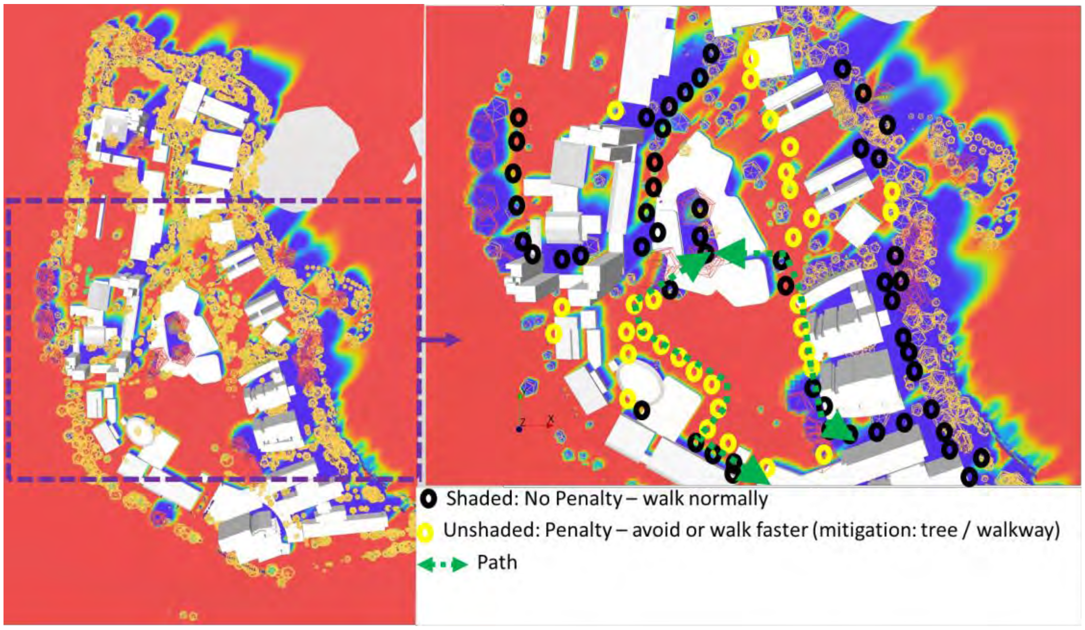


Figure 4: HELYX solar radiation simulation (left) to identify shaded and unshaded paths in the courtyard square (right).

Figure 5 shows the ability to import the point data for the coordinates in the simulation domain which can be added as weightage for the human flow impact. The response time for walking behavior will be expected to be slower when the heat is negligible or low while it becomes faster when the solar radiation is high in the unshaded condition. This relationship can be different depending on the time of the day and months of the year when the sun path is moving between the northern and southern hemispheres.

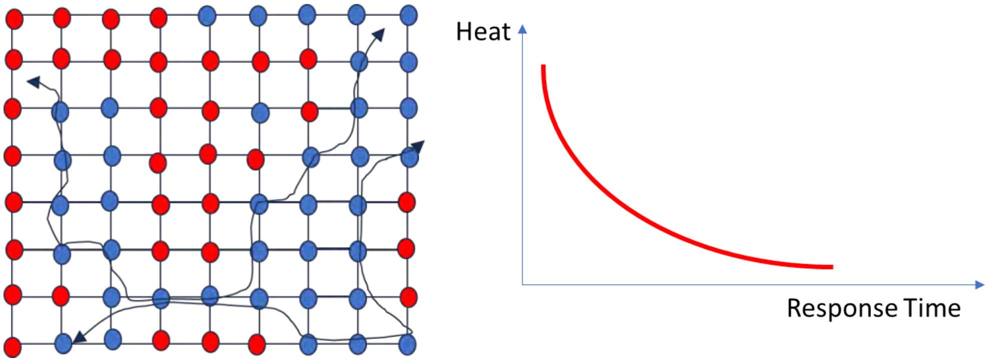


Figure 5: Coordinates with shaded (red) and unshaded (blue) paths to choose (left) and the heat-response time relationship (right).

4 WALKABILITY MEASUREMENT

Melnikov et al 2022 investigated the pedestrian path choices from the impact of buildings and vegetations shading in the Nanyang Technological University campus which affects the walking behavior. Ignatius et al., 2024 had done the pilot thermal walks in the NUS campus before by having the sensors moving together with the participants. This helps to capture their surrounding environmental conditions as they navigate through different paths in campus. Figure 6 shows an example from a participant's walk which included UTown area. The participant also voted at certain intervals along the route to declare the thermal comfort level of the checkpoints. The sky view factor, which is the solar radiation exposure, the air temperature, wind speed, relative humidity and total radiation received play a role in affecting the thermal comfort and wellbeing.

Select Run: Run 10

Run Start Time: 2023-11-03 14:24:20

Figure 6: A pilot thermal walk conducted in Kent Ridge campus (BEAM 2025).

Figure 7 shows the latest mobile weather station sensors integration for easier movement for future thermal walk studies. The latest mobile sensor being tested is Chaosense Comfort Cube. It is being tested against the traditional net radiometer and globe thermometer to further divide the shortwave and longwave radiation exposure received from different directions to the person who is walking. This helps to differentiate the contribution from the up, down, north, south, east, and west directions when the person is walking outdoors. The sun position, cloudiness level, surrounding material and their finishes as well as nighttime stored heat release affect the amount of longwave and shortwave contributions from the various directions. These details are helpful to identify the main source of the person's discomfort when they walk around. It could be overwhelmingly dominated by the shortwave radiation but there could be more information from the longwave radiation in the environment at the time of the day when walking through the space.

Figure 7: The mobile weather station (left) and measurement comparison with static sensors (right).

Figure 8 shows the SensMax mmWave radar under testing with weatherproofing enclosure for outdoor walkability detection of human and vehicular traffic (SensMax 2024). The signal strength test showed that the trajectories of the human movement was not compromised behind the shield. This guarantees same performance when deployed in the outdoor environment under direct solar radiation and rain.

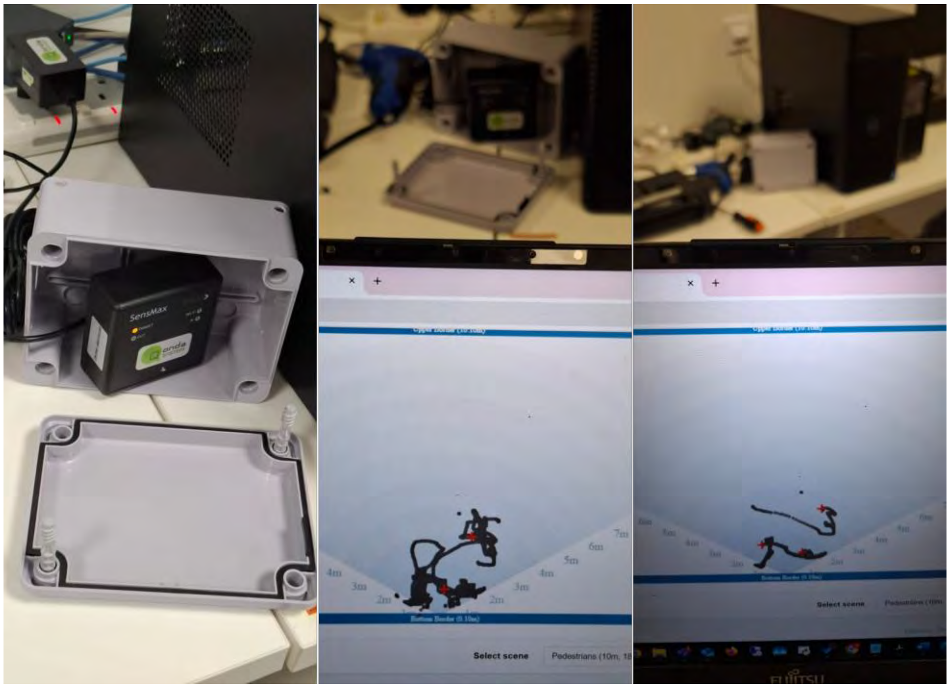


Figure 8: SensMax mmWave radar sensitivity and coverage tests with weatherproofing enclosure.

Figure 9 shows the potential location of the SensMax at an internal UTown bus stop. This is one of the major arrival and departure points which supplies the people count entering and exiting the site from the south. The site coverage of 10m with a horizontal 120° and vertical 60° sweeps should be sufficient to capture the people and vehicles from both directions.

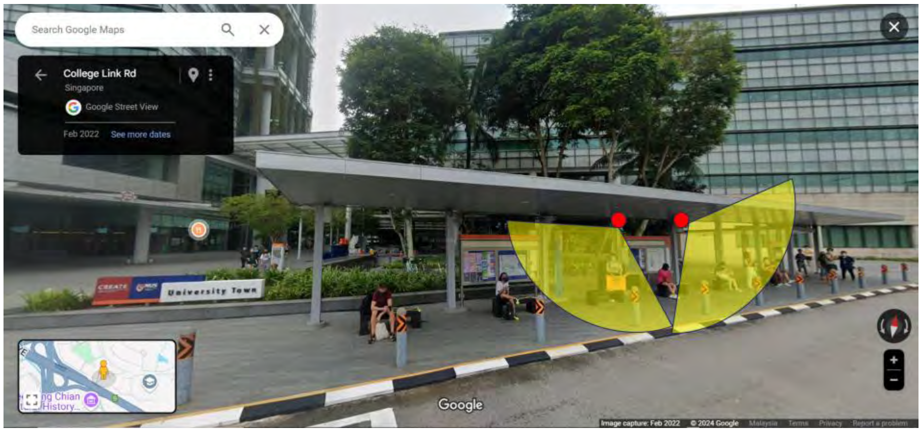


Figure 9: SensMax mmWave radar potential location in UTown.

5 ABM SIMULATION SETUP

There are some ABM software that handles crowd simulation in the market such as the latest Grasshopper plugin, Flow (snhm 2025). The Aruki Smart Crowd Model is another which is developed by Sarvi 2025 from his 20 years of research in the transportation field of crowd navigation and evacuation starting from insects (Dias et al 2012; Shahhoseini and Sarvi 2017) to humans. The behavior model embedded is a result of the many experiments of human flow based on various scenarios such as junction angles (Hannun et al 2022), different exit choices, obstructions impact, door, and corridor dimensions. These empirical data form the basis for the human behavior in the ABM platform. It is powered by the Unity game engine with the capabilities for Microsoft HoloLens visualization too for first person view. This enhances the communication of the results to the stakeholders. Figure 10 shows the agents trajectories both in 2D and 3D visualizations. This helps to capture the flow coverage used for navigation. This example shows the crowd behavior involving 50 people together. The platform supports the import of 3D Building Information Modeling and OBJ geometry file formats. Users can also build most spaces from scratch directly.

Figure 10: Trajectories of 50 agents in the crowd.

Figure 11 shows the heat map generation of maximum density from the crowd simulation. In this example, the maximum density of the agents is displayed. For all the trajectories going through the site, the most crowded areas with maximum people per area can be identified in the red area down to the blue area which is not used at all for navigation.

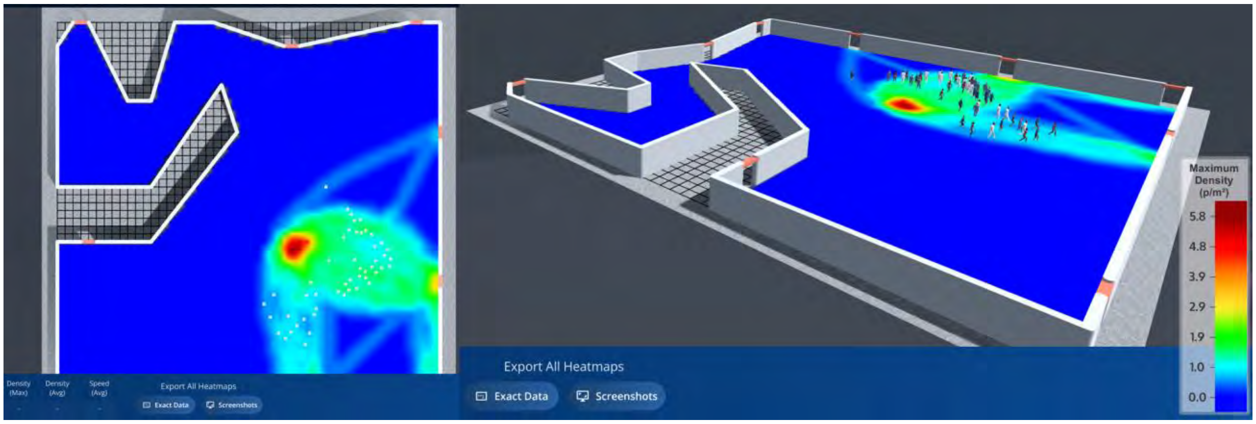


Figure 11: Maximum density of agents heatmap visualization.

The platform has the field potential function which allows the import of the weightage from any variables of concern. For the urban climate heat to thermal comfort context, variables of concern such as air temperature, surface temperature, mean radiant temperature and solar radiation received can be used. In addition, even the thermal comfort and heat stress indices such as Universal Thermal Climate Index (UTCI), Standard Effective Temperature (SET) and Wet Bulb Globe Temperature (WBGT) can be selected. Figure 12 shows the example of the points diagonally assigned from the bottom left corner to the top right corner of the domain to show the hot spots which agents will avoid. This is a good way to use the solar radiation data of shaded and unshaded area of the UTown which impacts the human flow navigation.

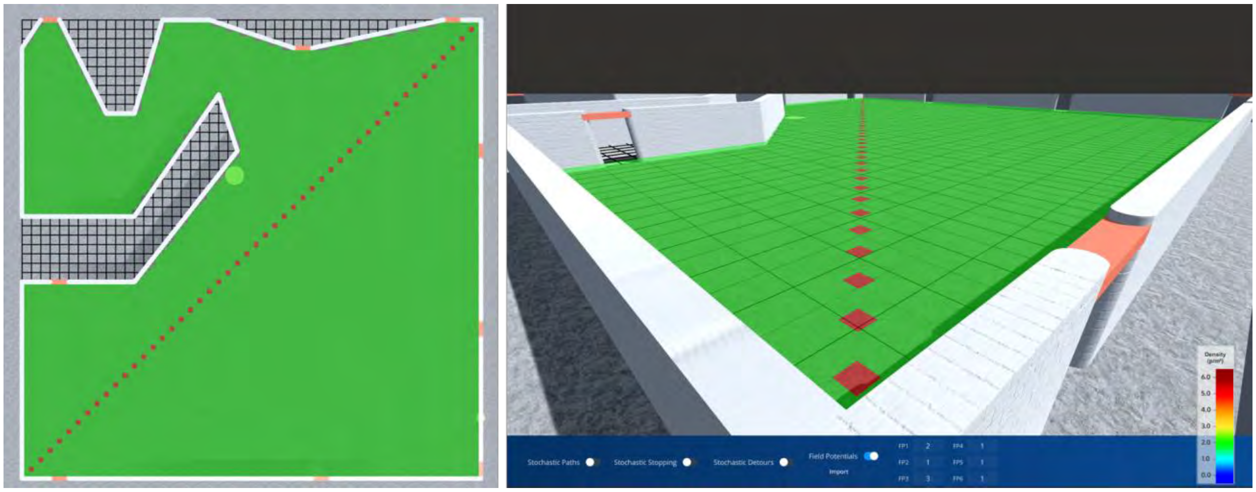
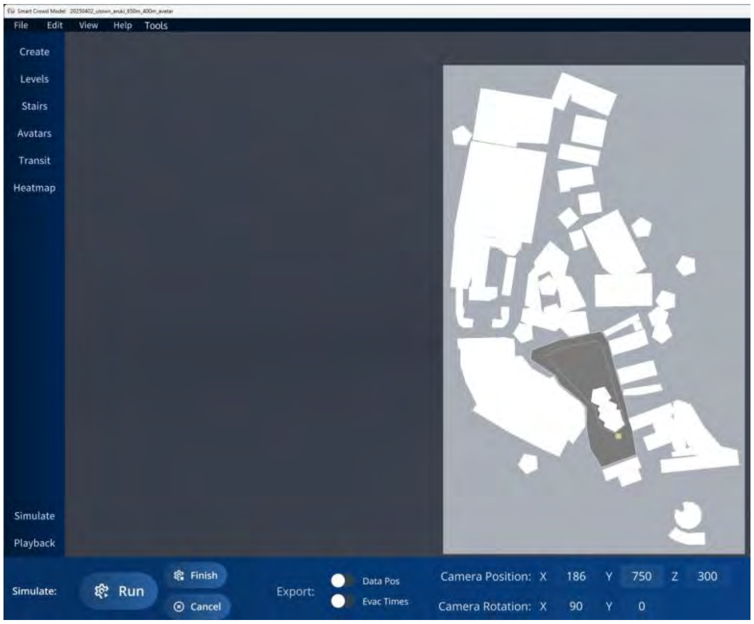


Figure 12: Maximum density of agents heatmap visualization.

The field potential allows the import of point data with their X, Y, Z coordinates. These can be different variables of measurement or simulation that can be imported as the CSV format. The major variables of concern that can affect the thermal comfort includes air temperature, relative humidity, mean radiant temperature, wind speed, ground received solar radiation and surface temperature. The freedom to pick any variable of concern and the impact it does to affect the agents can be multiplied to reach the desired impact for example mild to total avoidance based on the values in the CSV file. The file can be exported from ParaView, an open-source post-processing visualization engine by Kitware, Inc. 2025. The researcher or user can adjust the sensitivity weightages to the values measured or simulated accordingly from the data collection of people flow measured or observed on site. The field potential can take any variable of interest that is not just limited to thermal comfort or well-being.

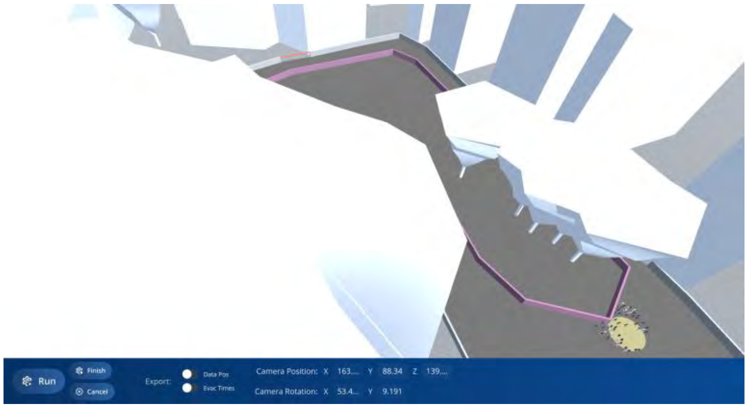
Figure 13 shows the UTown 3D model import into the Aruki Smart Crowd Model platform for the ABM crowd simulation. Figure 14 shows the agents navigation around the courtyard square based on the shortest path from the starting point at the south edge to the north edge based on the 2 paths surrounding the turf courtyard square.



Camera Position: X 186 Y 750 Z 300

Camera Rotation: X 90 Y 0

Figure 13: Maximum density of agents heat map visualization.



Camera Position: X 163.... Y 88.34 Z 139....

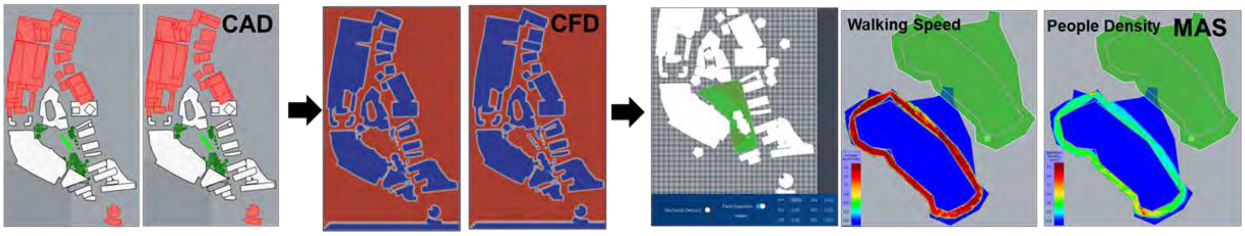
Camera Rotation: X 53.4... Y 9.191

Figure 14: Maximum density of agents heat map visualization.

6 CONCLUSIONS AND FUTURE WORKS

Good walkability potential promotes carbon reduction by minimizing motor transportation reliance. This can be done by planning good shading paths from the harsh urban climate in the hot and humid tropical climate. Environmental simulation such as CFD provides the best detail at the urban microclimate, district, building to local scales to capture the impact of the environment, including vegetation shading. The paper demonstrated the workflow employed on the NUS Kent Ridge campus from field measurements digital twin to environmental simulations and finally providing the thermal comfort weightages to the walkability via ABM simulations. The field measurements are useful to validate the simulation data as it is impossible to generate as many detailed data as simulation for walkability purpose.

Sensors such as SensMax mmWave radar and IR sensors are very useful to capture the people count data in large urban areas with limited power, Wi-Fi and Bluetooth coverages. Its performance is not deterred by the lighting condition such as AI cameras and it is much more versatile to be deployed with flexibility in the outdoor environment. Hence, its capability to handle the walkability coverage is much more promising. The personal climate exposure mobile weather station is also very useful to capture the direct contribution of the surrounding for a person when walking around, especially outdoors. This can pinpoint the exact contributions to the thermal (dis)comfort at the point of time and place when walking outdoors.



3D Model

Environmental Simulation

People Flow Simulation

Figure 15: Outdoor ABM walkability workflow.

Hii and Hasama 2024 demonstrated the pursuit of the full ABM workflow of pre stage, which handles the data collection, model and logic building to simulation stage of visualize, monitor, and analyze to the final post stage of prediction using AI Machine Learning training capabilities that is available for both AnyLogic and the Aruki Smart Crowd Model (still under evaluation stage currently). This is consistent for indoor, semi-outdoor and outdoor environments, which in this case is the NUS UTown area as shown in Figure 15. Similarly like the smart building of The GEAR, the NUS Kent Ridge has an extensive amount of sensors in the outdoor environment like a smart city. Hence, the ability to run them as a digital twin is possible by directly collecting the input people flow data into the server database which connects to the AnyLogic and Aruki directly to simulate the corresponding people flow real-time. The Aruki Smart Crowd Model is a suitable platform that handles crowd simulation well from empirical data collected from past human crowd experiments. The added contribution from the urban climate conditions gives the agents an additional layer of impact to their walking behavior. This contribution is necessary especially for the harsh tropical hot and humid outdoor environment.

The rich integration of environmental and people count sensors data makes the ABM simulations possible by gathering the boundary conditions, validating the data collected as well as for future predictions. The end goal is to provide better planning to optimize the spaces designed, avoid congestions, bottlenecks, and traffic jams because of the thermal environment impact. The ML trained data can be used to assess the different design options of future spaces to get the best outcome possible based on the current observed human flow behavior. The initial goals are to validate the current walkability behavior as a baseline study in campus to understand the current conditions as well as to support the best positions for additional tree planting for good shading towards the community. Once the behavior is well captured, the confidence gained from the simulation reliability can be used to support future climate change scenarios, master planning design of land use change, new building constructions and existing renovations. Other site-specific impacts to the walkability which are not caused by the climate which includes users' perception, clothing impact, metabolism rate, pavement material construction, terrain elevation variations which affects safety and lighting conditions based on the solar radiation intensity of the given time and date needs to be considered too for achieving more realism for the simulation. When we conduct walkability studies with participants, most of these impacts will be captured, especially with the terrain condition which will impact walking speed uphill and downhill with different inclination angles.

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