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Rethinking how multifunctional façades are made: optimizing composite structures via 3D printing

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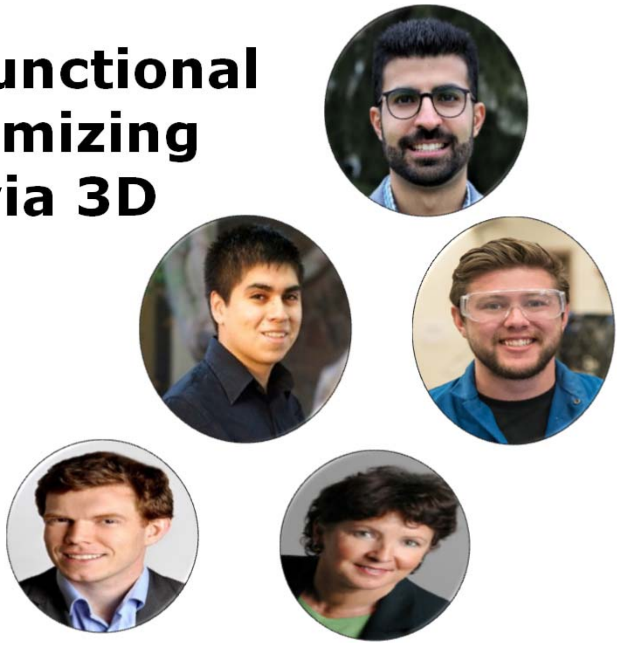

Ideal façade systems

A building's façade is the external envelope of a building, which provides inhabitants with protection from the environment. As a façade must be thermally-resistant, façades are commonly made from concrete. Concrete materials with high thermal resistance, mainly foam concrete, when used in façade systems, often require a larger thickness so as to provide sufficient strength and adequate insulation. This is due to a random pore structure in foam concrete, which leads to an exponential decrease in strength and stiffness as porosity is increased.

In this research, Ultra-High Performance Fiber-Reinforced Concrete (UHP-FRC) and green UHP-FRC (G-UHP-FRC) with very high compressive strength were used to develop a lightweight structure by engineering the voids in the material via 3D printing of the negative mold, referred to as Octet-Truss Engineered Concrete (OTEC).

Lattice structures: lightweight yet strong

The octet-truss lattice is well known for its high stiffness- and strength-to-weight ratios—it is very strong for the little that it weighs. This is because the octet-truss lattice is stretching-dominated, meaning that under compression, the members do not undergo significant bending loads, which would cause complex triaxial stresses and, hence, early failure. Therefore, all members mainly experience axial compression as illustrated in Figure 1. Alexander Graham Bell saw its potential in kites, and Buckminster Fuller used the octet lattice in his airplane hangar designs. Octet-truss lattices seem to be ideal for concrete as well, especially for UHP-FRC and G-UHP-FRC composites with ultra-high compressive strength. These highly structured materials can achieve much higher specific strength and stiffness than foam concretes with equivalent density.

Octet-Truss Engineered Concrete: a superior lightweight concrete structure

We took the octet-truss lattice and developed a method to create a lightweight concrete structure, by forming the concrete into octet lattice structures. The resultant concrete structure uses up to 66% less material but is still strong enough for many applications. Saving this material is important, on multiple fronts, such as to save costs on cementitious composite materials and to reduce the weight as well as the environmental impact. Production of cement alone (one constituent material used in concrete) is responsible for about 8% of carbon emissions in the world, so reducing the amount of concrete used in building façades will be beneficial for the environment.

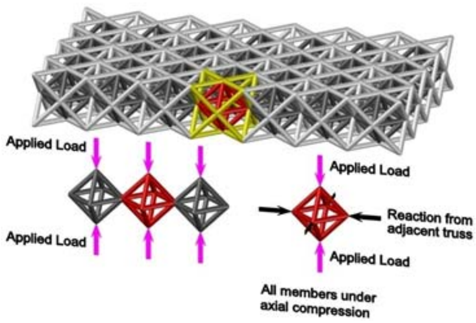

FIGURE 1 Stress flow in stretching-dominated octet-truss lattice

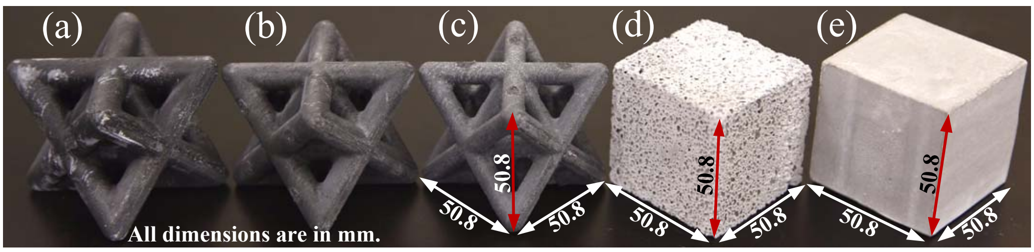

FIGURE 2 UHP-FRC OTEC unit cells with (a) 47%, (b) 54%, and (c) 66% porosities compared to (d) foam G-UHPC cube with 45% porosity and (e) solid G-UHP-FRC cube with 0% porosity.

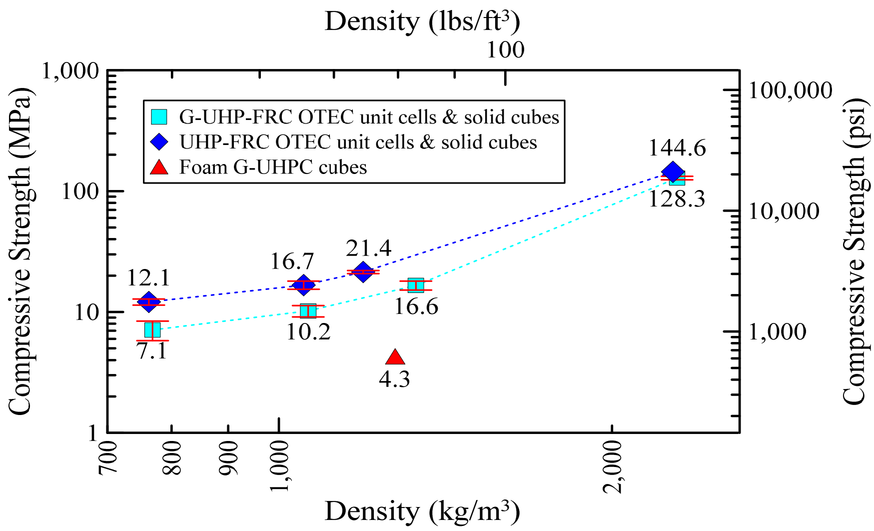

FIGURE 3 Compressive strength versus density for G-UHP-FRC and UHP-FRC OTEC unit cells and foam G-UHPC and solid G-UHP-FRC and UHP-FRC cubes.

We created and tested three configurations of OTEC unit cells with 47%, 54%, and 66% porosities, shown in Figure 2 (compared to foam Green Ultra-High Performance Concrete [G-UHPC] and solid G-UHP-FRC cubes with 45% and 0% porosity, respectively). The porosity was controlled by varying the diameters of the struts in the lattice. Compressive strength results versus effective density for all of these samples are illustrated in Figure 3, and they show that OTEC structures have up to about 400% of the compressive strength of typical foam G-UHPC, yet can exhibit this behavior with higher porosities (i.e., lower effective densities and hence lower material usage).

As concrete 3D printing technology advances, it is envisaged that OTEC structures could be directly 3D printed and used for a variety of applications including lightweight façade and flooring systems as well as load-bearing structural systems, such as space trusses, concrete shells, shear walls, and the like.

Polymeric reinforcement makes concrete ductile

While concrete is very strong, it is not able to deform significantly. Some applications require both the high compressive strength that concrete is able to provide and the ability to withstand high deflections. We developed a method to reinforce concrete with a polymeric lattice structure; by merging concrete's high strength with a polymer's high ductility, we create a composite with high toughness.

We 3D-printed octet truss lattices out of the polymer polylactic acid (PLA) on a standard fused deposition modeling printer. We then cast beams of lattice-reinforced concrete and tested them in four-point bending. We tested two versions of the structure: one with a low amount of polymeric lattice reinforcement (19% by volume), and one with a high amount of reinforcement (34% by volume). We found that the beams with a higher amount of polymeric reinforcement exhibited far higher ductility and toughness.

Phase changing materials keep you cool

We anticipate that this new platform for creating façades will allow us to incorporate phase-change materials (PCMs) as well. Using PCMs in façades will allow for heat storage, so that the building interior temperature remains cooler during the day. At night, the latent heat of fusion will be released, and the façade elements could potentially be designed to vent this heat preferentially to the outside environment.

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Indoor air pollution in the tropics

William Nazaroff

Particles and Haze

Particles released from biomass burning can contribute to severe regional air pollution. Buildings provide partial protection for occupants. We monitored indoor and outdoor particles in a mechanically ventilated and air-conditioned building during and after the 2013 haze event in Singapore. During the event, the average outdoor particle concentrations for diameters larger than 0.3 µm were considerably higher than those during the post-haze days (9-185 $\mu m^3\ cm^{-3}$ versus 1-35 $\mu m^3\ cm^{-3}$). However, the average number concentration of particles with diameters in the range 10-200 nm was substantially lower on the hazy days than on the post-haze days (11,400 to 14,300 particles cm^{-3} for hazy days, versus 23,700 particles cm^{-3} on post-haze days). The building's mechanical ventilation system attenuated the penetration and persistence of outdoor particles into the monitored building (see Figure 1). Indoor particle concentrations closely tracked the corresponding patterns of outdoor particle concentrations. For particles in the size range 0.01-1.0 µm, the size-resolved mean indoor/outdoor (I/O) ratios were in the range 0.12-0.65 with the highest mean I/O ratio at 0.3 µm (0.59 in AC on mode and 0.64 in AC off mode). (Reference: Chen et al., 2016).

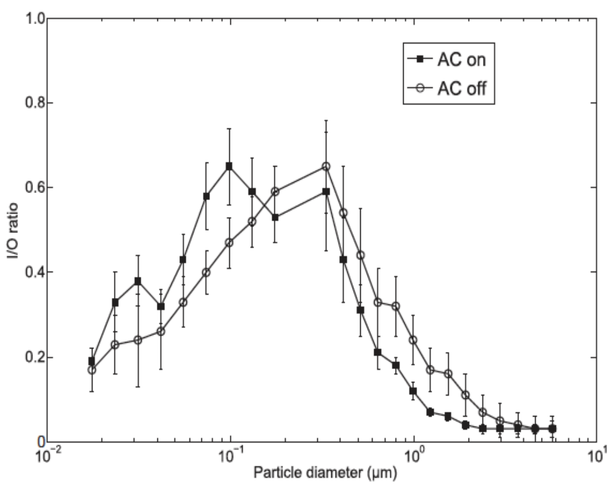

FIGURE 1 Size-resolved ratio of indoor to outdoor airborne particles as a function of particle diameter for an office building in Singapore during the year 2013 regional haze event.

Individual exposures to particulate matter vary (a) according to time patterns of behaviour and (b) with the different degrees of protection provided by buildings against penetration and persistence of outdoor particles. Utilizing real-time personal monitoring, we evaluated exposures to size-segregated fine particulate matter (PM) of five office workers for six days during the latter portion of the 2013 haze event. More than 80% of total daily exposures occurred indoors in workplaces and residences. The exposure factors for the five participants, quantifying the extent of exposure reduction associated with being indoors, had daily average values ranging from 0.32 to 0.75. Being indoors provides some incomplete protection against exposure to haze particles. (Reference: Zhou et al., 2015)

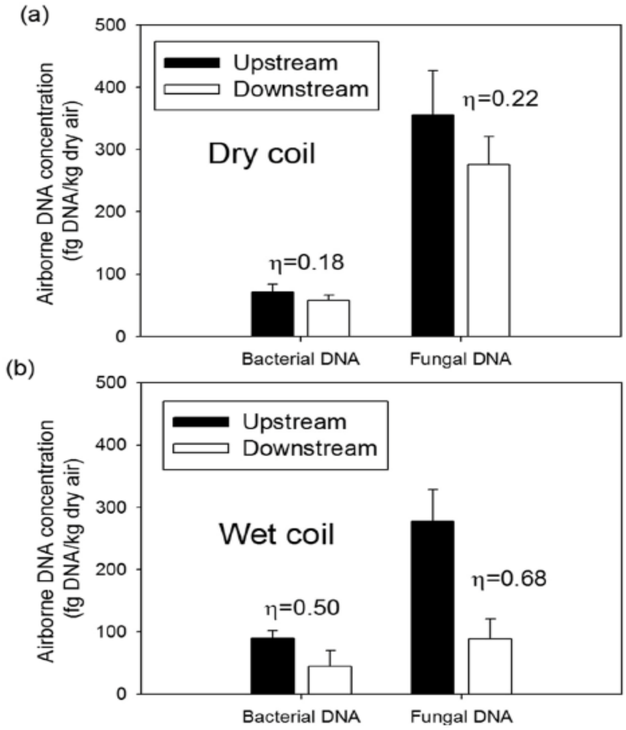

FIGURE 2 Measured (a) bacterial and (b) fungal DNA concentrations upstream and downstream of an air conditioning cooling coil, quantifying the degree of removal to coil surfaces.

Bioaerosols

Common fin-and-tube heat exchangers utilized for mechanical air conditioning in Singapore's warm and humid climate can modify microbial indoor air quality. Depositional losses of ambient bioaerosols and particles onto dry (not cooled) and wet (cool) coil surfaces were measured for different airspeeds passing through such a coil in a test apparatus. Total, bacterial and fungal DNA concentrations in condensate water produced by a wet coil were also quantified.

Results revealed that the deposition of bioaerosols and total particles is substantial on coil surfaces, especially when wet and cool. The average deposition fraction was 0.14 for total DNA, 0.18 for bacterial DNA and 0.22 for fungal DNA on the dry coil, increasing to 0.51 for total DNA, 0.50 for bacterial DNA and 0.68 for fungal DNA on the wet coil. Overall, as expected, deposition fractions increased with increasing particle size and increasing airspeed. Deposited DNA was removed from the cooling coil surfaces through the flow of condensing water at a rate comparable to the rate of direct deposition from air. (Reference: Wu et al., 2016).

Ventilation system filters process recirculated indoor air along with outdoor air. This function inspires the idea of using the filter as an indoor bioaerosol sampler. To better understand the potential, there is a need to investigate several factors that could limit the accuracy of such a sampling approach. We traced the accumulation of biomass on a filter over time as it functions normally. A ventilation system filter in a university library was sampled and analyzed for accumulating DNA at regular intervals over the course of 21 weeks. Total DNA rose monotonically, from 6.8 to 41 ng/cm^2 over the study period. Fungal DNA rose from 1.0 ng/cm^2 to 4.0 ng/cm^2 before showing a dip to 1.4 ng/cm^2 between weeks 6 and 10, indicating that DNA may not always be conserved on the filter. After the dip, fungal DNA then steadily rose to 4.1 ng/cm^2. Bacterial DNA loads stayed relatively constant at 0.5–0.6 ng/cm^2 until week 8 and then rose to 2.8 ng/cm^2 at week 21. This study supports the use of ventilation system filters as indoor bioaerosol samplers with a few caveats: 1) an outdoor reference is required to properly understand the contribution of outdoor bioaerosols; and 2) there is a need to better understand the persistence and durability of the targeted organisms on ventilation system filters. (Reference: Luhung et al., 2018)

Pollutant Exposures

Elevated indoor CO_2 levels are indicative of insufficient ventilation in occupied spaces and correlate with elevated concentrations of pollutants of indoor origin. Adverse health and well-being outcomes associated with elevated indoor CO_2 levels are based on CO_2 as a proxy; some emerging evidence suggests that CO_2 itself may impact human cognition. Using portable monitors, we conducted an exposure study with 16 subjects in Singapore to understand the levels, dynamics and influencing factors of personal exposure to CO_2. Participants carried a CO_2 monitor continuously for 7-day periods recording their exposure levels at 1-min intervals. A recall diary was maintained of time-microenvironment-activity budget. We found that the method of bedroom ventilation was a major determinant of CO_2 exposure. Approximately half of the participants slept in bedrooms employing ductless split air-conditioners (group “AC”); half slept in bedrooms naturally ventilated through operable windows (group “NV”). Median CO_2 exposure levels for AC vs. NV groups were significantly different. Mean daily integrated exposures for group AC were statistically higher than for group NV: 22,800 ppm h/d vs. 16,000 ppm h/d. Exposure events associated with potential adverse cognitive implications (duration > 2.5 h, average CO_2 mixing ratio > 1000 ppm) occurred, on average, at frequencies of 0.5 per day across all participants, 0.6 per day for AC participants and 0.2 per day for NV participants. The majority of such events occurred in the home (86%), followed by work (9%) and transit (3%). (Reference: Gall et al., 2016)

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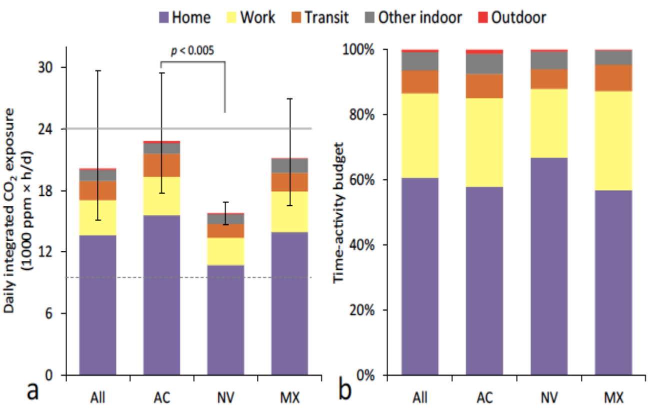

FIGURE 3 Average daily-integrated CO_2 exposure (left) and time-activity budget (right) apportioned by category of microenvironment. Horizontal lines in left-hand panel are shown for comparison to a hypothetical equivalent daily integrated exposure from continuous exposure to an average CO_2 mixing ratio of 1000 ppm (solid) and 400 ppm (dashed) for a 24-h period

WinIPS: WiFi-enabled Non-intrusive Indoor Positioning System

Xie Lihua, Han Zou

With the pervasive and wide availability of WiFi infrastructure and nearly every mobile devices (MDs) are equipped with a WiFi module, WiFi has been acknowledged as the most promising alternative to GPS for indoor context-aware services and location-based services. Conventional WiFi-enabled IPSs require users to install a dedicated App on their mobile devices (MDs) to scan the Received Signal Strength (RSS) of nearby routers for indoor localization which is intrusive and inconvenient. Moreover, the offline calibrated RSS radio map is vulnerable to temporal and environmental dynamics, serious localization errors may be introduced if the radio map is not updated adaptively.

To overcome these issues, we developed WinIPS, a novel WiFi-enabled IPS that provides real-time location estimation of MDs that carried by the occupants in a totally non-intrusive manner. Figure 1 depicts the flowchat of WinIPS. We upgraded the software of commercial off-the-shelf (COTS) WiFi routers so they can overhear the existing WiFi traffic, and accurately retrieve the RSS values and corresponding MAC addresses as identifiers of the MDs. Then, all the information is sent to a back-end server without requiring occupants to install any dedicated App. On the server side, the location of each MD, as well as its user are estimated by utilizing our proposed localization algorithms. Novel localization algorithms that empowered by advanced signal processing and machine learning methods are proposed to overcome the longstanding challenges of WiFi-enabled IPSs, including device heterogeneity, system robustness, environmental dynamics and signal feature selection. These works have been published in top journals, such as IEEE transactions on wireless communications, IEEE transactions on cybernetics, energy and buildings, and IEEE Internet of Things journal.

Moreover, WinIPS has been recognized by international awards, we participated in Microsoft Indoor Localization Competition and received the 3rd Place Award in the infrastructure-based category in the 2014 competition and achieved an indoor localization accuracy of 1.37m in 2015.

WinIPS provides comprehensive fine-grained occupancy information (including occupancy detection, counting and tracking) in an accurate, reliable, cost-effective and non-intrusive manner to optimize the energy efficiency and utility management in smart buildings. Furthermore, numerous location-based services (LBSs), such as indoor navigation (provide real-time guidance with an optimal path to the user's destination) and indoor geofencing (user location adaptive lighting and temperature control for personalized thermal comfort), have been developed. It has been implemented in 12 distinct indoor environments (e.g. airport, convention center, hotel, office space, lecture theater) with more than 10k m^2 providing people various location-based and context-aware services. As one of the applications, the system can provide occupant information for efficient building energy management.

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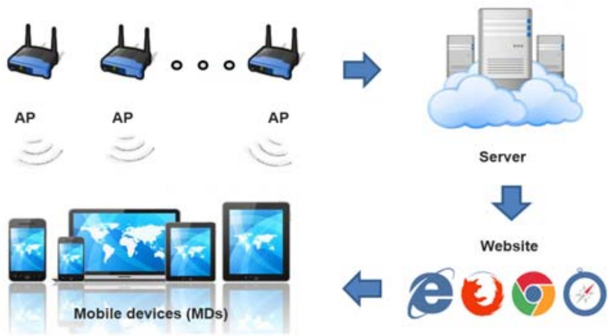


FIGURE 1 Flowchart of the WinIPS

Life-Cycle Approach for Green Concrete Use in Singapore

Claudia Ostertag

Singapore consumes large volumes of concrete to sustain its growth in construction. To comply with its Green Mark Scheme (GMS) it is necessary for Singapore to take action in consuming concrete products with lower carbon footprint.

As part of SinBerBest Phase I, the Excel-based Green Concrete Life Cycle Analysis (LCA) tool developed at UC Berkeley was used to quantify and suggest alternatives for reducing the environmental impacts of concrete consumption in Singapore. To achieve this goal, two approaches were investigated:

a. Strategically selecting the countries for import of cement and aggregates to use in concrete manufacturing in Singapore;
b. Replacing cement with 60% waste materials (industrial by-products).

Using the Green Concrete LCA tool, the following results were obtained:

1) Cement production in China and Taiwan result in higher levels of energy consumption and global warming potential (GWP) due to their inefficient kiln technologies and use of fossil fuels in cement kilns.
2) Share of energy use in terms of cement production-related fuel use and electricity use is relatively equivalent among the various importing countries as well as fuel use in transportation of cement.
3) Transportation impacts of aggregates from China is significant. Major reason being China's location with respect to Singapore.
4) Heavy (residual) fuel used in transportation of aggregates dominate the energy consumption of the total transportation. Similarly, major air pollutants (CO, NO_X, PM_{10}, and SO_2) are predominantly caused by transportation of aggregates in proportion to higher amount of aggregates per unit volume of the concrete mix.
5) Electricity use for processing coarse and fine aggregates is the major source of methane (CH_4) and nitrous oxide (N_2O) together with non-methane volatile and volatile organic compounds (NMVOCs and VOCs). Accordingly, Thailand with a 70% share of natural gas in the electricity mix emits the highest amount of CH_4 and NMVOCs while Indonesia with the highest share of distillate fuel in the mix is responsible for the highest N_2O rate per unit weight of aggregates.
6) Malaysia is the environmentally cleanest source for Singapore due to its vicinity as well as its cleaner electricity grid mix, efficient production technologies and greener fuel mixes. By importing aggregates and cement from Malaysia, a reduction of 11% in GWP and 31% in embodied energy can be achieved.
7) The impact of concrete can be further reduced through 60% cement replacement by industrial waste products as shown in the Figures below (where PC, FA, RHA, and LF represent ordinary Portland cement, Class F-Fly ash, Rice Husk Ash, and Limestone Flour, respectively).

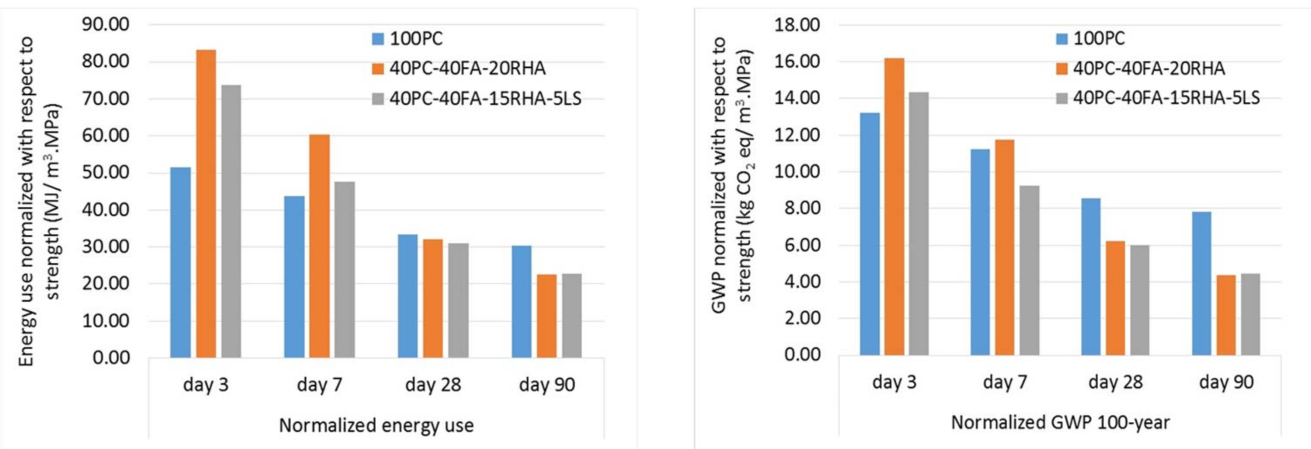


FIGURE 1 Energy use and global warming potential (GWP) for Portland cement, fly ash, rice husk ash and limestone flour

Gamification Towards Improving Human-Building Interaction and Energy Efficiency in Smart Infrastructure: A Deep Learning Approach

Ioannis Konstantakapoolos, Costas Spanos

A generalized gamification approach (namely Social Game), is used as a novel framework for smart building infrastructure with the goal of motivating human occupants to consider personal energy usage and to have positive effects on their environment. Human interaction in the context of cyber-physical systems is a core component and consideration in the implementation of any smart building technology. Research has shown that the adoption of human-centric building services and amenities leads to improvements in the operational efficiency of these cyber-physical systems directed toward controlling building energy usage. In our experiment at Nanyang Technological University campus we introduce a strategy that incorporates humans-in-the-loop modeling by creating an interface to allow building managers to interact with occupants and potentially incentivize energy efficient behavior. Using data gathered from occupant actions for resources such as room lighting, we forecast patterns of resource usage to demonstrate the performance of the proposed methods on ground truth data. The results of our study show that we can achieve a highly accurate representation of the ground truth for occupant resource usage. For demonstrations of our infrastructure and for downloading de-identified, high-dimensional data sets, please visit our website at smartNTU demo web portal: https://smartntu.eecs.berkeley.edu.

Bottom up implementation of gamification: From building occupants to smart grid

Recently, utility companies have invested in demand response programs that can address improper load forecasting while also helping building managers encourage energy efficiency among building occupants. Commonly, the implementation of these programs is enacted on a contract basis between utility providers and the consumers under arranged conditions of demand/usage. The building managers will then be bound by contract to operate according to the agreed-upon schedule. However, the conditions of these contracts are static and do not consider dynamic changes in occupant behavior or preferences, which can result in discrepancies in demand/usage expectations. To facilitate the adoption of more dynamic protocols for demand response, our setup features a *gamification interface* (seen in the building level in Figure 1) that allows building managers to interact with a building's occupants. By leveraging our gamification interface, retailers and utility companies at the provider level can utilize a wealth of dynamic and temporal data on building energy usage—extending even to occupant usage predictions—in order to customize demand response program approaches to observed or predicted conditions. Above all, our gamification interface is designed to support engagement and integration on multiple levels in a human-centric cyber-physical system.

Figure 1 also presents a block diagram of our proposed research design framework toward building energy management from both a top-down and bottom-up perspective, motivated by previous model illustrations. The block diagram consists of three layers: *the smart building layer, the data management layer, and the top human-centric cyber-physical systems layer*. Each layer has some connection between its respective components and upper level abstractions. From the proposed bottom-up framework, the aggregated occupant patterns are processed and passed to an artificial intelligence layer that is capable of real-time energy forecasting, which can then be integrated with applications like demand response programs.

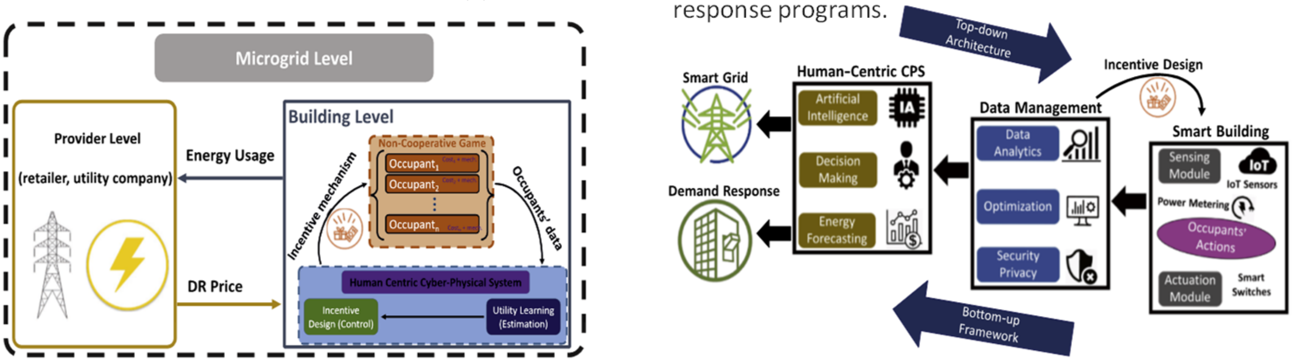


FIGURE 1 Human-centric cyber physical systems framework

Through optimization and data analysis, the proposed design framework leverages advanced incentive design schemes aimed at engaging smart building occupants. In addition, the data management layer provides the opportunity to implement security and privacy protocols against malicious attacks.

Gamification through machine learning/deep learning

However, game theoretic analysis typically relies on the assumption that the utility function of each individual agent is known a priori. Instead, we propose a novel benchmark utility learning framework that employs robust estimations of occupant actions toward energy efficiency. To improve forecasting performance, we extend the benchmark utility learning scheme by leveraging Deep Learning end-to-end training with deep bi-directional Recurrent Neural Networks (RNN) --- Figure 2. We apply the proposed methods to high-dimensional data from a Social Game experiment designed to encourage energy efficient behavior among smart building occupants. Using data gathered from occupant actions for resources such as room lighting, we forecast patterns of resource usage to demonstrate the performance of the proposed methods on ground truth data. The results of our study show that we can achieve a highly accurate representation of the ground truth for occupant resource usage.

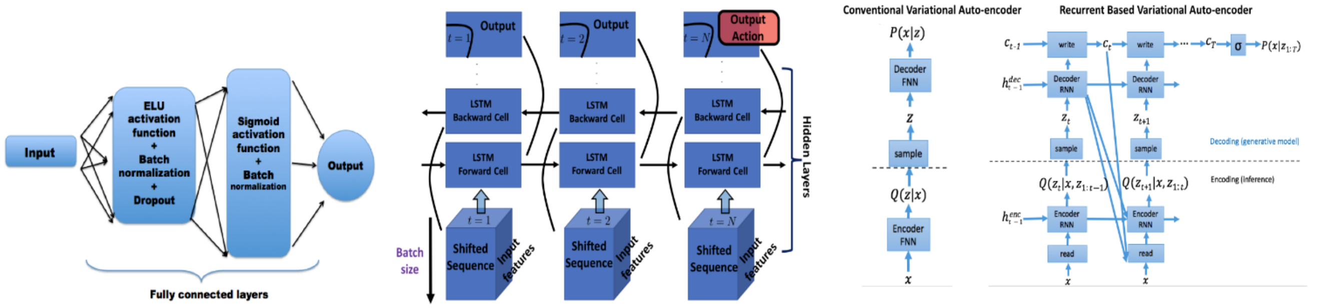
Leveraging the latest Deep Learning models, like recurrent neural networks, we try mainly to address the issue of time dependence by looking at temporal dependencies within the data. Recurrent neural networks have the capability to allow information to persist, even over long periods, by simply inserting loops that point to them. As we see in the architecture of a deep bi-directional recurrent neural network in Figure 2 (b), information passes from one-time step of the network to the next. The information of the network passes to successor nodes.

In the case of a bi-directional recurrent neural network, information flows also in the opposite direction to the predecessor. In a simple implementation, however, recurrent neural networks tend to either vanish or become incapable of modeling long-term dependencies. In our proposed novel sequential utility learning model, we enable an end-to-end training using Long Short Term Memory cells (LSTM). Mainly, LSTM includes several gates that decide how long-term—short-term relations should be modeled. The overall output of the LSTM cell is a combination of sub-gates describing the term dependencies

On top of the existing data set resulting from our experiment, researchers can create other even larger data sets based on the existing ones. Using such a Deep Learning model, we can acquire generated samples by simply enabling the latent space of the auto-encoder and re-sampling using the decoder component. In Figure 2 (c), we provide the overall idea behind training a variational auto-encoder. We use two hidden layers in encoder and decoder while tying parameters between them. Also, the latent space is modeled using a Gaussian distribution. By using this architecture of deep auto-encoder, however, we limit the generative model in applications in which the data process has a natural time-series dependence. Hence, we proposed the implementation of a recurrent based variational auto-encoder. In its architecture shown in Figure 2 (c), the proposed recurrent based variational auto-encoder allows time-series modeling for progressive refinement and spatial attention in the shifted tensor inputs. Using progressive refinement, the deep network simply breaks up the joint distribution over and over again in several steps resulting in a chain of latent variables. This gives the capability to sequentially output the time-series data rather than compute them in a single shot. Moreover, a recurrent based variational auto-encoder can potentially improve the generative process over the spatial domain. By adding time series in the model as tensors with shifted data points, we can reduce the burden of complexity by implementing improvements over small regions of the tensor input at a time instance (spatial attention).

Gamification in action: deep learning approaches versus machine learning

To evaluate the effectiveness of our proposed deep learning framework, we present the AUC scores of a representative example for comparison. From the results, it is clear that deep RNN outperforms the majority of alternative algorithms. One important remark is that deep RNN exceeds even when compared to Random Forest, which is considered a top-performing, robust classification model. Deep NN also achieved better performance in some examples over the Random Forest classifier, but this is not a general case.



((a)) Architecture of proposed deep neural network ((b)) Architecture of deep bi-directional recurrent neural networks ((c)) Conventional and recurrent based deep auto-encoder

FIGURE 2 Deep Learning Architectures

Figure 3 introduces bar charts representing AUC scores for ceiling fan usage (on/off). Prediction results are divided into AUC scores for the two scenarios “step-ahead” (including sensors) and “sensor-free” (without using sensors). Upon examination of these results, it is clear that deep RNN outperforms all other Deep Learning and machine learning models.

modeling and simulating human-building interaction toward improving energy efficiency. To demonstrate the utility learning methods, we applied them to data collected from a smart building social game where the goal was to have occupants optimize their room’s resources. We were able to estimate several agent profiles and significantly reduce the forecasting error compared to all benchmark models.

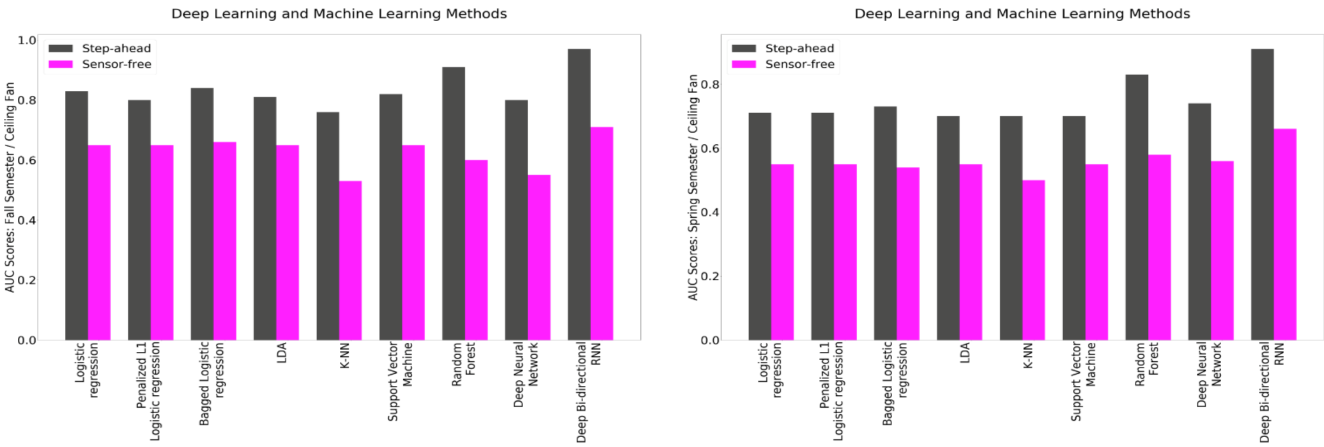
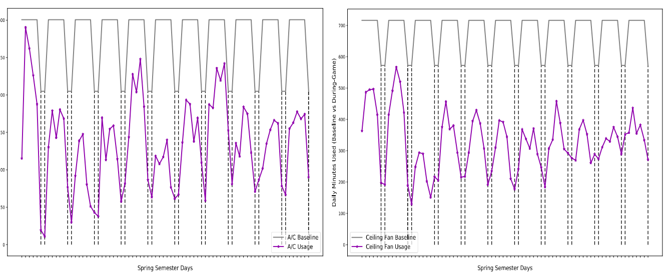


FIGURE 3 Machine Learning & Deep Learning Models AUC Accuracy

Deep Learning architecture handles sequential data process with an effect of improving the overall accuracy. In the Social Game data, we apply these methods specifically to smart building social game data; however, it can generalize to other scenarios with the task of inverse modeling of competitive agents, and it provides a useful tool for many smart infrastructure applications where learning decision-making behavior is crucial. Under our gamification application, occupants were highly motivated to drastically reduce their energy impact (Figure 4). This result is even more significant considering the fact that no effort was directed toward optimizing the incentive design for encouraging energy efficient behavior.



((a)) A/C daily average usage vs. baselines

((b)) Ceiling fan daily average usage vs. baselines

FIGURE 4 Usage during experiment vs usage before the experiment

What’s next?

Our study/experiment presents a general framework for utility learning in sequential decision-making models. We leveraged several Deep Learning architectures and proposed a novel sequential Deep Learning classifier model. We also introduced a framework that serves as a basis for creating generative models, which are ideal for

The deep sequential utility learning framework outperformed all other models being considered, and it improved prediction accuracy to an extraordinary degree in specific examples. This last result shows that a Deep Learning architecture that handles a sequential data process has the effect of improving the overall accuracy. In this application we apply these methods specifically to smart building social game data; however, it can generalize to other scenarios with the task of inverse modeling of competitive agents, and it provides a useful tool for many smart infrastructure applications where learning decision-making behavior is crucial. Under our gamification application, occupants were highly motivated to drastically reduce their energy impact. This result is even more significant considering the fact that no effort was directed toward optimizing the incentive design for encouraging energy efficient behavior. Hence, research in optimal incentive design mechanisms should be pursued in the context of this work.

Furthermore, special attention should be given to the management of pricing and how it affects the dynamics between the smart building and utility provider levels for applications like demand response programs. In general, we have demonstrated that our proposed framework can be used successfully for the purposes of accurately forecasting energy usage. However, Deep Learning models require a continuous feed of data and are not particularly robust to missing data points. This poses a challenge to many real-world applications, especially in such cases that might result in IoT sensors losing connection. Hence, we identify this as a limitation that should be addressed for our assumed Deep Learning models. Despite these constraints, we have shown that our implementation of a gamification approach to human-building interaction in smart infrastructure offers tremendous opportunities for improving energy efficiency and smart grid management.

Simulator of Light into Active Buildings with the Heliodon: A Hardware-in-the-Loop Approach

Jiawei Chen, Khalid Mosalam

More than thirty percent of the total energy consumption in modern societies is due to the building industry. Among the energy use in both residential and commercial buildings, a significant portion can be attributed to lighting and heating and cooling loads, which are closely related to the design of the building envelopes and fenestration systems. The optimal design of the complex building envelopes requires knowledge of the thermal and photometric properties of the system in question, which can be either inaccurate using numerical simulation only or costly using conventional tests of full-scale building systems.

A hardware-in-the-loop (HiL) simulation framework is being developed in this research to combine the high fidelity of physical modeling with the versatility of numerical simulation. The Simulator of Light into Active Buildings (SLAB) is one realization of this hybrid approach for testing complex fenestration systems like the active (dynamic) façades. Combined with a Heliodon in the testbed of SinBerBEST, the SLAB system can simulate the long-term lighting performance of complex fenestration systems in any building.

The Simulator of Light into Active Buildings (SLAB)

The developed hardware-in-the-loop (HiL) system, namely the Simulator of Light into Active Buildings (SLAB), has four main components. These include the following: the controller, the plant, the sensor, and the actuator (Figure 1).

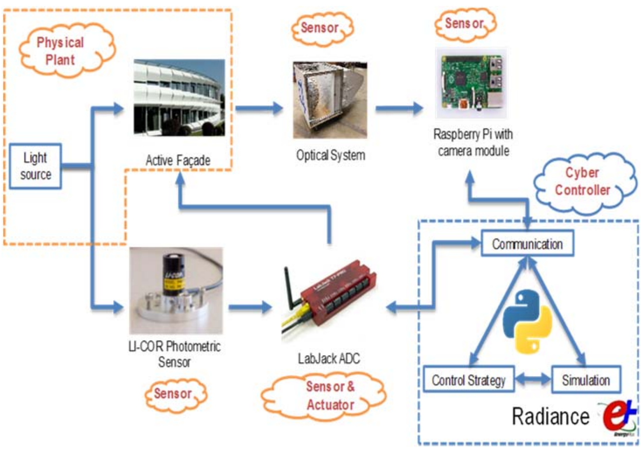


FIGURE 1 The Framework of the SLAB

The controller consists of the numerical model of the building and the control strategy of the active façade system. On the other hand, the active façade system itself is the plant, which is tested physically. The interface between the controller and the plant includes the actuator controlling the movement of the active façade and the sensors measuring the response of the plant. For the purpose of daylight simulation, the response of interest is the emitted light intensity (in terms of luminance) from the active façade. Therefore, a parallel goniophotometer is developed as the light sensor converting the multidimensional luminance data from the façade into the input of the numerical model of any hypothetical building to be considered in the study.

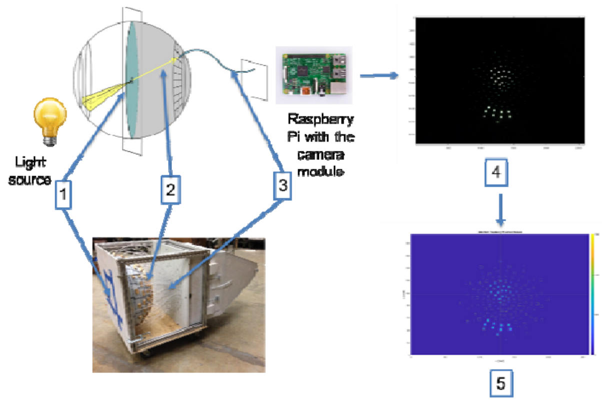


FIGURE 2 The Optical System of the SLAB

The SLAB system utilizes a novel parallel goniophotometer (Figure 2) to measure the output luminance component of the active façade system. The goniophotometer is shown on the lower left corner of Figure 2. The light from the light source reaches the aperture of the sensor (No. 1 in Figure 2) from all directions. Subsequently, the light propagates inside an opaque dome (No. 2 in Figure 2) and reaches the optical fibers at the back of the dome. The geometry and the interior matte black coating of the dome ensure that the light reaching each optical fiber is from one specific direction corresponding to the Klems Basis, widely used in the daylighting industry. The optical fibers relay the light signal to the backend through total internal reflection (No. 3 in Figure 2). The signals are then represented by a High Dynamic Range Image (HDRI) using the camera module of a Raspberry Pi and further processed to determine the luminance components (No. 4 and No. 5 in Figure 2).

Research capabilities combining the SLAB and the Heliodon

The SLAB is a suitable tool for research and development of complex fenestration systems. It has the capability of accurately characterizing the bidirectional transmittance distribution function of the complex façade rapidly and directly feeding that information into numerical models to calculate the daylight performance as well as other design parameters of the building design. This combined with the ability of the Heliodon to simulate the overcast sky, would greatly expedite the simulation process of complex building envelopes.

The Heliodon system (Figure 3) consists of a sun simulator and a turntable. The building model can be mounted on the turntable. The Heliodon simulates the overcast sky condition with the Tregenza sky patches in the following way. First, the turntable turns to different positions, where the location of the sun simulator relative to the building model corresponds to that of one sky patch relative to the building. Then, the sun simulator simulates the light condition of that one patch and measurements like the illuminance can be taken from the building model. Finally, after all the sky patches have been simulated, the results are summed together to generate the final outcome.

Although currently the Heliodon is mostly used by the architecture community to conduct qualitative studies on shade and lighting, it is rather obvious that by combining the SLAB (a smaller version of the current SLAB, to comply with the Heliodon limitations, in place of the building model) with the Heliodon, the efficiency and applicability of the HiL simulation can be significantly improved. This is because one can easily generate the desired sky conditions with the Heliodon and simulate the response of the complex façade and the building with the SLAB. A large amount of simulations can be performed to generate data on the façade system, opening up the possibility for new ways of the analysis and design of innovative energy-efficient building envelopes.

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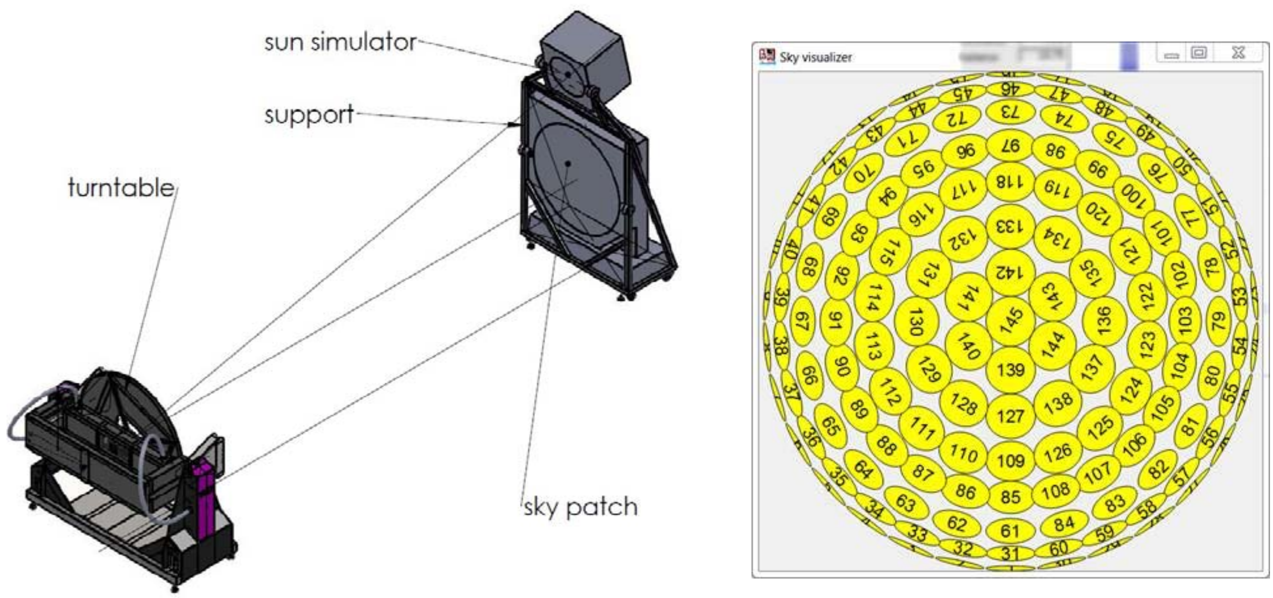


FIGURE 3 Heliodon and the Sky Patch

Annual SinBerBEST Symposium 2019

The SinBerBEST Annual Symposium took place at CREATE Tower in Singapore on Monday, August 5, 2019. The theme of this Symposium was: People, buildings and data – shaping a sustainable future. During this meeting, keynote lectures were presented from external speakers and SinBerBEST principal investigators, Energy Market Authority leadership and presenters from post-doctoral scholars. The three external speakers were Professors Jeffrey Siegel, Marilyne Andersen and Rahul Mangharam from University of Toronto, École polytechnique fédérale de Lausanne and University of Pennsylvania respectively. A total of 44 posters on program research works were on display in the nearby CREATE gallery for the attendees.

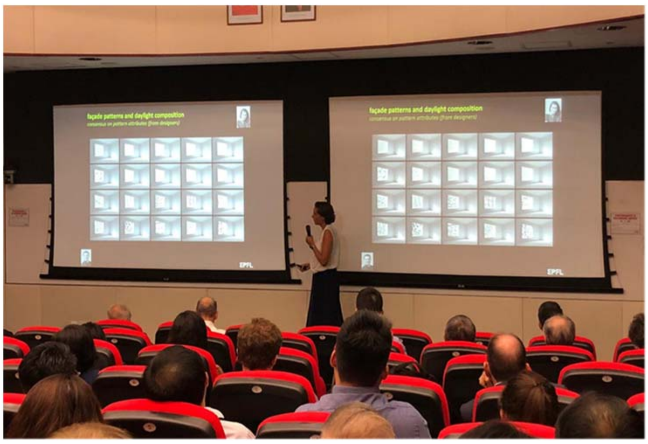
The program began with the opening address from the NRF chairman Dr. Lim Khiang Wee. This was followed by a lecture from Prof Spanos on the program highlights and achievements. Keynote speakers Prof Siegel gave a talk on the future of air cleaning, Prof Andersen on daylighting experience in buildings while Prof Mangharam gave a talk on using machine learning and control for volatile electricity markets for building applications. Mr Bernard Nee from the Energy Market Authority gave a keynote on managing the energy transition.

From SinBerBEST, Prof Schiavon gave a lecture on using energy efficient air movement to cool in the indoor environment. Prof Miller lectured on crowd-sourced machine learning models for city-scale analytics. Prof Su shared his research on the token based scheduling algorithm to reduce building energy consumption and Prof Mosalam provided lecture on uncertainty quantification and hybrid simulation for energy efficient building envelopes.

Post-doctoral scholars participating in this symposium were Drs. Sum, Arjunan, Toby Cheung and Radhakrishnan. Topics discussed include plug-load management technology, meta-resonators in building materials for wireless communications, building energy benchmarking system and occupant's environmental satisfaction survey in Singapore commercial buildings.

Towards the end of the symposium, Prof Spanos and Schiavon announced the 2019 award winners for the program. Dr Han Zou won the outstanding scientist award for his excellent works on the internationally recognised WiFi-based indoor positioning system and cutting-edge WiFi-enabled IoT platform for device-free occupancy sensing. The best paper award goes to the paper entitled "Development of the ASHRAE global thermal comfort database II" published in the Journal of Building and Environment in September 2018. The major output of this paper is a thermal comfort field survey database collected from over 60 contributors around the world who shared their raw data for wide dissemination. The distinguished service award goes to Er You Chun for her outstanding work on devising a novel administrative solution to the complex problem of transporting two large cooling coils from Singapore to Berkeley and back again, having exemplary service- and excellence-oriented attitude and improving workplace practice via the "open purchase order" system.

Presentation slides are given here: http://sinberbest.berkeley.edu/archive/presentations



Lecture and poster sessions

Interview with Drs. Ning Baisong, Jia Hongyuan and Li Jiayu

Dr Jia Hongyuan recently joined SinBerBEST as a researcher joining Drs Ning Baisong and Li Jiayu who were already in the program. They conduct research in the field of human comfort and building nexus. We were impressed by the engineering expertise of these three scholars, related to IAQ, thermal comfort and human-centeric HVAC operations and energy simulation. Their technical abilities and past research experience made them ideal additions to the SinBerBEST's research team. We asked them about their past experience, current research and their hopes for the future.

Can you briefly describe your education background?

Dr. Li: I completed my PhD program at Tianjin University where I tried to utilize both computational and experimental fluid dynamic methods to optimize airflow distributions in various built environments. Before I came to Singapore, I spent one year at RWTH Aachen University in Germany as a joint PhD student and three months at CSIRO in Australia.

Dr. Ning: My undergraduate background is in mechanical engineering from Guizhou University, China. After that, I began my graduate study (also on mechanical engineering) in Hunan University, China. Between 2014 and 2016 I spent 2 years on a visiting study at the University of California Berkeley. I completed my PhD in 2017.

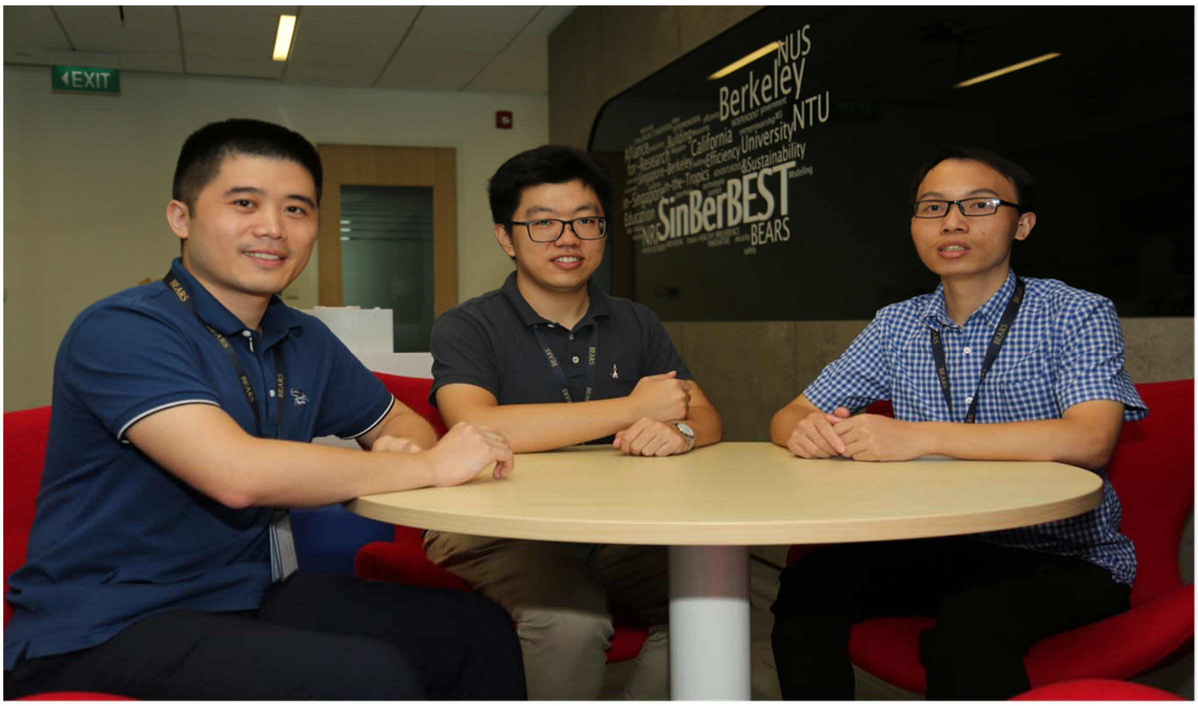
Dr. Jia: I received my bachelor degree in Built Environment in 2013 and completed my Ph.D. in heating, ventilation and air-conditioning in Chongqing University, China in 2019. During my PhD training, I became a visiting scholar at the Simulation Research Group in Lawrence Berkeley National Laboratory from 2016 to 2017.

What drew you to SinBerBEST?

Dr. Li: I heard about the program from a former colleague, Dr. Shichao Liu who used to work in SinBerBEST. When I was in Germany, I received the recruitment email -- I thought it was a good opportunity and I submitted my resume immediately.

Dr. Ning: I came to know about the program while I was doing my PhD. I was impressed by the program objectives and research topics. After my graduation, I realised there is a need for me to further my research and that SinBerBEST will serve as a good opportunity to fulfil that goal.

Dr. Jia: I first heard about the program from two SinBerBEST PIs, Professors Adrian and Clayton Miller. I checked out the program through the website and noticed the splendid testbed facility and support team. I realised that SinBerBEST will be an ideal platform for me to conduct research on energy modelling and calibration at various scales. And I believe my proficiency in building energy simulation can contribute to the program's success too.



Drs. Jia Hongyuan Li Jiayu and Ning Baisong

How does your work at SinBerBEST build on your past research?

Dr. Li: My past research was more on fundamental fluid mechanics both numerically and experimentally. Now, my research works is more on the application of those fundamental theories to solve problems in the real world.

Dr. Ning: My previous research was focused on the design and operation of building HVAC systems. Since I am familiar with heat transfer of HVAC systems, my work now at SinBerBEST will be focusing on the thermal performance evaluation and operation of cooling coils in air handling units for the tropical climate. The research also involves solving heat transfer problems using simulation and experimental methods.

Dr. Jia: My PhD research was focused on thermal characteristics of radiant cooling systems. This involved detailed energy modelling and calibration of testbeds. The experience and knowledge gained will be valuable for my research now at SinBerBEST. It will help me to know how to conduct data analysis and how to develop a robust energy modelling and calibration process.

How can your research benefit people working in the building and other industries?

Dr. Li: Under SinBerBEST, I'm trying to find a better ventilation strategy and indoor airflow distribution to maximize occupants' thermal comfort and improve the indoor air quality.

Dr. Ning: My current work is on the performance evaluation and application of state-of-the-art cooling coils, namely adaptable coils and super-hydrophobic coated coils. The innovative cooling coils have the potential of improved thermal performance. These could save building energy and improve humidity control, which are of great importance in the tropics.

Dr. Jia: Building energy modelling can provide valuable support for exploring energy potentials of design alternatives. However, there are a lot of input parameters that need to be specified in a detailed simulation. Hence, it is important for me to evaluate and improve the accuracy and reliability of the energy models and conclusions derived from them. This can be done using uncertainty analyses and calibration technologies. More importantly, there are trade-offs among data resolution, parameter and model uncertainties. It is crucial to develop a framework to evaluate the feasibility of various modelling detail levels, taking into account the measured data streams available and input parameter uncertainty. Once that is achieved, predictions will be more reliable and insightful.

Now that you have been in Singapore for some time, what are your impressions?

Dr. Li: Singapore is a vibrant and open country. Food is good, transportation is convenient, and people are very friendly. I am enjoying almost everything here.

Dr. Ning: I am impressed by the fresh air and clean environment at Singapore. I also like the friendly, collaborative, and innovative working environment at SinBerBEST.

Dr. Jia: I love the friendly people and innovative working environment in the program. With regards to Singapore, I am extremely impressed by the cultural diversity as well as considerations and efforts in the balance of preserving nature and pursuit of modernization.

What are your longer term goals?

Dr. Li: My long-term goal is to make our living environment more comfortable and healthier through research. I think it is meaningful and exciting, and I'd like to try my best and devote myself to it.

Dr. Ning: The long term goals I would like to pursue is to make our life better through improving the indoor built environment using innovative technologies and knowledge. This requires persistent and time-consuming effort on research. I hope my work experience at SinBerBEST will be a good starting point.

Dr. Jia: I believe the postdoctoral training in SinBerBEST will provide an optimal time to expand my research skills and shape my career trajectories. My longer term goal is to acquire a university faculty position.

SinBerBEST Addition

Ming Jin and Ruoxi Jia, former Graduate Student Researchers at UC Berkeley who met through the SinBerBEST program, just welcomed their son, Walter Jin, to the world.

He is wearing a SinBerBEST onesie, a gift from the SinBerBEST team at UC Berkeley.

Congratulations, Ming and Ruoxi!

SinBerBEST

The SinBerBEST program, funded by the National Research Foundation (NRF) of Singapore, is a research program within the Berkeley Education Alliance for Research in Singapore (BEARS). It comprises of researchers from University of California, Berkeley (UCB), Nanyang Technological University (NTU) and National University of Singapore (NUS). SinBerBEST's mission is to advance technologies for designing, modeling and operating buildings for maximum efficiency and sustainability in tropical climates. This newsletter, published quarterly, is to showcase the excellence of SinBerBEST faculty, post doctoral fellows and students.

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