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TOWARDS THE DIGITAL TWINNING AND SIMULATION OF A SMART BUILDING FOR WELL-BEING

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ABSTRACT

Smart cities and buildings are enabled by the Internet of Things (IoT) sensor infrastructures integration and monitoring in the current Industry 5.0 era. Environment sensing, people and robots counting enable the simulations of both digital twin and agent-based modelling (ABM). This enables the understanding of the impact between the built environment and humans. The movement analysis allows planning and design of spaces as well as utilizing machine learning methods to train the trajectories for space usage prediction. Human behavior and social interaction comprehension is important to generate people friendly spaces. The GEAR is a smart, green, and WELL certified building embedded with sensors as a living lab for research and development. The diverse workspace layouts create an ideal testbed to study human and built environment interactions. This pursuit is to achieve more sustainable and better designed spaces for human well-being in the fast-changing world.

1 INTRODUCTION

As climate change and Urban Heat Island make cities hotter today, urban sustainability with the heat mitigation strategies for better human thermal comfort becomes critical to achieve the commitment targets under the UN's 2030 Sustainable Development Agenda and Paris Agreement. In cities, we spend almost 90% of our time inside buildings (Klepeis et al. 2001) and hence, our behavior is heavily shaped by the built environment. Therefore, creating conducive environments impacts the occupants' well-being. The emergence of smart buildings and cities embedded with IoT sensors enables the measurement of both the conditions of humans and the environment. This allows for the digital twin and agent-based modeling (ABM) simulations to occur to monitor past to real-time conditions of both domains. These simulation approaches have gained popularity in publication trends among the ten employed in Industry 4.0 (de Paula Ferreira et al. 2020) which includes virtual commissioning, virtual reality, augmented reality, hybrid simulation, system dynamics, discrete event simulation, petri nets simulation and artificial intelligence.

2 THE SMART BUILDING

The GEAR (Global Engineering, Architecture & Real Estate) is a smart building (The GEAR 2023) and a living lab for exploring emerging built environment research and development topics such as digital twins, occupant well-being, and ABM. This smart building is in line with the Smart Nation initiative established in 2014 (Kong and Woods 2018) and to pursue the intelligent data-driven building automation goal (IEA 2024). Hotdesking flexibility and hybrid ventilation (which mixes natural and mechanical ventilation) in the pursuit of well-being and sustainability, are features included in addition to the traditional office layout and ventilation systems. This allows the study of space utilization and ventilation mode choices.

As part of the commitment to have a sustainable and well-being focused workplace, it tracks the parameters that inform the stakeholders of the environmental conditions. As a WELL certified (WELL 2023) and Super Low Energy building (BCA 2024), it requires relevant sensors to monitor, manage and maintain the status. Therefore, there are Indoor Air Quality (IAQ) sensors in the building as well as wearables to match occupants' well-being to the utilized spaces. Since occupancy last year, the first post-occupancy evaluation survey was conducted among the occupants (BCA-HPC 2018). The overall environment analyzed considering the spatial comfort, thermal comfort, lighting quality and noise levels have been positive with satisfaction exceeding 90% of the occupants. The satisfactory parameters include daylight, humidity, temperature, sound, and visual privacy. Occupants also feel positive about the availability of vegetation in the building to reduce stress and improve recovery during breaks. This is promising since we did a survey on greenery and spaciousness that can improve mood and productivity in the VR environment that focuses on the atrium space design in The GEAR (Mihara et al 2023).

2.1 Digital Twin Platform

Figure 1 shows the overall digital twin platform where the sensors data are integrated for management and research purposes. The sensors monitor many parameters such as utilization of electricity, water, rooms, energy generation, spaces occupancy rate, parking capacity, structural vibration, and earth movement. The data can then be used to validate the individual spaces performance. Next, the analytics will assist in the optimization of the space control based on users and occupancy rate feedback. This is part of the smart Facilities Management (FM) feature to make the building easier to maintain at the post occupancy stage. Overall, the final goal is to be sustainable by optimizing water and energy usage while still achieving occupants' well-being.

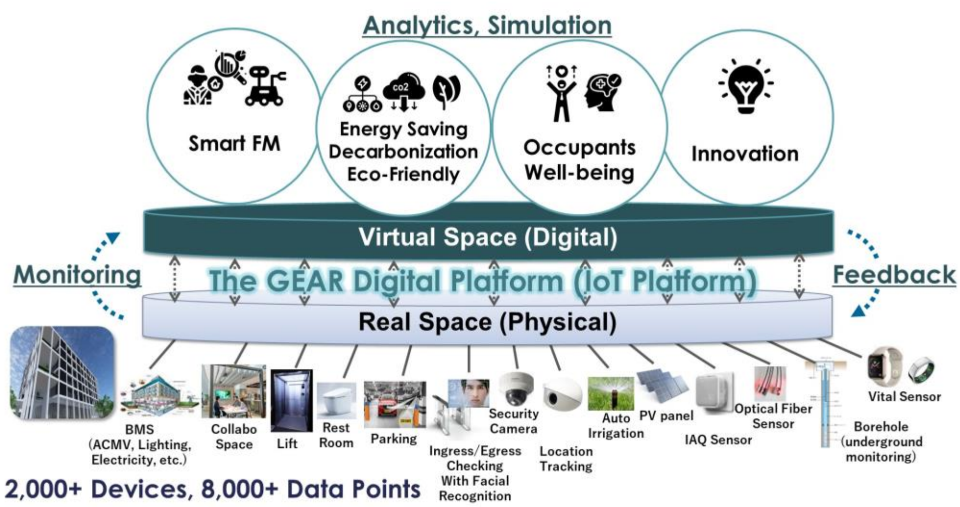

Figure 1: The digital twin platform of sensors integration for monitoring, analytics, and simulation.

The integration of robots into the built environment such as the workspace is getting more common nowadays to overcome manpower shortages in specific industries such as security, healthcare, hospitality, and construction. The integrated FM system considers the communications and movements of both occupants and robots in the building. The robots function as concierge information, patrol as well as food and beverages deliveries. This integration enables robots to move between different levels by going through gantries and using lifts to execute the tasks. The next goal is to track and simulate robots' movement in the ABM platform with other occupants in the building.

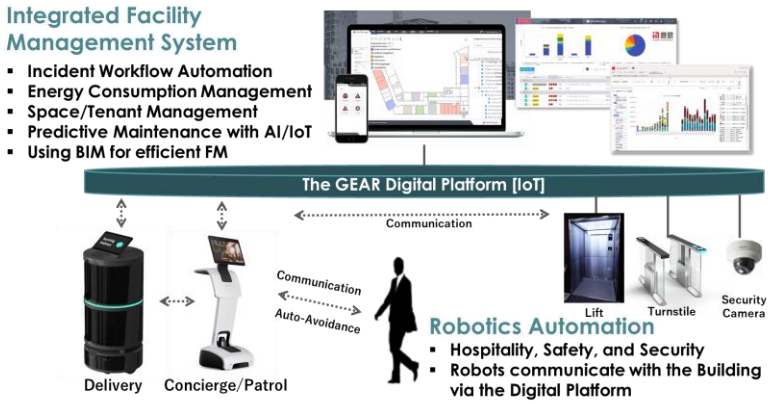

Figure 2: The digital platform integration of humans and robots (Temi 2024) in a facility.

2.2 3D Visualizations

The collected environmental and people count data enable 3D visualizations of the parameters. Figure 3 shows the example of the air temperature distribution and the occupants' distribution for every floor in the building. There are other environmental parameters to visualize which includes humidity, noise, illuminance, pressure, CO_2 (carbon dioxide), TVOC (total volatile organic compounds) and $PM_{2.5}$ (particulate matter of 2.5 micrometers). This gives a real-time overview of the overall environmental performance of all the spaces. Any anomalies can be easily identified by the visualization for quick troubleshooting. For the occupancy rate monitoring, this allows for better management of bottlenecks when it increased significantly because of special circumstances such as incoming visitors for events organized.

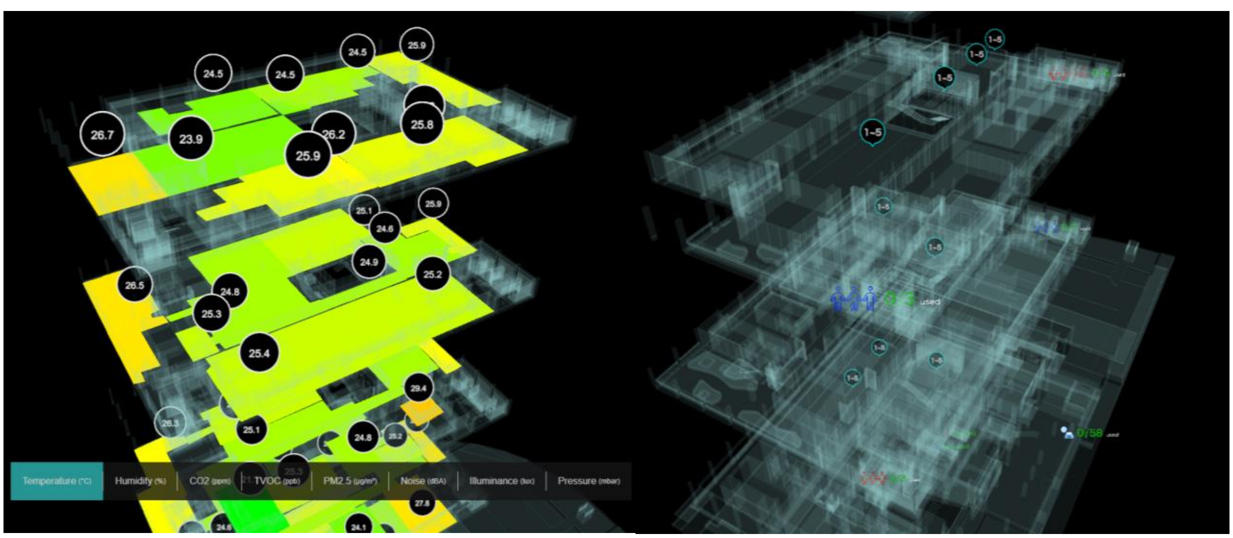

Figure 3: The indoor zonal environmental parameters (left) and people count (right) visualizations.

2.3 Occupants' Well-Being

The occupants' vital data are good indicators of well-being. This includes the measurement of sleep quality and stress level as shown in Figure 5. The end goal is to link them to the specific spaces used in the building so interventions can be made to improve the situation if necessary. This feedback loop is important to tweak the workplace condition to respond and improve the occupants' well-being.

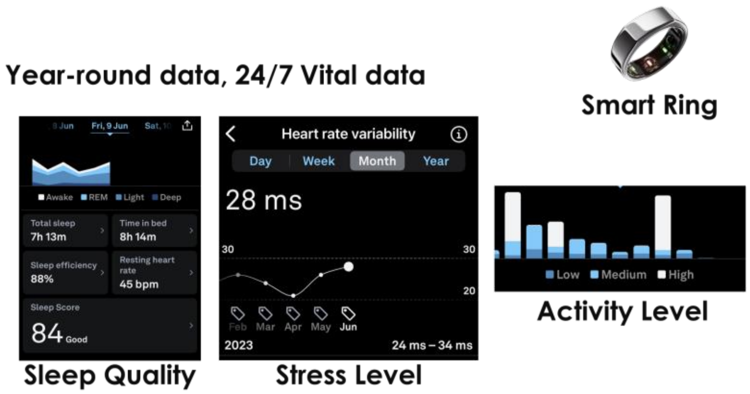

Figure 5: Smart ring (Oura 2023) tracking of the sleep quality, stress level and activity level.

2.4 AI cameras

The data-driven approach of using video footage to learn crowd behavior has been done in New York (Zong et al. 2015) and Seoul (Lee et al. 2007). It is common today to use AI cameras for occupant counting and tracking. It is also the default sensor used in the building for the same purpose. The occupant's movement can be tracked to every floor and room usage. This gives an activity history to the frequently used paths and spaces. This information helps the facilities management to identify the popular spaces such as meeting rooms, offices, pantries, and balconies utilized.

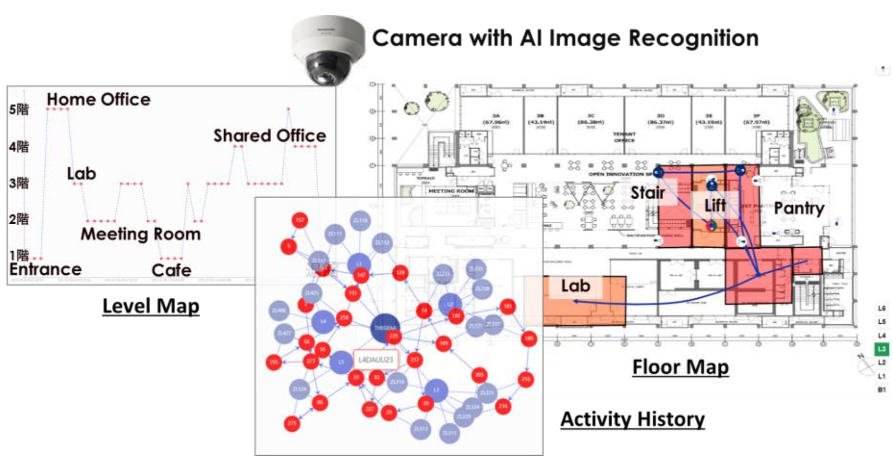

Figure 6: People movement tracking.

Emotional analysis is a feature of the AI camera that can predict occupants' wellness too. There are a few emotions that can be predicted based on the face expressions which include happy, anger, disgust, sad, fear and surprise moods. This will assist in the prediction of the level of energy, stress, social engagement, and stress. The emotion analysis algorithm used is by SOLO 2023, which has done and still doing extensive research in this field.

2.5 Other people tracking and counting methods

The amount of people entering and exiting a space as well as their traveling speeds are basic information required for ABM simulation. Therefore, it is paramount to have reliable sensors to measure these parameters. Typically, the acceptable accuracy in the industry is at least 90%. People tracking can be done using various methods from detecting thermal body heat, WIFI, mmWave radar, IR, BLE (Bluetooth low energy), UWB (ultra-wideband), LIDAR and via LoRaWan network. The benefit of using non-optical sensor options is the privacy concern especially in the public realm. In addition, some sensors do not require dedicated power sources, so it is more flexible to be deployed in any space, especially outdoors.

In hot tropical environments, using heatic captured thermal data (Butrl 2023) to estimate human activity is challenging with the thermal signature interference from the sunlight. UWB tracking can be done using the tags but requires a line of sight which is very infrastructure heavy. Therefore, using the combination with BLE is better as this integrates items tracking by zone and specific item in the zone. In today’s ubiquitous mobile device environment, using the LoRaWan network for effective counting of people for large areas (both indoor and outdoor) is more effective.

mmWave radar sensor (SensMax 2023) can be used for people counting indoors or outdoors and insensitive to lighting as well as weather conditions. IR sensor can be used for counting bidirectional people crossing the line of a path, corridor, door, gantry, escalator, staircase, or travellator. There is intention to use the SensMax sensors in The GEAR to compare with the accuracy of the AI cameras.

The hardware seamless integration and accuracy are critical for reliable boundary condition inputs and analysis for the simulation later. The confidence of the tracking technology of both the occupancy and environment conditions will help establish a good real-time digital twin and ABM simulation. The tracking can also give hints or clues of the occupant behavior in space choices for analysis at the later stage.

3 ABM & HUMAN BEHAVIOR

ABM is a microscopic computational model for simulating interactions among autonomous agents to comprehend or replicate their collective behaviors in a system. There are four most popular algorithms, namely force-based, velocity-based, vision-based, and data-driven learning-based agent navigation (van Toll and Pettré 2021). Abar et al. 2017 reviewed 85 ABM and simulation tools applied in various domains, scales, and complexity. There are 17 relevant in the built environment from the large population urban planning scale to the microscopic pedestrian crowd flows for normal and fire evacuation scenarios.

The simulation motivation is the belief that people’s behavior can shape and be shaped by the environment as shown in Figure 7. Therefore, the environment qualities affect people’s behavior so tweaking them will impact people positively or negatively. This includes the choices of paths or spaces to use because of well-being, thermal comfort, crowdedness, and privacy considerations. Hence, the study of human and environment (including buildings) interaction is the scope of interest.

Some behavior theories are applied in the construction of agent cognitive behavior. In the GAMA platform, the BEN (Behavior with Emotions and Norms) (Bourgais et al. 2020). BEN's cognitive engine allows expressive and realistic design on agents, which is based on the Belief-Desire-Intention philosophy of action by Bratman 1987. Uddin et al. 2022 uses the theory of reasoned action (ToRA) by Fishbein and Ajzen 2009. The model defines the beliefs that drive the attitude with the motivation and norms accepted by society that combined to ultimately create the intention of a behavior. ABM platforms such as Performance Moderator Functions server (PMFserv) models occupant physiology, stress, coping style, emotions, cognitive appraisal, perception on object affordance as well as social awareness (Jia et al. 2019).

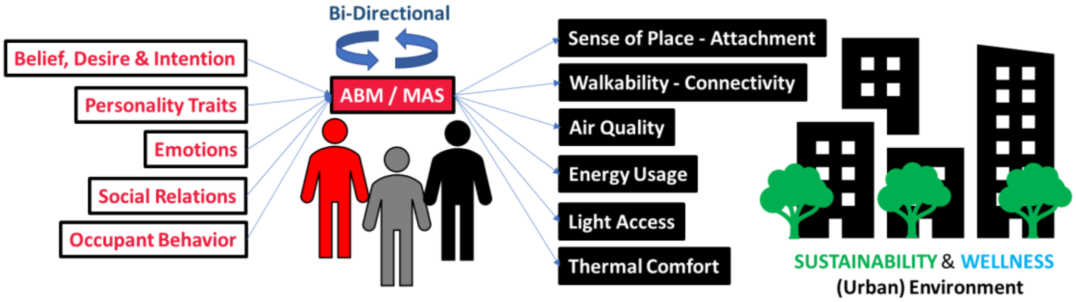

Figure 7: Human-environment interaction.

The ABM simulation has been done at various scales in the urban built environment as shown in Figure 8. This ranges from the larger regional, urban to the smaller district, building and indoor scales. The scales of interest to start with is district to building and indoor scales. Once the simulation is robust and reliable enough, the impact and connection to the larger regional and urban scales can be pursued to link them together. In the end, the impact from both spectrums should be integrated into a full simulation.

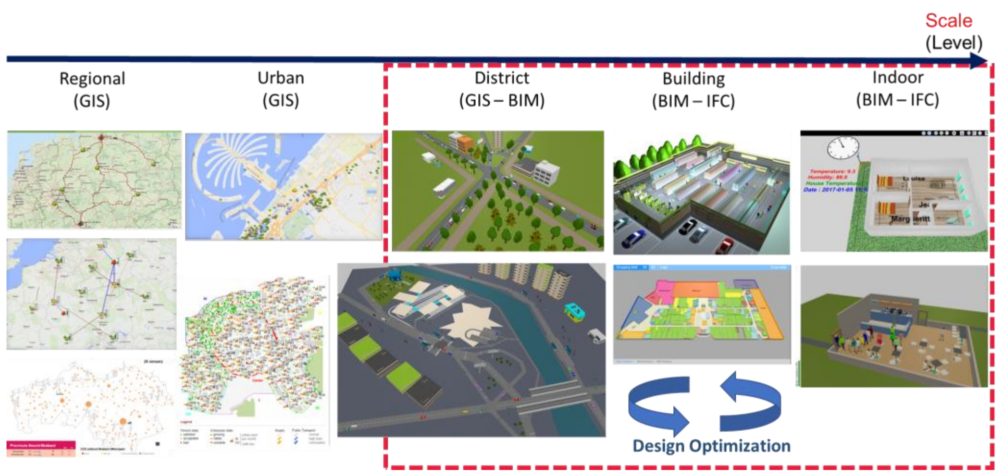

Figure 8: The ABM application from the largest (left) to the smallest urban environment scales (right) (AnyLogic 2024).

3.1 Occupant Behavior

Understanding occupant behavior inside buildings is critical from the sustainability, resilience, and well-being standpoints since we can improve energy performance and occupant comfort. There are 27 behavioral theories identified by Heydarian et al. 2020 which are further divided into psychological, sociological, and economic categories. Psychological theory is applied more than the rest with the Theory of Reasoned Behavior / Theory of Planned Behavior, Norm Activation Model, Value Belief Norm, and Theory of Interpersonal Behavior being the most popular.

Uddin et al. 2021 reviewed different modelling approaches of occupant behavior used and identified that there is lack of real data, validation or verification using the ABM approach. Malik et al. 2022 reviewed 10 relevant ABM tools in the field with MATLAB, Python, Java, or C++ programming under the IEA EBC Annex 79 group. Furthermore, there is interest to link this to the BIM by making use of the building properties impact on occupant behavior (Micolier et al. 2019; Uddin et al. 2022). The availability of sensors in buildings creates better opportunities to predict occupant behavior for validation.

3.2 Emotions, traits, and social interactions

A popular emotion theory, the Ortony, Clore, and Collins (OCC) model (Ortony et al. 1988), defines the 22 emotion types according to psychologically significant situations. The prediction of emotions for the setting in the ABM simulation can either be estimated from the sensors or via surveys.

In addition, occupants have different personality traits which are defined by the OCEAN model (McCrae and John 1992). These traits can be traced to the American personality psychologist, Mr. Lewis R. Goldberg's personality theory known as The Big Five or the Five Factor Model. This encompasses traits such as openness, consciousness, extroversion, agreeableness, and neuroticism levels. These attributes can be collected via surveys to be included in the ABM simulation. There were large geopsychology studies conducted to identify regional personality traits distribution at country scale in Great Britain, United States and Germany (Renfrow et al. 2015; Ebert et al. 2019; Ebert et al. 2022).

Social interaction analysis is an important aspect to quantify human engagements in the spaces of interest. There are many metrics proposed and under research in the field such as:

- Action Office by Robert Propst, Herman Miller
- Distance based Network Effects by Carlo Ratti
- Isovist by Clifford Tandy, Michael Benedikt
- Proxemics by Edward T. Hall
- Social Capital by Robert D. Putnam
- Social Networks, Weak Ties by Matthew Jackson, Mark Granovetter
- Social Physics by Alex Pentland
- Space Syntax by Michael Batty, Bill Hillier
- Triangulation (applied outdoors) by William H. Whyte

Social relationships (Svennevig 2000) can be set in the ABM simulation on a few variables such as:

- solidarity, which is the mutual rights and obligations,
- familiarity, which is the mutual knowledge of personal background,
- mutual affect, which is the emotional commitment,
- trust, which is the degree of doubt to belief,
- dominance, which is the power ranking influence and
- liking, which is the degree of hatred to fondness.

The possibility to use relevant metric/s for measuring the intensity of social interaction in the physical space will be a useful measurement of space design success. This helps to quantify the qualitative aspects of the space that are conducive for better social integration, which is an integral part of occupant behavior too.

3.3 The GEAR ABM simulation workflow

The objective of the people flow simulation is to establish a good space usage prediction methodology for space design and planning purposes. The aim is to design and plan spaces that are optimum for occupancy while avoiding bottlenecks and dead spaces. The environmental and social parameters calculated, measured, or simulated are meant to establish the reasons for such statuses to occur. Such links can help to plan and design future spaces more effectively by considering the sustainability and well-being impacts.

The workflow is divided into 3 stages of pre, simulate and post processing as shown in Figure 9. In the preprocessing stage, the human, robot, and traffic data from the sensors installed can generate the count and traveling speed in and around the building. These inputs can be added into the ABM / MAS platforms such as AnyLogic and Smart Crowd Model (Smart Human AI 2023). Both are using the social force model that has the collision avoidance with other objects while picking the shortest route. These are the current platforms selected for research exploration for the available features and components for simulation to fulfill the entire workflow. The ability for these platforms to import 3D models is crucial not just for presentation purposes with visualizations using Java or game engines at the later stages but for the ability to consider spaces at various elevations or floors and terrain. The path sequencing for every route in the building can be built and tracked with the monitored data for every floor and method used such as travelator, staircase, and lift.

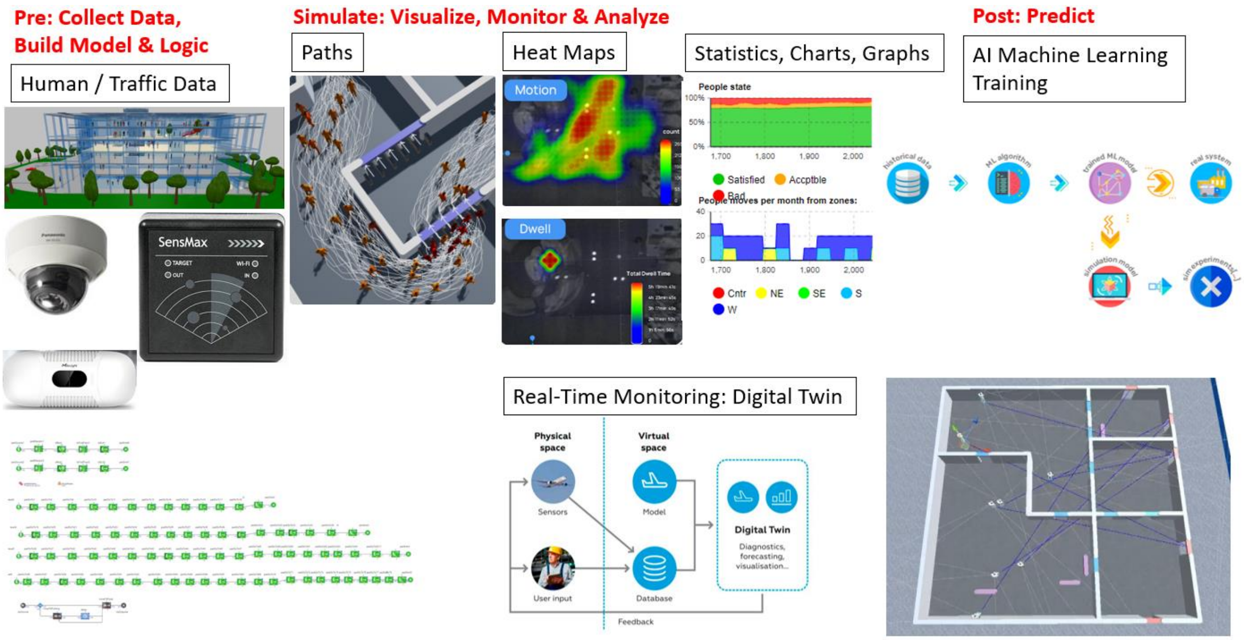

Figure 9: The full ABM workflow (AnyLogic 2023; Smart Human AI 2023; SensMax 2023; Milesight 2023).

At the simulation stage, the paths travelled can be mapped on the floor plates. The aggregated behavior for a timeline of interest can be visualized as heatmaps. This includes motion and dwelling maps. The count can be shown in graphs and charts as well. The ability to directly link the monitored databases to the simulation databases enables the creation of the digital twin. This can be real-time or slight delay interval depending on the connection speed. At the final postprocessing stage, the data collected can be used for machine learning training for prediction purposes. This can be on different scenarios, space configurations, layouts, or other what-if scenarios. This will be the basis for the performance prediction of new design spaces in the future.

3.4 The environmental simulation linkage

Sinha, K. and Rajasekar, E. 2020 did field measurement to build the thermal comfort index directly in the ABM platform for the impact of in an underground metro station in India. For the prediction of environmental performance for thermal comfort and well-being, simulation software such as ENVI-Met, ClimateStudio, Rhinoceros's Grasshopper ecosystem of Honeybee, CityComfort, Urban Modeling Interface or CitySim is required as shown in Figure 10. Albdour and Baranyai 2019 did a comparison of eight microclimatic simulation tools for thermal climate indices, meteorological parameters, and outdoor design strategies. Among these tools (Rayman, ENVI-met, ANSYS CFD, Autodesk CFD, CitySim Pro, TAS, Meteodyn, Honeybee, and Ladybug), ENVI-Met is the most capable considering the features under those categories.

There were attempts done to bring ENVI-Met results to the ABM platforms such as with GAMA (Estacio et al. 2022), AnyLogic (Jia and Wang 2021) and Quelea (Khan 2022). They explored the impact of outdoor thermal comfort in the built environment for affecting ideal trees spacing, walkability, walking speed and walking routes. Melnikov et al 2022 did pedestrian path choices in Singapore impacted by the urban climate and shading which will be useful for outdoor ABM simulations in the tropics.

These environmental simulation software can be used to validate the measured data on site and be used for prediction of new designs later. The application can be done in indoor, semi-outdoor and outdoor spaces. As using hybrid ventilation and natural ventilation spaces is one of the mitigation strategies to carbon emissions, the way human behavior changes or adapts to these new spaces will also create different tolerances of thermal comfort. This is crucial to design future buildings by understanding the thresholds tolerable.

Figure 10: The environmental parameters simulation integration with ABM platforms.

4 THE GEAR LESSONS LEARNT

The opening ceremony was held on 4th August 2023 (The GEAR 2023) with more than half a year spent commissioning and finetuning the sensors to work well on the same platform. There are challenges for putting them together in an optimized manner to serve their purposes well. It is still too early at the current stage to have empirical data to establish the success of the digital twin and simulation of the smart building for wellness. The consensus is also to allow the occupants to settle down to the spaces to familiarize themselves with the usage for at least a year of monitoring. Figure 11 shows the methodology employed in progress to reach digital twin status in the future for The GEAR.

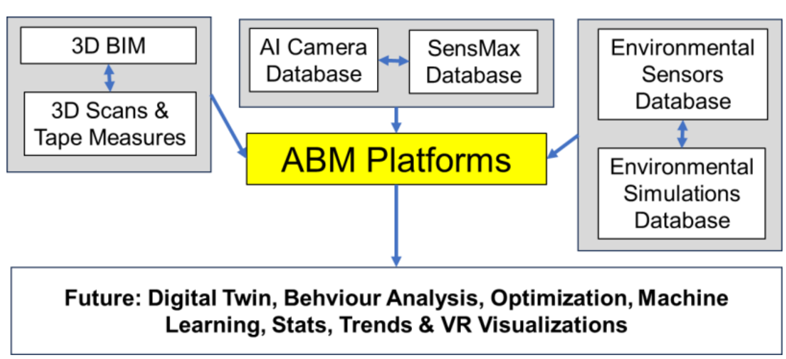

Figure 11: The methodology in progress applied in The GEAR

The first stage was to acquire the 3D BIM (Building Information Modeling) available from the construction team. The work done was to prepare the model for agent-based modeling platforms such as AnyLogic and GAMA for trial and error. Most of the explorations involve the 3D CAD file formats and image textures. Figure 9 top left image shows The GEAR's earliest demonstration for the opening ceremony with human and car traffic inside the AnyLogic platform. The current stage is to put in furnishings and vegetations, which are not available in 3D in the BIM. Manual tape measurements and 3D scanning were done using Leica BLK2GO to include furnishing for integration in the final ABM platform.

There are more than 300 AI cameras and face recognition readers in The GEAR. This is still at the early stage to improve the overall performance. The face recognition readers achieved 100% accuracy, but the AI cameras achieved lower than 70%. The trajectories' average x and y coordinates position error is less than 1meter, the accuracy of posture (sitting and standing) detection is more than 90% while the trajectory coverage is less than 50%. There is still much room to position them well to get good coverage and better integration between zones among different cameras. The positioning and view angle must take into account the obstructions from furnishings and vegetations as well as the brightness of the solar access around the windows that impaired tracking accuracy.

Currently, the SensMax sensors are still in progress to get approval from building owner to be positioned around the building to validate the accuracy of detection against the AI cameras and the ground truth by self-observation. The target is to allow these sensors to be used in spaces where privacy is a concern and outdoor spaces where there are no power sources available as they can be powered by solar panels with power banks. Srikanth et al. 2022 had employed it in the university environment together with Bluetooth (BLE) tracking. The centrality measure used in the research is a good metric to consider for potential social interaction points in spaces.

Environmental sensors are embedded in almost every space in the building to monitor the performance and impact on human wellness. The trial test done so far is to connect the database to AnyLogic to impact people's behavior if the thermal comfort condition is not favorable. This includes conditions such as when the air temperature exceeds 28 ^{o}C without enough wind flow exposure. For environmental simulations, the current status is to explore the method to bring in the specific x,y,z coordinate variables into the ABM platforms. We will set conditions of how this impact agent behavior, such as walking speed or avoidance.

5 CONCLUSIONS & FUTURE WORKS

We currently live in an era of interconnected sensor rich environments which enables smart buildings and cities to thrive. The ability to sense ourselves and the environment helps to create more sustainable and well-being oriented built environments which is mutually beneficial. Therefore, the effort should be spent to be able to accurately link the useful data for further research analysis and simulation. The main challenge is to link quantitative parameters to qualitative parameters of interest in the field such as well-being, thermal comfort, productivity, concentration, emotions, and social interactions. There exists possible indicators, metrics, and indirect parameters that can predict the qualitative aspects of the occupant behavior. The more effort in place to model occupant behavior accurately, the better the prediction of well-being as well as intervention in the built environment.

The future work is to expand the smart building research topics to the district scale urban environment with semi-outdoor and outdoor spaces considered once the confidence of modeling it with a certain degree of accuracy is achieved. The same principles will apply with the challenges of deploying sensors distributed in a wider horizontal space. The difficulties of mounting locations, network connectivity, security and power sources concerns will need to be addressed. The potential scale of application in the outdoor environment is in our research collaborator in National University of Singapore as they have installed extensive network of weather stations around the Kent Ridge campus. They had attempted to establish thermal comfort link to behavior for flexible work arrangements and helped improve better space cooling planning (Mosteiro-Romero et al 2024).

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