RGC Ref. No.:
UGC/FDS16/P01/20
(please insert ref. above)

RESEARCH GRANTS COUNCIL
COMPETITIVE RESEARCH FUNDING SCHEMES FOR THE LOCAL SELF-FINANCING DEGREE SECTOR

FACULTY DEVELOPMENT SCHEME (FDS)

Completion Report
(for completed projects only)

Submission Deadlines:	*1. Auditor's report with unspent balance, if any: within* ***six*** *months of the approved project completion date.* *2. Completion report: within* ***12*** *months of the approved project completion date.*

Part A: The Project and Investigator(s)

1. Project Title
Improved Indoor Air Quality (IAQ) management through Scientific IAQ monitoring and App Survey with an indication of energy demand reduction

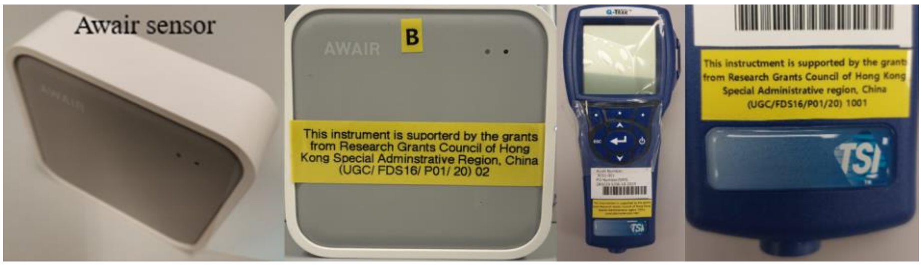
2. Investigator(s) and Academic Department(s) / Unit(s) Involvedl

Research Team	Name / Post	Unit / Department / Institution
Principal Investigator (1/8/2022-31/12/2023)	Dr Tony LEE Associate Professor	School of Science and Technology Hong Kong Metropolitan University
Principal Investigator (1/1/2021-31/07/22)	Dr Jie HAN Assistant Professor	School of Science and Technology Hong Kong Metropolitan University
Co-Investigator	Dr Xi CHEN Research Assistant Professor	Department of Mechanical and Automation Engineering The Chinese University of Hong Kong
Co-Investigator	Dr Carlin Chun-fai CHU Assistant Professor	Department of Computer Science The Hang Seng University of Hong Kong

3. Project Duration

	Original	Revised	Date of RGC / Institution Approval *(must be quoted)*
Project Start Date	01/01/2021	01/01/2020	
Project Completion Date	30/06/2023	31/12/2023	4/7/2022
Duration *(in month)*	30	36	4/7/2022
Deadline for Submission of Completion Report	30/06/2024	31/12/2024	4/7/2022

4.4 Please attach photo(s) of acknowledgement of RGC-funded facilities/equipment.



Part B: The Final Report

5. Project Objectives

5.1 Objectives as per original application

1. Explore scientific IAQ measurement strategies through IAQ monitoring and data analysis;
2. Improve the pitfalls and inadequacies in 2019 Hong Kong IAQ Scheme;
3. Develop a personal experience survey through a mobile app survey system;
4. Build up a metamodel for energy demand optimization through sets of personal experience surveys.

5.2 Revised objectives

Date of approval from the RGC: N/A

Reasons for the change:

5.3 Realisation of the objectives

(Maximum 1 page; please state how and to what extent the project objectives have been achieved; give reasons for under-achievements and outline attempts to overcome problems, if any)

Objective 1 **Explore scientific IAQ measurement strategies through IAQ monitoring and data analysis** was fully achieved. On-site IAQ monitoring, including indoor air temperature, CO_2 concentration, PM2.5, TVOCs, and relative humidity, was carried out in selected lecture theatres at different seasons and times, including the class and non-class times. To explore scientific IAQ measurement, different time-interval measurements (5, 10, 15, investigated and 30 mins) were investigated, and the monitoring process with 5 or 10 min of the intervals was recommended. According to our studies, we conducted 2 sensor points, 4 sensor points and 6 sensor points in a lecture hall. It was found that for educational buildings, due to the high intensity of populations, the IAQ measurements are greatly affected by time intervals and adjacent measuring point density. The relevant data and conclusions from this study have been published in the journal *Buildings 2022*.

Objective 2 **Improve the shortcomings of the 2019 Hong Kong IAQ Scheme** was fully achieved. Our study revealed that the 2019 Hong Kong IAQ Scheme's 8-hour average data does not accurately represent the short-term exposure of students, who typically spend around 3 hours in the classroom. Unique IAQ challenges exist in different classrooms due to factors like higher occupancy and specific pollutant sources. Some recommendations are concluded below: Implement a time-segmented IAQ assessment (e.g., measurements every 5 or 10 minutes) to better reflect actual student exposure. Prioritize indoor air temperature, followed by CO_2 concentration and relative humidity, based on statistical analyses of stakeholder preferences derived from survey data. Then, based on the developed predictive models and the measured min-based indoor parameters, the indoor comfort sensation is predicted, and detailed comfort ranges are given, which can guarantee the comfort sensation and achieve energy-saving purposes. Combined with energy-saving envelopes and windows and predictive comfort models, the total energy consumption in buildings can be reduced by 30-40%, without scarifying comfort sensations. The relevant data and conclusions from this study have been published in the journal *Sustainablity 2023*.

Objective 3 **Develop a personal experience survey through a mobile app survey system** was fully achieved. The predictive mean vote (PMV) method was used in our personal experience survey. The contents were designed based on the requirements shown in ANSI/ASHRAE Standard 55-2017. The students' sensation votes on the thermal environment, IAQ, and overall comfort were obtained, by collecting a total of 1055 results at different time periods. The findings from this research have been published in the journal *Buildings 2022*.

Objective 4 **Build up a metamodel for energy demand optimisation through sets of personal experience surveys** was fully achieved. Through the finite difference methods, the numerical building model has been developed, which can provide a robust tool for temperature and energy evaluations. When the indoor temperature remains at a comfortable level (as predicted by Objective 3), the energy consumption of the target building across China has been evaluated. According to the developed numerical building model and thermal sensation and IAQ sensation models, an entire integrity prediction and assessment module has been newly presented, especially for synthetically IEQ and energy evaluations in Hong Kong. Based on this module and the online mobile app survey system, the relationships among building thermal performances, energy consumption, and overall indoor comfort sensations are discussed. According to the comparison of the relationships among roof, wall, and indoor air temperatures, indoor air temperatures are the most important parameter that significantly affects the overall comfort sensations. The results indicate that in recommended comfort ranges of controlled indoor parameters, the energy consumption can be reduced by about 10% with the indoor temperature increasing by 1℃, considering the Hong Kong weather conditions. Thus, extra indoor cooling should be avoided, and the recommended indoor comfort ranges can help stakeholders to achieve this purpose. The relevant data and conclusions from this study have been published in the journals *Applied Energy 2021 and Sustainability 2023*.

5.4 Summary of objectives addressed to date

Objectives *(as per 5.1/5.2 above)*	**Addressed** *(please tick)*	**Percentage Achieved** *(please estimate)*
Explore scientific IAQ measurement strategies through IAQ monitoring and data analysis;	✓	100%
Improve the pitfalls and inadequacies in 2019 Hong Kong IAQ Scheme;	✓	100%
Develop a personal experience survey through a mobile app survey system;	✓	100%
Build up a metamodel for energy demand optimization through sets of personal experience surveys.	✓	100%

6. Research Outcome

6.1 Major findings and research outcome

(Maximum 1 page; please make reference to Part C where necessary)

A total of four published journal manuscripts and one conference paper were published. The another manuscript is currently under preparation.

1. **Review Paper:** This research discusses the current development and state-of-the-art technologies in indoor comfort assessments, especially for university buildings.
2. **Thermal and IAQ Sensations Study:** This research investigates the actual thermal sensations and indoor air quality (IAQ) perceptions of university students through on-site environmental measurements, and through developed predictive models, the comfortable ranges of indoor parameters are given.
3. **Numerical Building Model:** This study develops a numerical model to explore the relationships between energy consumption and comfort sensations. According to the built numerical model, the energy saving potential of building with recommended comfort indoor settings is investigated.
4. **Energy System Analysis:** This paper examines energy systems that provide cooling power for space cooling and investigates the potential application of ground-source heat pump systems in building environments.

The research focused on the overall comfort experienced by university students in a mechanically ventilated classroom located in a tropical region with low background noise and pollution. Regression models were created to predict comfort sensations based on a personal experience survey and measured indoor data. The numerical building model serves as a robust tool for evaluating temperature and energy consumption, highlighting the connection between indoor comfort and energy-saving potential.

Key Results:

1. Comfort Preferences: Survey analysis revealed that the proportions of students reporting “Not Comfortable” were 3.1% for “Cool” 5.1% for "Neutral," and 19.0% for "Warm," indicating a preference for cooler indoor environments. Cooler conditions also help students tolerate higher CO_2 concentrations.
2. Influencing Factors: The most significant factors affecting overall comfort were found to be temperature (T_{op}), followed by CO_2 concentration, and relative humidity (RH). Temperature accounted for 50% of the variance in overall comfort, while CO_2 contributed 20%, and RH 19%. This suggests that interactions among these factors are important.
3. Comfort Ranges: A comfortable temperature was determined to be between 21.5–23.8°C, with CO_2 levels under 1095 ppm and RH between 47–63.5%. These recommended values are lower than those set by the Hong Kong government, suggesting that more precise thresholds could enhance indoor comfort, especially for short-term assessments.
4. Integrated Assessment: Both IAQ and thermal conditions should be evaluated together to prevent discomfort. The comfort thresholds for thermal sensation (TS) and air quality (AS) were determined to be 2.3–3.1 and 1–1.55, respectively.
5. Design Implications: Understanding the relative importance of comfort factors can guide building design. The coefficient for AS (0.32) was higher than for TS (0.18), indicating that air quality has a greater impact on overall comfort. The significance of these factors varies by building, necessitating tailored prediction models.
6. Cooling Performance: Buildings designed with cooling materials on roofs, walls, and windows showed improved cooling performance, reaching sub-ambient indoor temperatures. In a case study using Hong Kong weather data, cooling demands were reduced from 75 W/m² to 30 W/m², achieving 60% energy savings while maintaining comfort.
7. National Cooling Demand: The national average cooling demand for standard buildings in China is 95.7 W/m². In contrast, buildings with cooling coatings and Low-E windows have a lower average cooling demand of 52.7 W/m² during summer.

These findings contribute valuable insights for improving indoor comfort and energy efficiency in building design and management.

6.2 Potential for further development of the research and the proposed course of action (Maximum half a page)

The personal experience survey was conducted in a large classroom space at Hong Kong Metropolitan University (HKMU). While this specific room provided valuable insights, it is important to note that the findings may not be representative of all types of rooms within the university or other settings. The selected classroom was mechanically ventilated year-round, which means that the thermal comfort and IAQ conditions experienced by participants may differ significantly from those in naturally ventilated spaces.

As a result, the outcomes of this study should be interpreted with caution when applied to environments that rely on natural ventilation. Different rooms, such as auditoriums, laboratories, or offices, may exhibit varying thermal dynamics and user comfort due to differences in ventilation strategies, occupancy patterns, and building materials.

In future research, the researchers plan to broaden the scope of their questionnaire survey by including a variety of room types within the university building as well as in commercial buildings. This will allow them to capture a more comprehensive set of data regarding user experiences across diverse environments. By examining both mechanically and naturally ventilated spaces, the researchers aim to better understand how different ventilation methods impact thermal comfort and overall satisfaction. This expanded approach will enhance the validity of the findings and provide valuable insights for improving indoor environmental quality in various settings.

7. Layman's Summary

(Describe <u>*in layman's language*</u> *the nature, significance and value of the research project, in no more than 200 words)*

This study investigated university students' comfort levels in a classroom under varying temperature, humidity, and carbon dioxide (CO_2) conditions. Researchers surveyed students and measured environmental factors to identify key elements influencing comfort sensations.

Building on the 2019 Hong Kong IAQ Scheme, the study advocates for a refined indoor testing method that incorporates time-segmented IAQ assessments, suggesting measurements every 5 to 10 minutes instead of over 8 hours. This approach aims to better capture students' thermal and IAQ sensations immediately. Additionally, placing at least three sensors between adjacent air conditioning vents is also recommended to ensure uniform comfort across the classroom.

According to on-site experimental investigations and coupling with the newly developed empirical models, the more accurate thresholds of main indoor parameters to achieve indoor comfort are recommended, which are capable of providing control suggestions for building-integrated air-conditioning systems.

Through the efficienct numerical building model, the relationships among energy consumption and variations of basic indoor parameters (within recommended comfort ranges) are disclosed. The results can give design and operation suggestions for applying entire cooling systems, with lower energy consumption, higer coefficient of performances (COP), but without scarifying indoor comfort sensations.

Part C: Research Output

8. Peer-Reviewed Journal Publication(s) Arising Directly From This Research Project

(Please attach a copy of the publication and/or the letter of acceptance if not yet submitted in the previous progress report(s). All listed publications must acknowledge RGC's funding support by quoting the specific grant reference.)

The Latest Status of Publications				Author(s) *(denote the correspond-ing author with an asterisk*)*	Title and Journal / Book *(with the volume, pages and other necessary publishing details specified)*	Submitted to RGC *(indicate the year ending of the relevant progress report)*	Attached to this Report *(Yes or No)*	Acknowl-edged the Support of RGC *(Yes or No)*	Accessible from the Institutional Repository *(Yes or No)*
Year of Publication	Year of Acceptance *(For paper accepted but not yet published)*	Under Review	Under Preparation *(optional)*						
2021				Lin-Rui Jia, Jie Han*, Xi Chen, Qing-Yun Li, Chi-Chung Lee and Yat-Hei Fung	Interaction Between Thermal Comfort, Indoor Air Quality and Ventilation Energy Consumption of Educational Buildings: A Comprehensive Review / *Buildings*	2022	yes	yes	yes
2022				Lin-Rui Jia, Lin Lu*, Jianheng Chen, Jie Han,	A Novel Radiative Sky Cooling-Assisted Ground-Coupled Heat Exchanger System to Improve Thermal and Energy Efficiency for Buildings in Hot And Humid Regions / *Applied Energy*. 322, 119422.	No	yes	yes	yes
2022				Lin-Rui Jia, Qing-Yun Li, Xi Chen, Chi-Chung Lee and Jie Han*	Indoor Thermal and Ventilation Indicator on University Students' Overall Comfort / *Buildings*	No	yes	yes	yes
2023				Lin-Rui Jia, Qing-Yun Li, Jie Yang, Jie Han*, Chi-Chung Lee* and Jian-Heng Chen	Investigation of the Energy-Saving Potential of Buildings With Radiative Roofs and Low-E Windows in China / *Sustainability*	No	yes	yes	yes
			Yes	Lin-Rui Jia, Qing-Yun Li, Jie Han*, Chi-Chung Lee*	Experimental Investigation on Indoor Air Quality for University Students in Hong Kong	No	No	yes	yes

9. Recognized International Conference(s) In Which Paper(s) Related To This Research Project Was / Were Delivered

(Please attach a copy of each conference abstract)

Month / Year / Place	Title	Conference Name	Submitted to RGC *(indicate the year ending of the relevant progress report)*	Attached to this Report *(Yes or No)*	Acknowledged the Support of RGC *(Yes or No)*	Accessible from the Institutional Repository *(Yes or No)*
2024	Optimizing Renewable Energy Heating: An Integration of TRNSYS Simulation of Solar and Ground Heat Exchange Systems	2024 IEEE International Symposium on Product Compliance Engineering - Asia (ISPCE-ASIA)	No	Yes	Yes	Yes

10. Whether Research Experience And New Knowledge Has Been Transferred / Has Contributed To Teaching And Learning

(Please elaborate)

Through this project, the PIs gained lot of experiences of onsite investigation and testing. These experiences and techniques furnishing the PIs' teaching in undergraduate science and testing courses. Sharing of research ideas, approaches and findings of this project in different occasions is inspiring to undergraduate students and enhancing their interest in science and research. The project is also a good reference for the students to construct their own research idea in their final year project.

11. Student(s) Trained

(Please attach a copy of the title page of the thesis)

Name	Degree Registered for	Date of Registration	Date of Thesis Submission / Graduation
N/A			

12. Other Impact

(e.g. award of patents or prizes, collaboration with other research institutions, technology transfer, teaching enhancement, etc.)

N/A

13. Statistics on Research Outputs

	Peer-reviewed Journal Publications	Conference Papers	Scholarly Books, Monographs and Chapters	Patents Awarded	Other Research Outputs (please specify)	
No. of outputs arising directly from this research project	4	1	0	0	Type	No.

14. Public Access Of Completion Report

(Please specify the information, if any, that cannot be provided for public access and give the reasons.)

Information that Cannot Be Provided for Public Access	Reasons
N/A	