Sweating Building: A Study of Self-Cooling Hydrogels for Application in Adaptive Architecture

Sweating Building: A Study of Self-Cooling Hydrogels for Application in Adaptive Architecture

A Thesis Submitted to the Department of Architecture
Harvard University Graduate School of Design, by

Jiqi Zhu (Tod)

In Partial Fulfillment of the Requirements for the Degree of
[Master of Architecture]

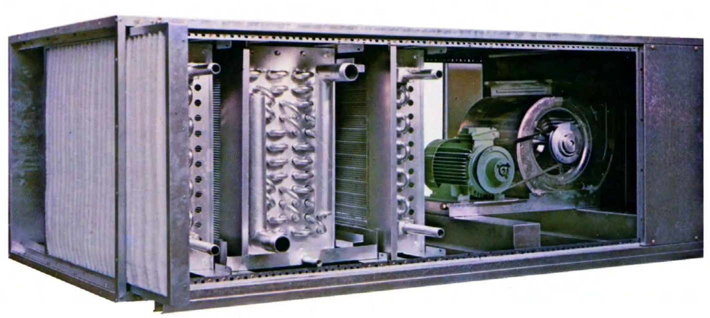
January, 2024

Jiqi Zhu (Tod)

Martin Bechthold

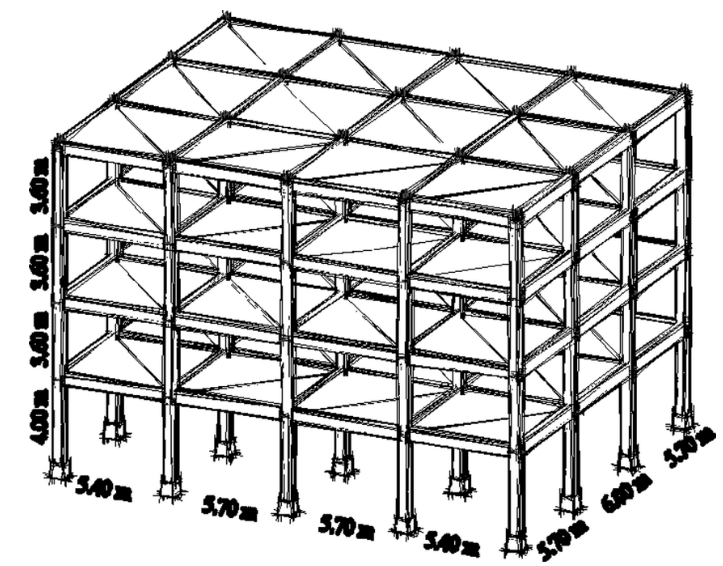
Holly Samuelson

Rational Air Handling



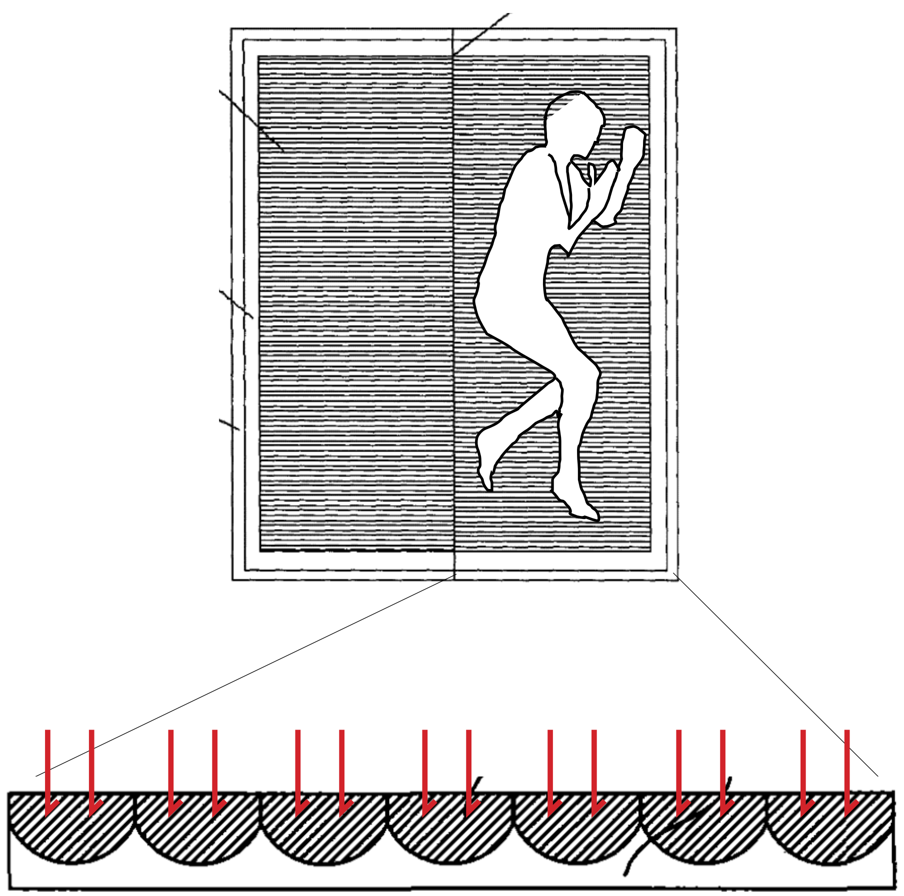
Basic Design_Air Handling Unit

Typical Frame



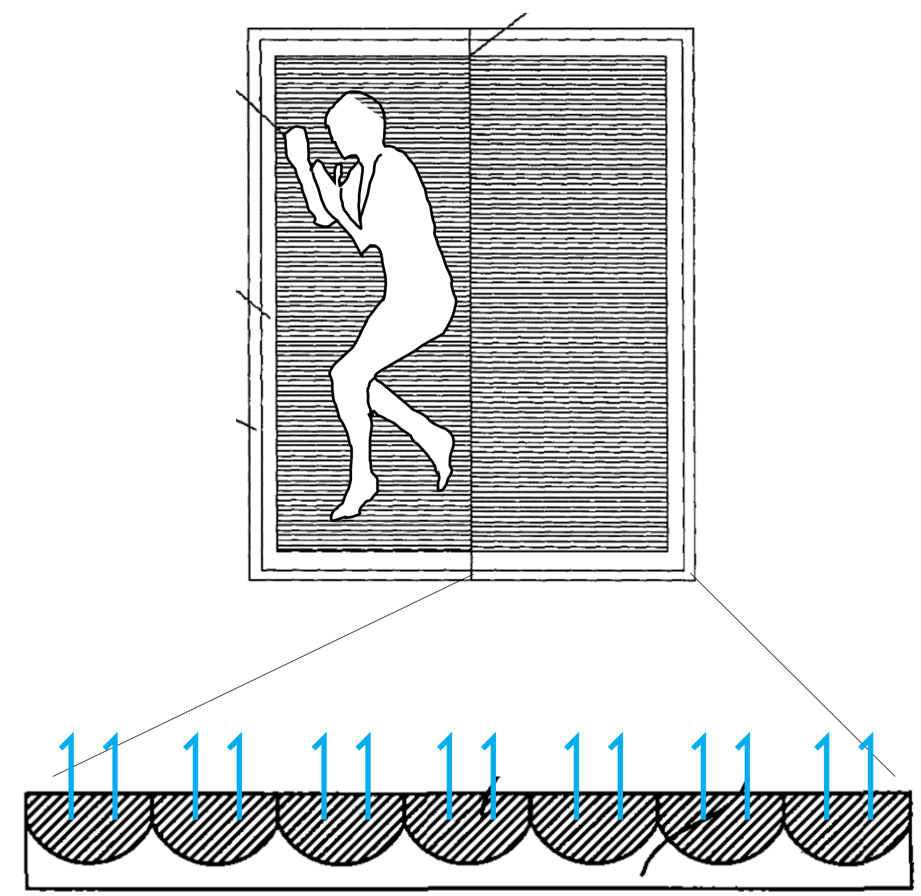
Typical_Reinforced Concrete Frame

Bamboo Sheets_Absorption



With human body atop: Absorbs sweat and slowly heats up

Bamboo Sheets_Evaporation and Cooling



Without human body atop: Liquid within bamboo evaporates and cools down the sheet

Water Cycle for Passive Cooling

$$m * H_{vap} = \sum |Q_i|$$

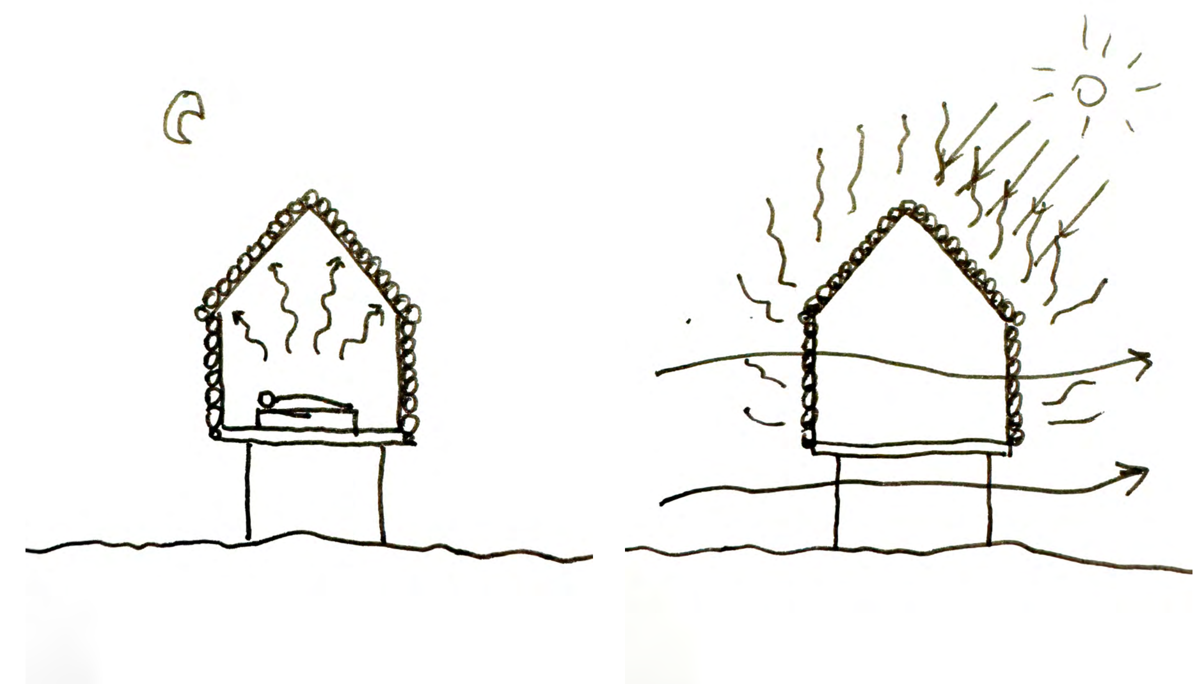
$m = \textit{Mass of the water through the system}$

$H_{vap} = \textit{Heat of vaporization} = {}^{2.4kj}/_{g}$

$Q_i = \textit{Cooling Load}$

Absorption - Evaporation - Cooling

Self-Cooling Prototype

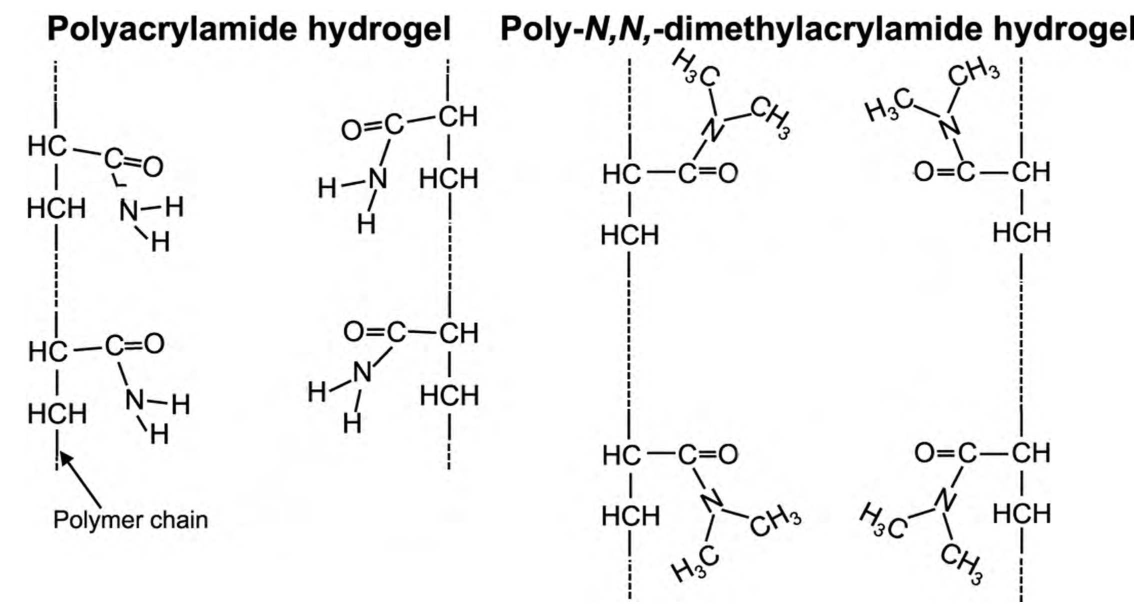


Diurnal Water Cycle for Passive Cooling

DN-Gel_Dry State State

Acrylamide_Alginate DN Gel_Calcium Cross-link

Synthetic Hygroscopic Material

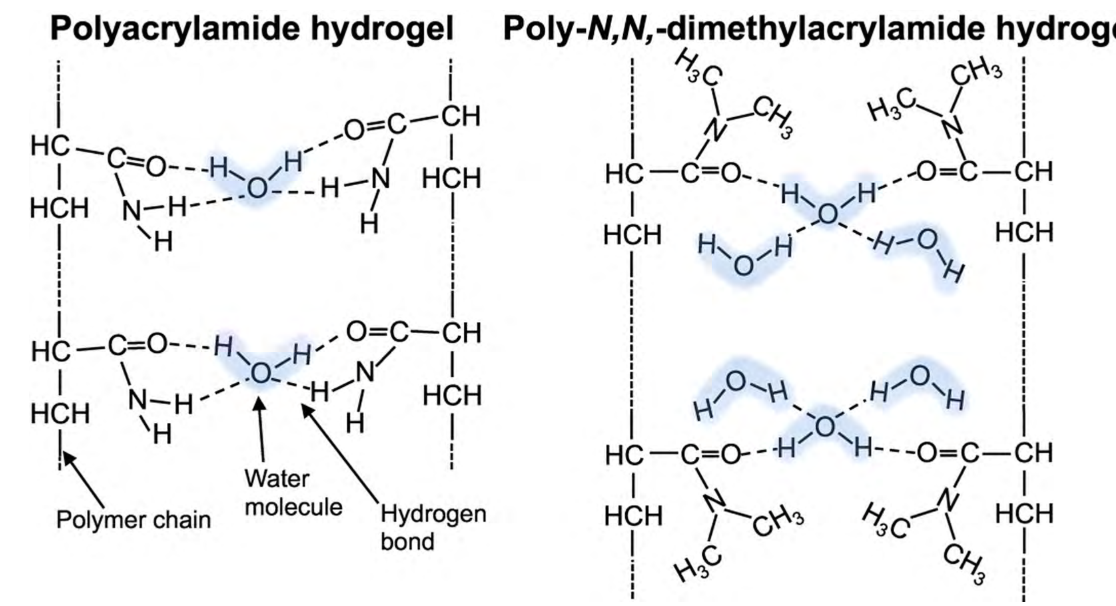


Polymer Structure and Water Absorption Mechanism_Hydrogel

DN-Gel_Post-Swollen

Acrylamide_Alginate DN Gel_Calcium Cross-link

Synthetic Hygroscopic Material



Polymer Structure and Water Absorption Mechanism_Hydrogel

Fabrication of Legacy DN-Gel Panel - Prep and Mix

Acrylamide, Alginate, N.N-Methylenebisacrylamide (MBAA cross-linker), Ammonium Persulfate (photoinitiator), N,N,N,N-tetramethylethylenedia mine (TEMED)

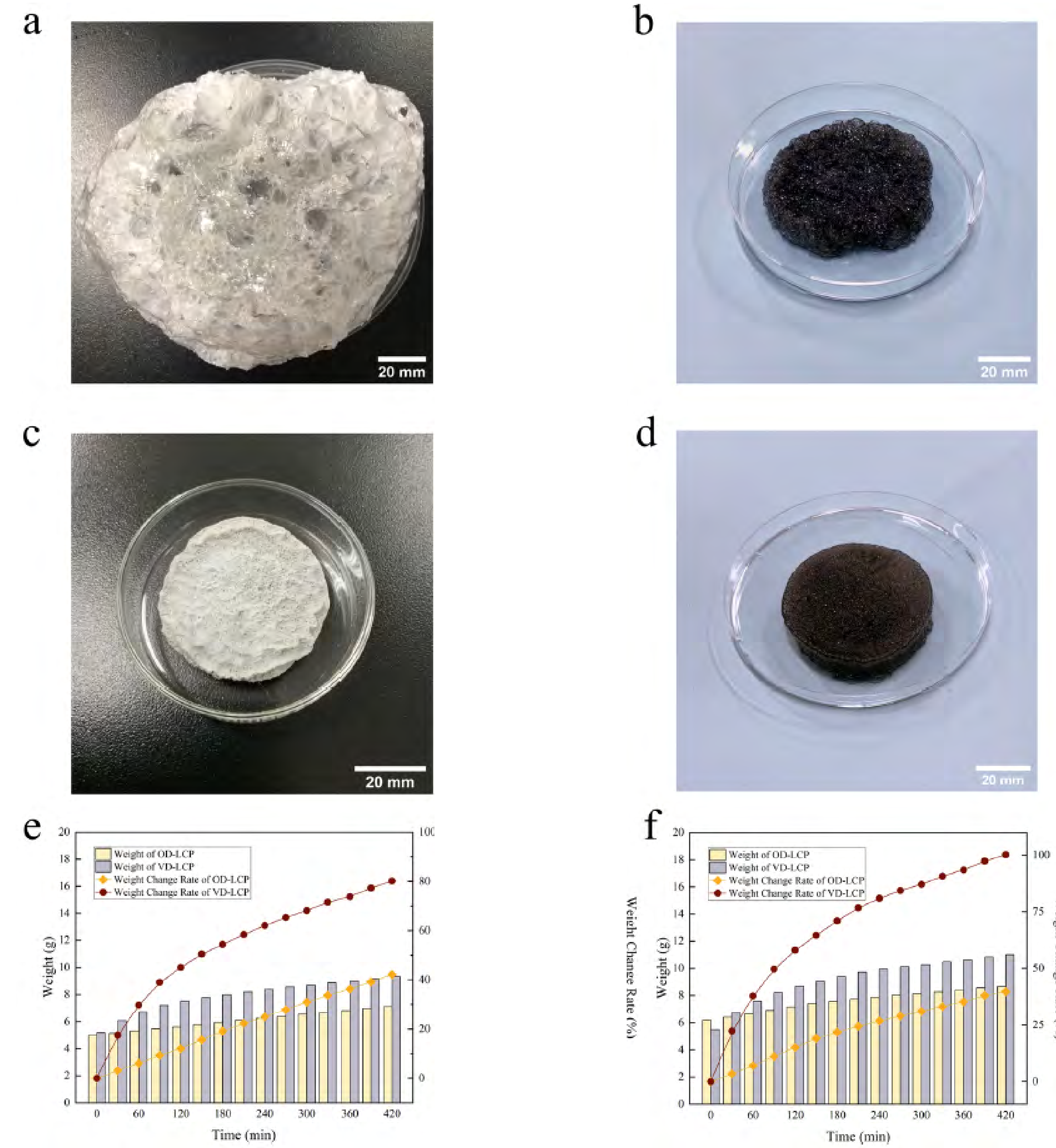
Dry/Swollen State and Glimpse of Cooling Effect

Fuse with polyester foam; Cure under UV light (60 degrees elcius); Stabilize in 70% RH

DN-Gel Samples

Acrylamide-Alginate DN Gel samples of different scale and shape

DN-Gel Samples



Lyu, Tong et all. "Macroporous Hydrogel for High-Performance Atmospheric Water Harvesting." ACS Applied Materials & Interfaces 14, no. 28 (July 20, 2022)

Dry DN-Gel Test Panel

Formal Exploration

Swollen DN-Gel Test Panel

Maximized Surface Area for Evaporation Speed

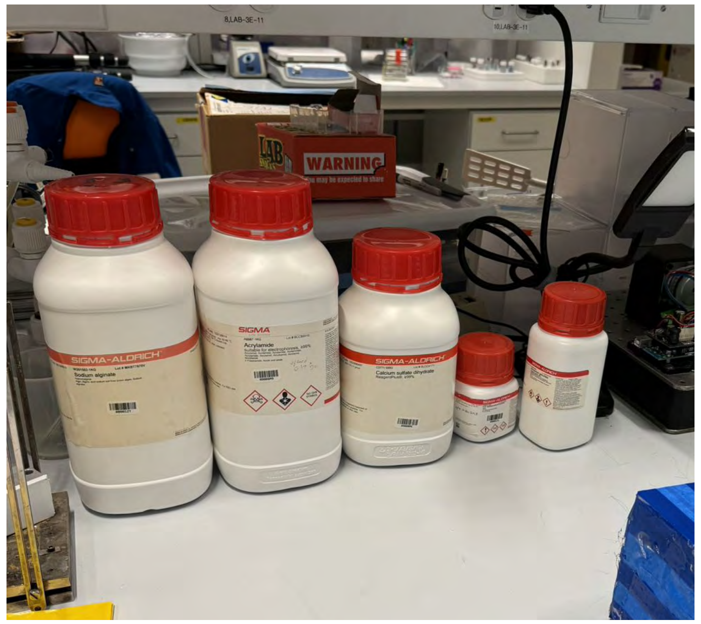
Mold

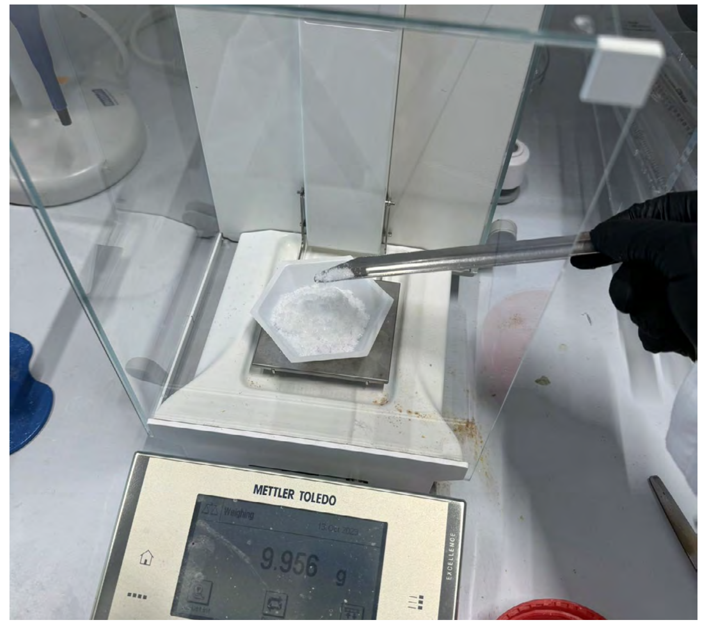
Hygienic Issue

Deformation

Stability Issue

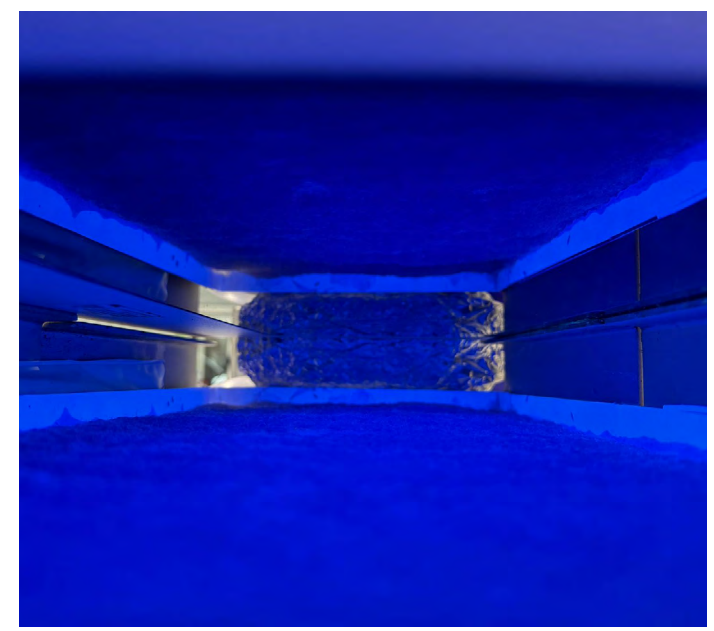
Fabrication of Polyester-Gel Panel - Prep and Mix

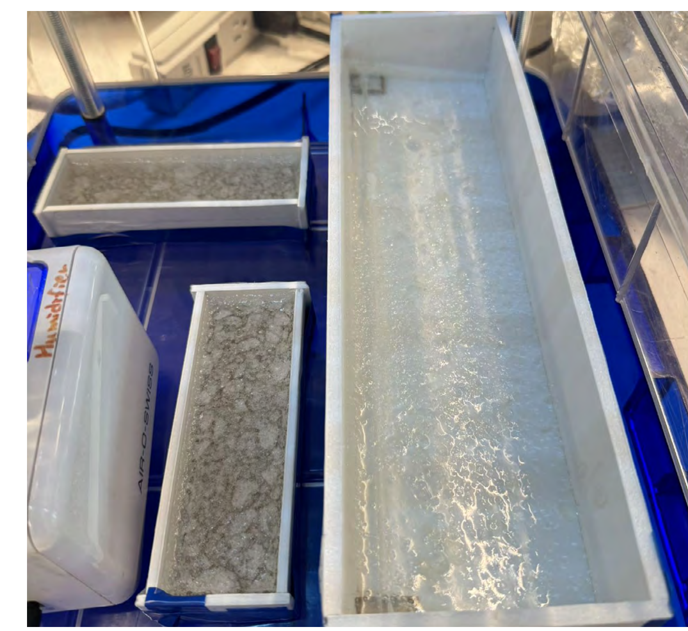




Acrylamide, N.N-Methylenebisacrylamide (MBAA cross-linker), Ammonium Persulfate (photoinitiator), N,N,N,N-tetramethylethylenedia mine (TEMED), Cobalt Acetate Tetrahydrate

Pour and Cure





Fuse with polyester foam; Cure under UV light (60 degrees elcius); Stabilize in 70% RH

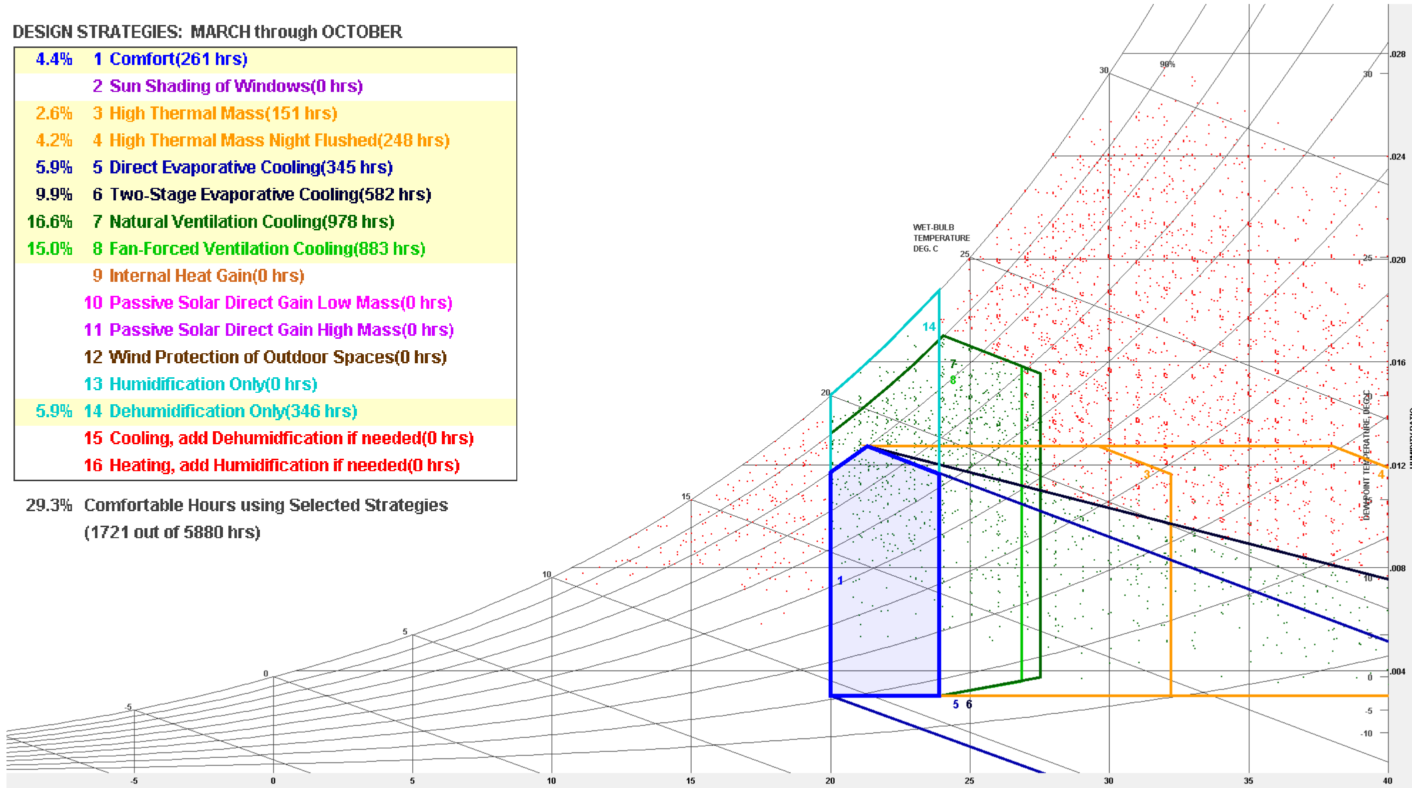
Polyester-Hydrogel

SN-Gel + Polyester Foam

Cobalt-Polyester-Hydrogel Panel

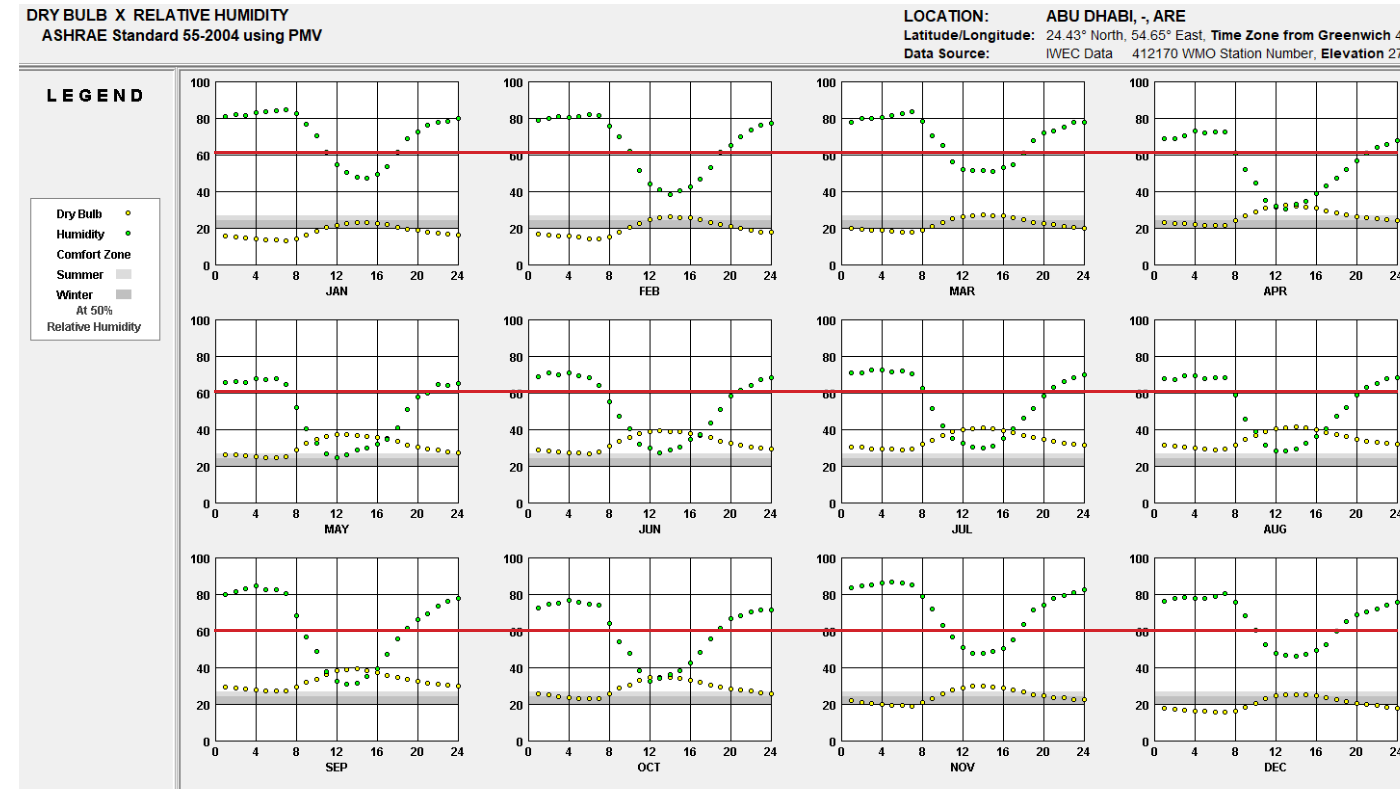
SN-Gel + Cobalt + Foam

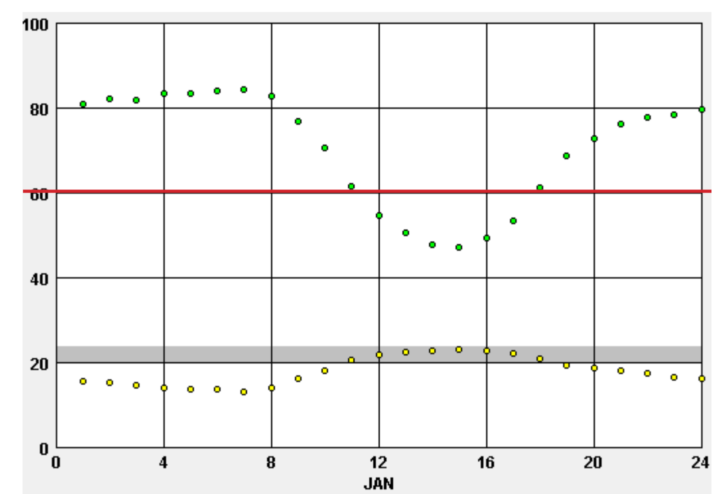
Abu Dhabi



Climate Studies

RH and Dry Bulb Temp by Month





Threshold RH 60%

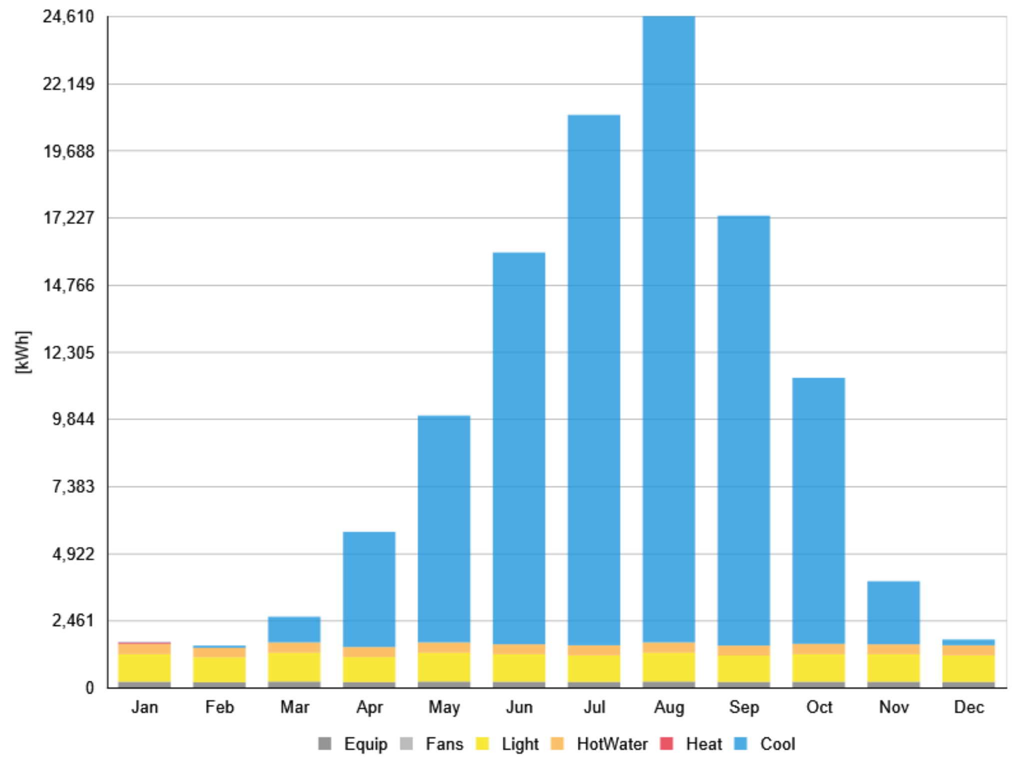
Site

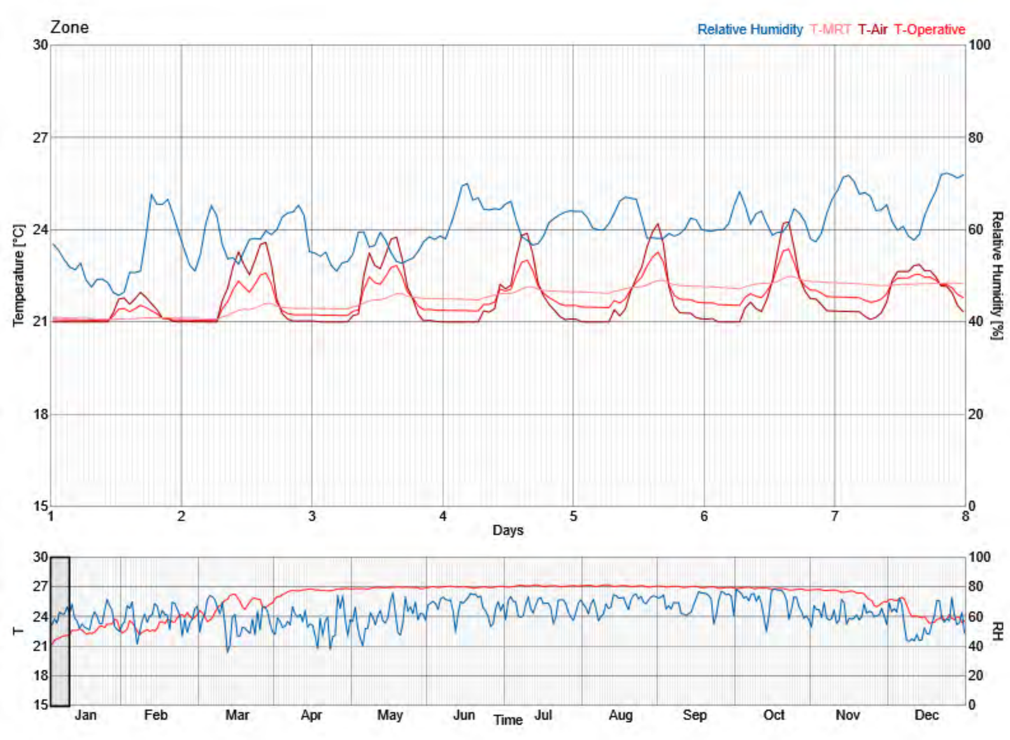
Abu Dhabi, South of Bahyah Football Field and Old Bahya

Program

Farm School

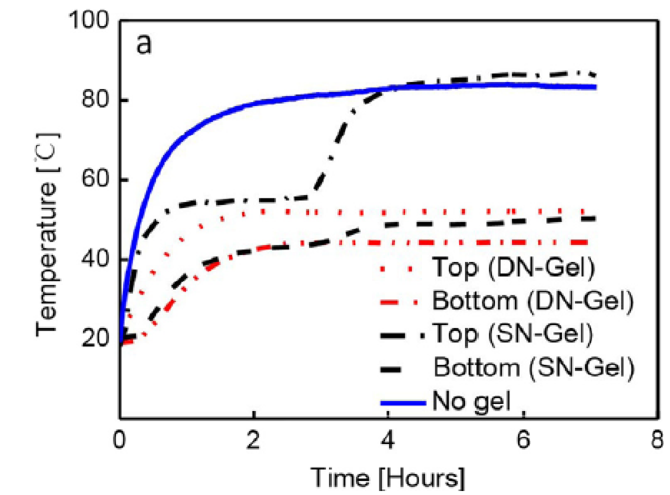
Energy Simulation

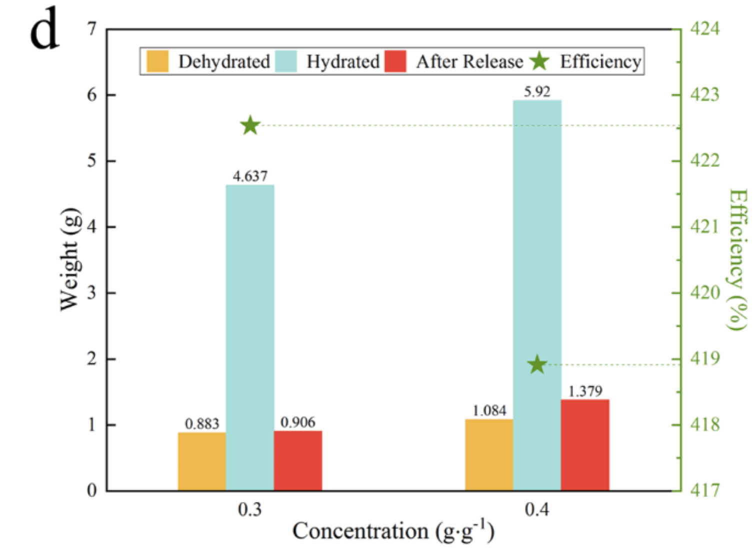




22,000 kWh for Cooling

Energy Simulation





"In addition, LCP hydrogels can absorb1.93g/g water overnight (13h) at RH 90% and easily release up to 99.38% of the absorbed water via the photothermal effect under 500W/m2 light. It is estimated that the daily water yield can reach up to approximately 2.56kg/kg*day with three cycles."

Lyu, Tong et all. "Macroporous Hydrogel for High-Performance Atmospheric Water Harvesting." ACS Applied Materials & Interfaces 14, no. 28 (July 20, 2022)

$$m * H_{vap} = \sum |Q_i|$$

$m =$ *Mass of the water through the system*

$H_{vap} =$ *Heat of vaporization* $= {}^{2.4kj}/_{g}$

$Q_i =$ *Cooling Load*

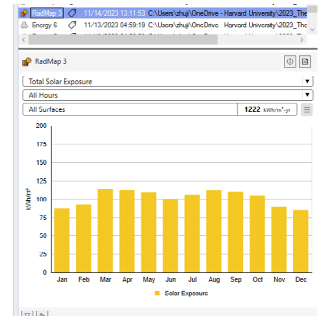
$Y =$ *Water Handling Capacity of Hydrogel Panel*

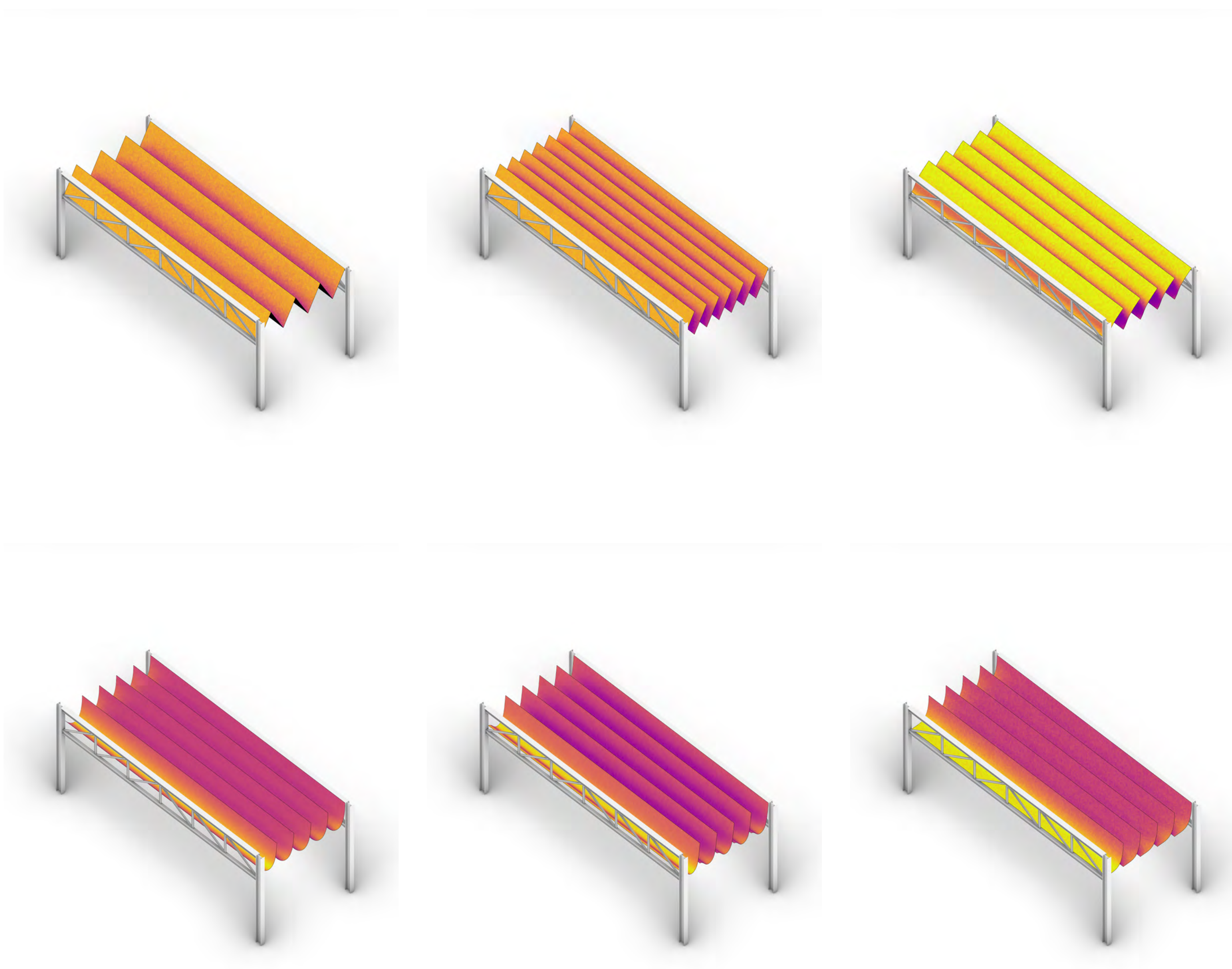
$$\sum |Q_i| = \frac{22000\ kWh \cdot \frac{3600kJ}{kWh} \cdot COP}{30\ d} = 14.4 \cdot 10^6\ kJ$$

$$m = \frac{\sum |Q_i|}{H_{vap}} = \frac{14.4 \cdot 10^6\ kJ}{\frac{2.4kJ}{g}} = 6.0 \cdot 10^6\ g$$

$$A = \frac{m}{Y} = \frac{6.0 \cdot 10^6\ g}{\frac{1.2g}{g} \cdot \frac{2311g}{m^2}} = 2164\ m^2$$

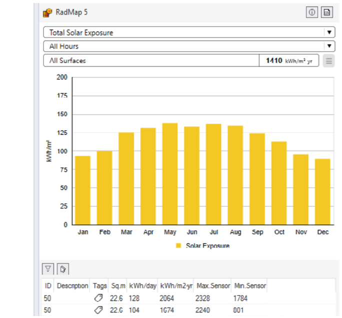
Daylight Simulation

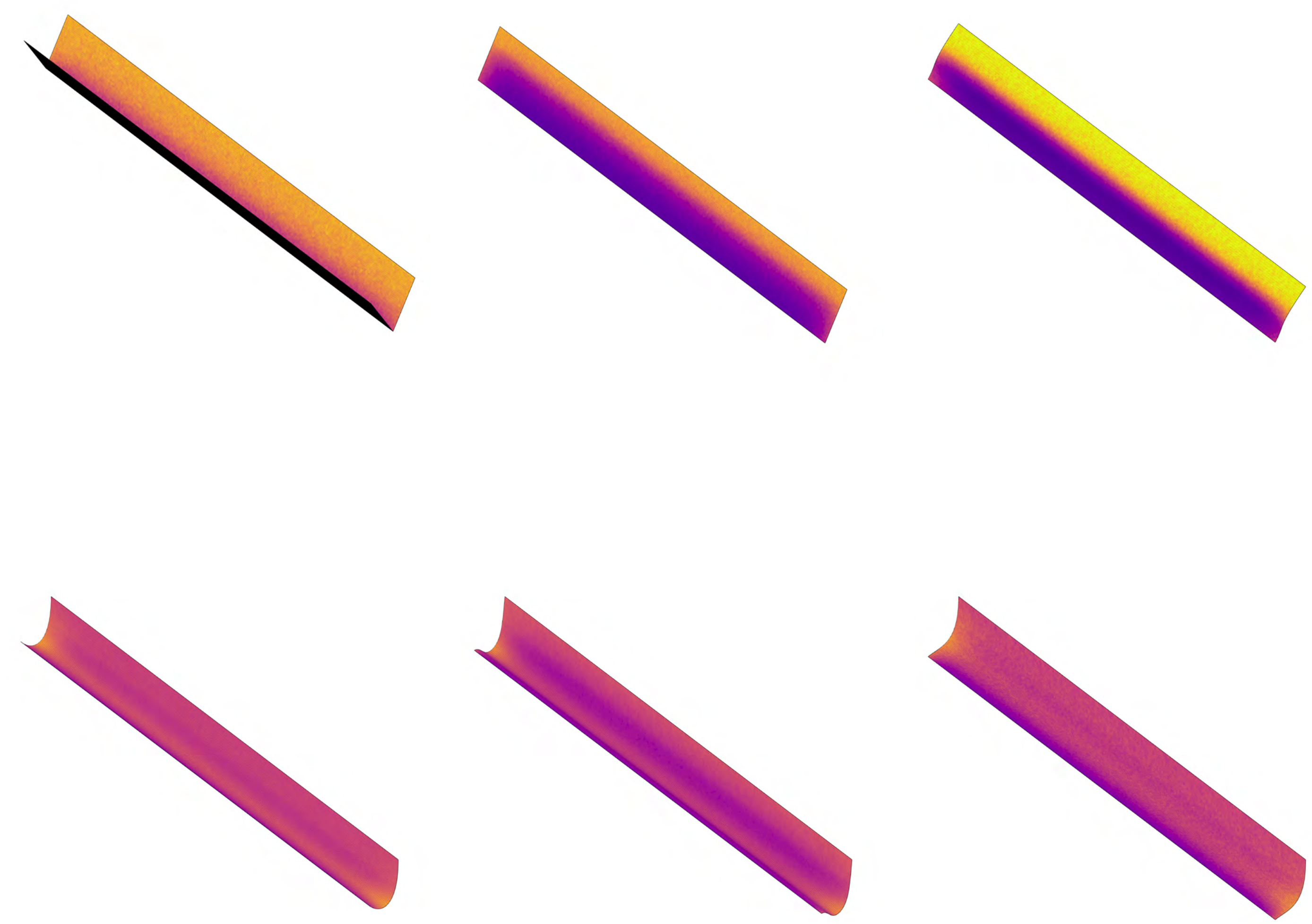




Typical Module

Section Optimization





Typical Polyester Roof Module

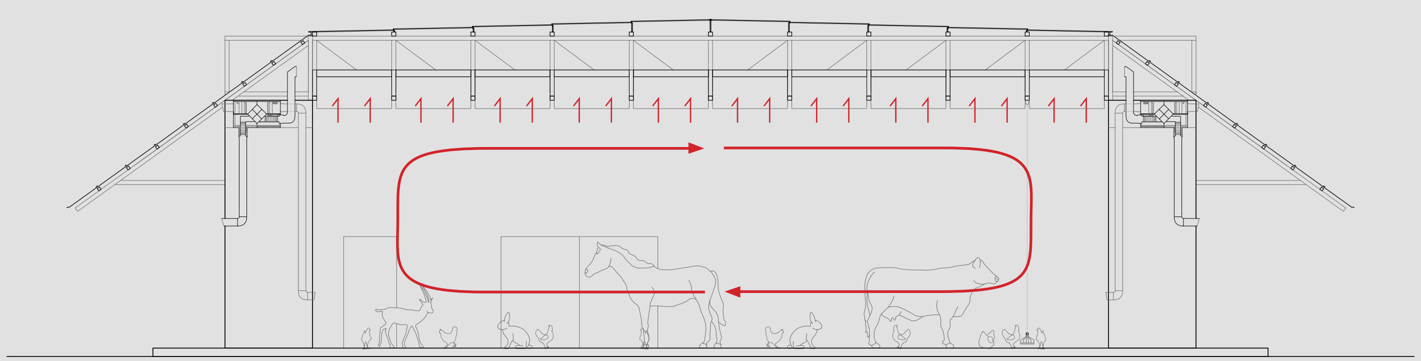
Model

Birdeye View

Model

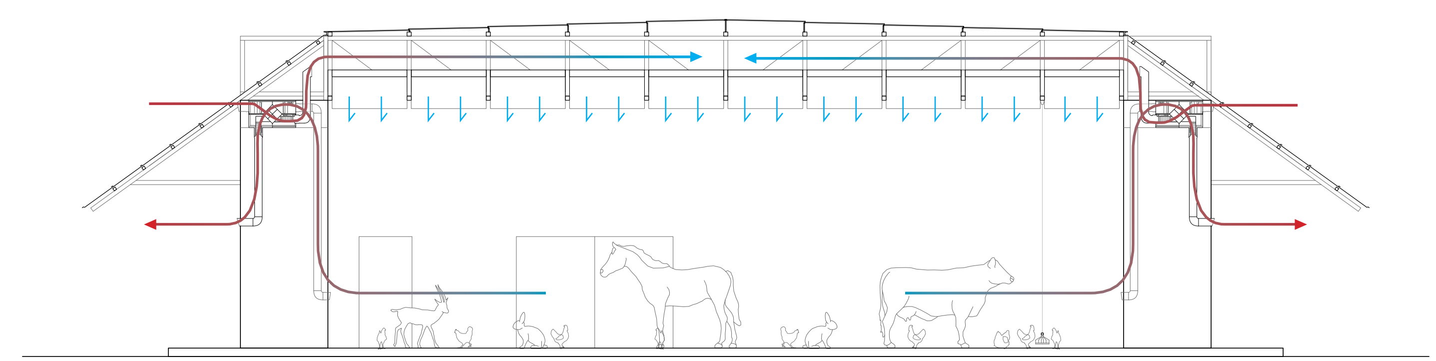
Section

Night



Absorption_Heating

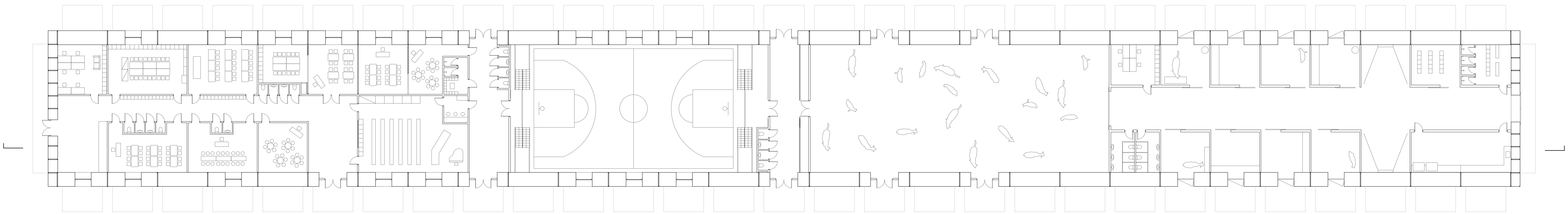
Day

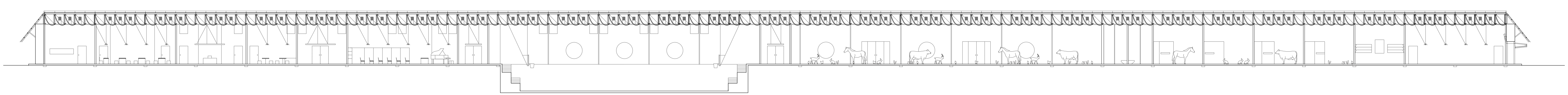


Desorption_Cooling

Plan

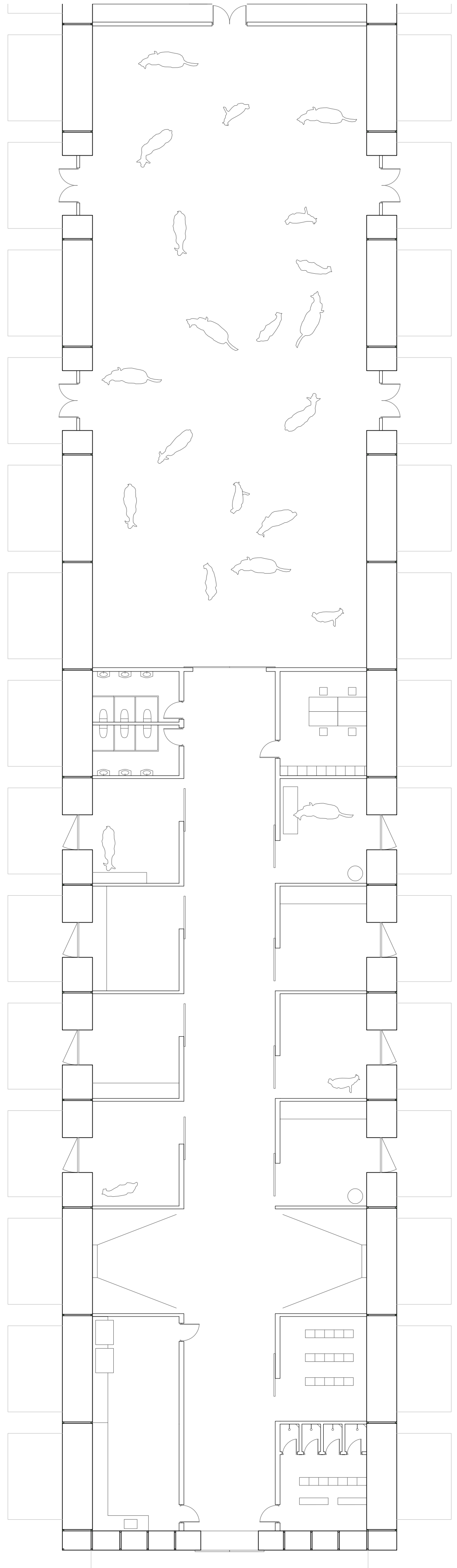
Plan



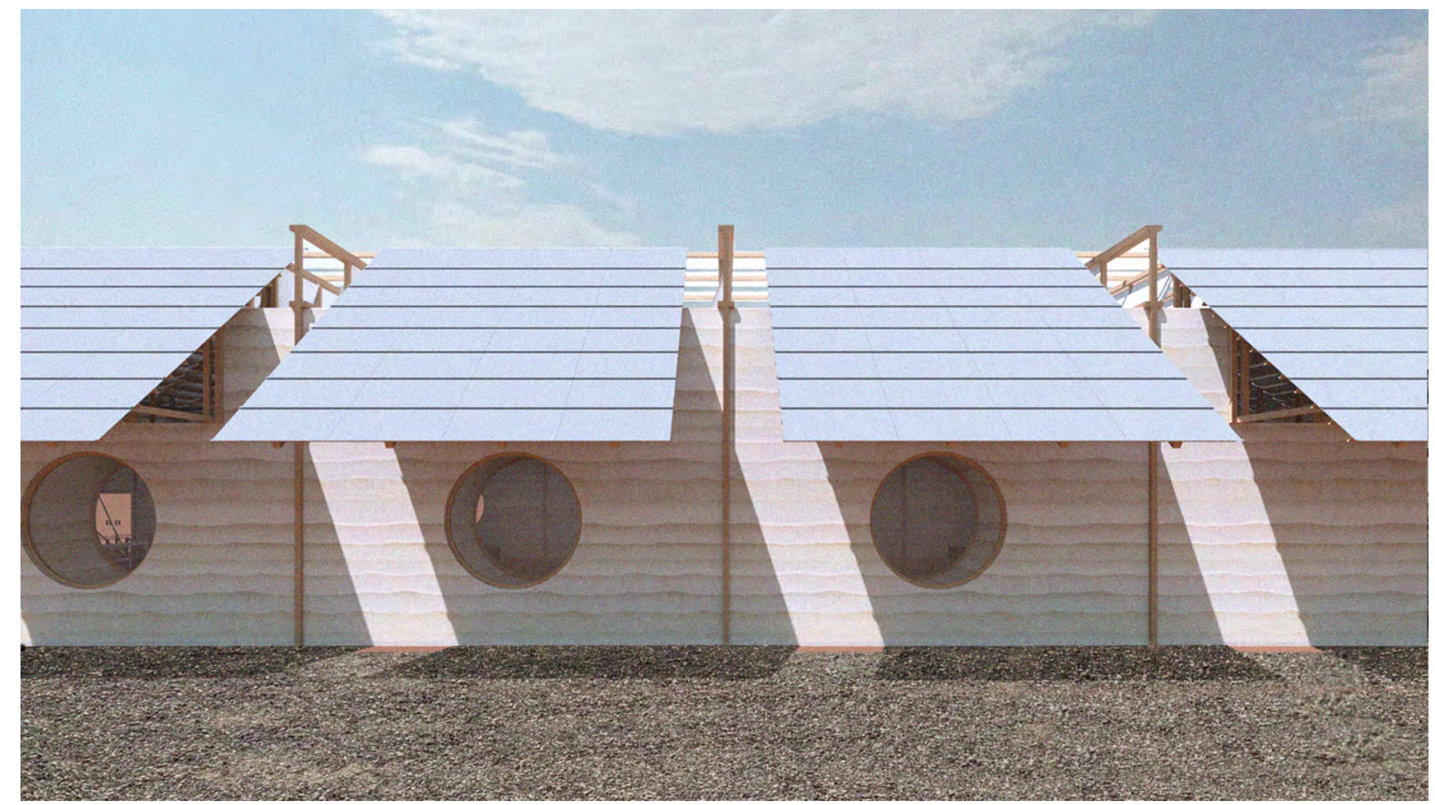


Section

Section

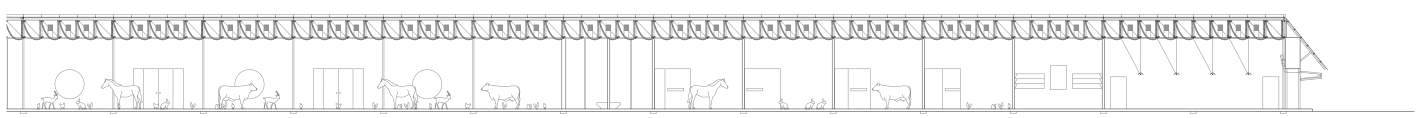


Plan



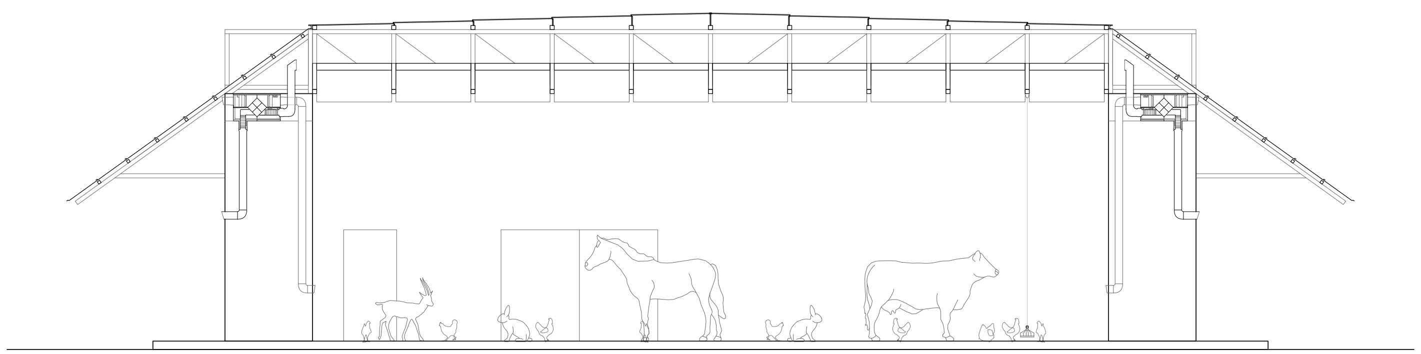
Farm_South Section

Section

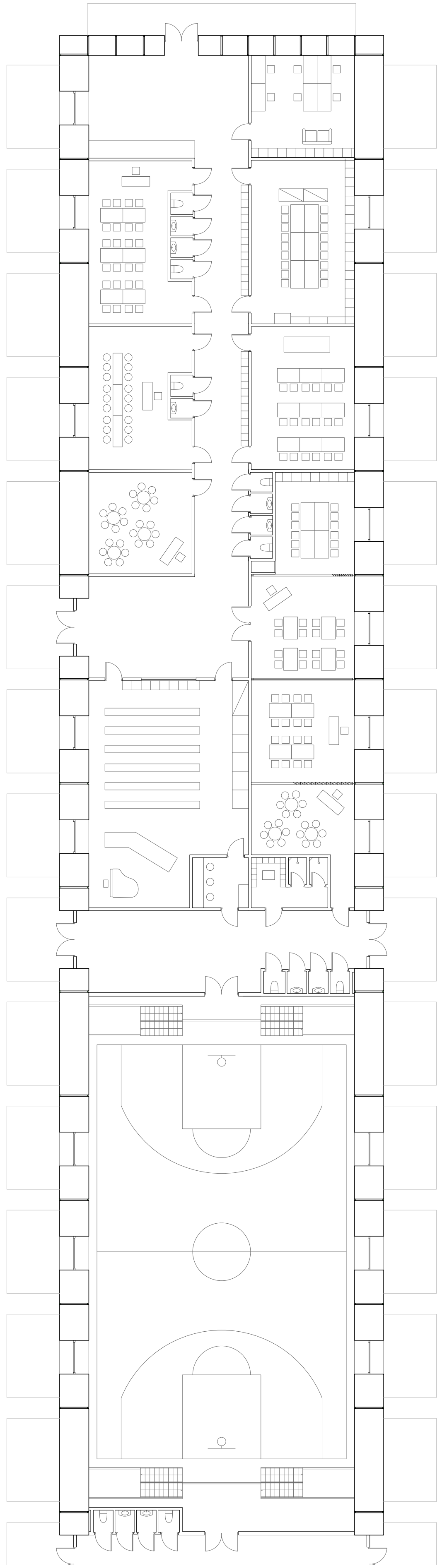


Farm_South Section

Section



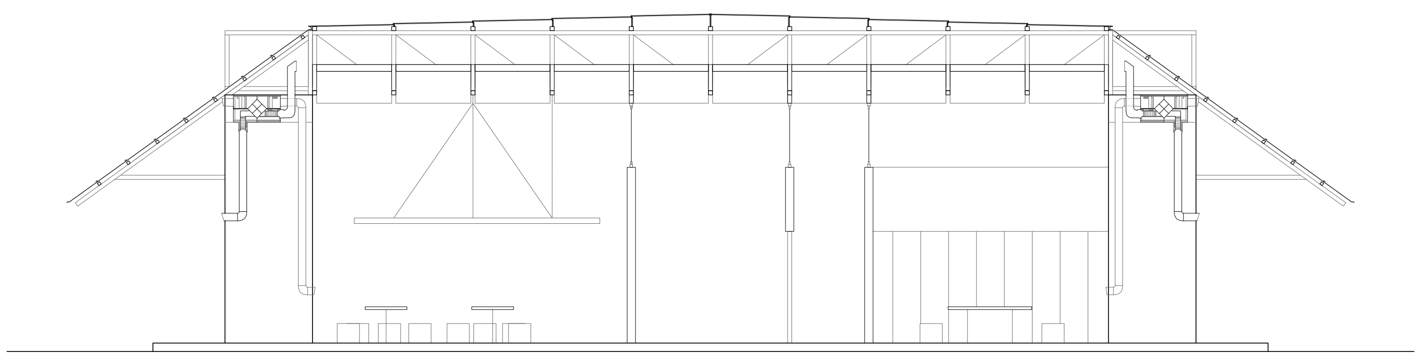
Interior Field



Plan

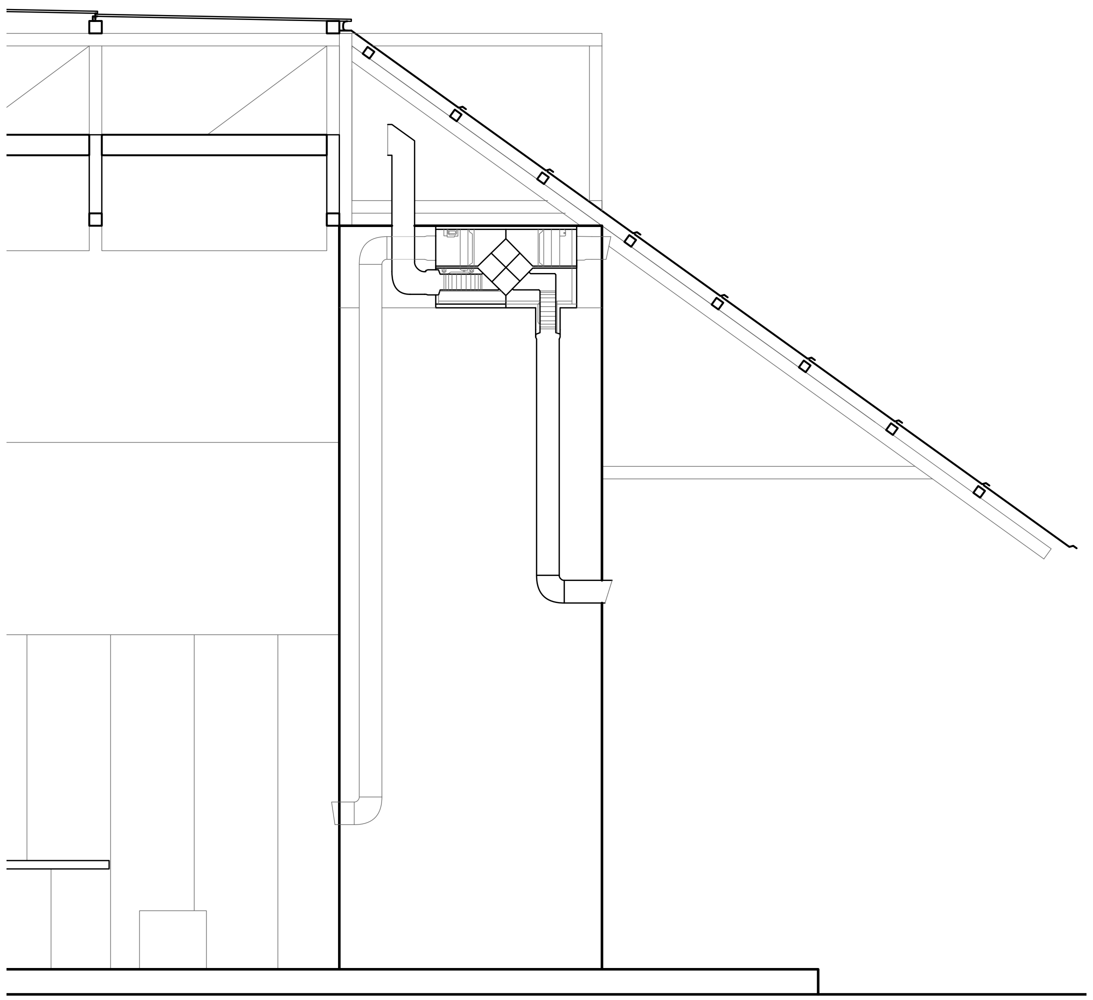
School_North Section

Section



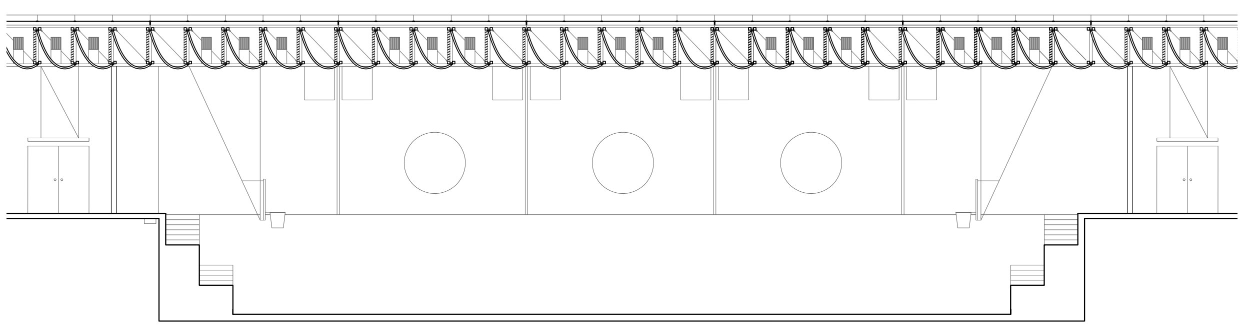
Workshop

Module



Model and Section

Gym



1. Cui, Shuang, Chihyung Ahn, Matthew C. Wingert, David Leung, Shengqiang Cai, and Renkun Chen. “Bio-Inspired Effective and Regenerable Building Cooling Using Tough Hydrogels.” Applied Energy 168 (April 2016): 332–39. https://doi.org/10.1016/j.apenergy.2016.01.058.

2. Jian, Yukun, Baoyi Wu, Xuxu Yang, Yu Peng, Dachuan Zhang, Yang Yang, Huiyu Qiu, Huanhuan Lu, Jiawei Zhang, and Tao Chen. “Stimuli-Responsive Hydrogel Sponge for Ultrafast Responsive Actuator.” Supramolecular Materials 1 (December 2022): 100002. https://doi.org/10.1016/j.supmat.2021.100002.

3. Lyu, Tong, Zhaoyang Wang, Ruonan Liu, Kun Chen, He Liu, and Ye Tian. “Macroporous Hydrogel for High-Performance Atmospheric Water Harvesting.” ACS Applied Materials & Interfaces 14, no. 28 (July 20, 2022): 32433–43. https://doi.org/10.1021/acsami.2c04228.

4. Shi, Ye, Ognjen Ilic, Harry A. Atwater, and Julia R. Greer. “All-Day Fresh Water Harvesting by Microstructured Hydrogel Membranes.” Nature Communications 12, no. 1 (May 14, 2021): 2797. https://doi.org/10.1038/s41467-021-23174-0.

5. Sun, Jeong-Yun, Xuanhe Zhao, Widusha R. K. Illeperuma, Ovijit Chaudhuri, Kyu Hwan Oh, David J. Mooney, Joost J. Vlassak, and Zhigang Suo. “Highly Stretchable and Tough Hydrogels.” Nature 489, no. 7414 (September 2012): 133–36. https://doi.org/10.1038/nature11409.

6. Wu, Hangfei, Yuli Xiong, Duohuan Yu, Peixin Yang, Huihui Shi, Lu Huang, Yali Wu, Mufeng Xi, Peng Xiao, and Lin Yang. “Fe–Co Controlled Super-Hygroscopic Hydrogels toward Efficient Atmospheric Water Harvesting.” Nanoscale 14, no. 48 (2022): 18022–32. https://doi.org/10.1039/D2NR04830B.

7. Adera, Solomon, Lauren Naworski, Alana Davitt, Nikolaj K. Mandsberg, Anna V. Shneidman, Jack Alvarenga, and Joanna Aizenberg. “Enhanced Condensation Heat Transfer Using Porous Silica Inverse Opal Coatings on Copper Tubes.” Scientific Reports 11, no. 1 (May 21, 2021): 10675. https://doi.org/10.1038/s41598-021-90015-x.

8. Cally, Owh, David James Young, and Xian Jun Loh. “Thermogelling Polymers and Their History.” In Biodegradable Thermogels, edited by Xian Jun Loh and David James Young, 1–22. The Royal Society of Chemistry, 2018. https://doi.org/10.1039/9781788012676-00001.

9. Dawson, Terence J., and Shane K. Maloney. “Thermal Implications of Interactions between Insulation, Solar Reflectance, and Fur Structure in the Summer Coats of Diverse Species of Kangaroo.” Journal of Comparative Physiology B 187, no. 3 (April 2017): 517–28. https://doi.org/10.1007/s00360-016-1043-8.

10. Epstein, Alexander K., Boaz Pokroy, Agnese Seminara, and Joanna Aizenberg. “Bacterial Biofilm Shows Persistent Resistance to Liquid Wetting and Gas Penetration.” Proceedings of the National Academy of Sciences 108, no. 3 (January 18, 2011): 995–1000. https://doi.org/10.1073/pnas.1011033108.

11. Fratzl, Peter, Michael Friedman, Karin Krauthausen, and Wolfgang Schäffner, eds. Active Materials. De Gruyter, 2021. https://doi.org/10.1515/9783110562064.
Ishikawa, Akira, Martin Despang, William Chapman, and Socrates Bratakos. “DOCTOR OF ARCHITECTURE,” n.d.

12. Jeong, Byeongmoon, Sung Wan Kim, and You Han Bae. “Thermosensitive Sol–Gel Reversible Hydrogels.” Advanced Drug Delivery Reviews 64 (December 2012): 154–62. https://doi.org/10.1016/j.addr.2012.09.012.

13. Jiang, Tengyao, Xinpeng Zhao, Xiaobo Yin, Ronggui Yang, and Gang Tan. “Dynamically Adaptive Window Design with Thermo-Responsive Hydrogel for Energy Efficiency.” Applied Energy 287 (April 2021): 116573. https://doi.org/10.1016/j.apenergy.2021.116573.

14. Khoo, Chin Koi, and Jae-Won Shin. “Designing with Biomaterials for Responsive Architecture,” n.d.

15. Kim, Philseok, Tak-Sing Wong, Jack Alvarenga, Michael J. Kreder, Wilmer E. Adorno-Martinez, and Joanna Aizenberg. “Liquid-Infused Nanostructured Surfaces with Extreme Anti-Ice and Anti-Frost Performance.” ACS Nano 6, no. 8 (August 28, 2012): 6569–77. https://doi.org/10.1021/nn302310q.

16. Kuroda, Nobu. “Conservation Design for Traditional Agricultural Villages: A Case Study of Shirakawa-Go and Gokayama in Japan.” Built Heritage 3, no. 2 (June 2019): 7–23. https://doi.org/10.1186/BF03545724.

17. Kwok, Yu Ting, Kevin Ka-Lun Lau, Alan Kwok Lung Lai, Pak Wai Chan, Yahya Lavafpour, Justin Ching Kwan Ho, and Edward Yan Yung Ng. “A Comparative Study on the Indoor Thermal Comfort and Energy Consumption of Typical Public Rental Housing Types under Near-Extreme Summer Conditions in Hong Kong.” Energy Procedia 122 (September 2017): 973–78. https://doi.org/10.1016/j.egypro.2017.07.454.

18. Lencina, M.M. Soledad, Eugenio Fernández Miconi, Marcos D. Fernández Leyes, Claudia Domínguez, Ezequiel Cuenca, and

19. Hernán A. Ritacco. “Effect of Surfactant Concentration on the Responsiveness of a Thermoresponsive Copolymer/Surfactant Mixture with Potential Application on ‘Smart’ Foams Formulations.” Journal of Colloid and Interface Science 512 (February 2018): 455–65. https://doi.org/10.1016/j.jcis.2017.10.090.

20. Li, Yan, Hongwu Du, and Ceren Sezer. “Sky Gardens, Public Spaces and Urban Sustainability in Dense Cities: Shenzhen, Hong Kong and Singapore.” Sustainability 14, no. 16 (August 9, 2022): 9824. https://doi.org/10.3390/su14169824.

21. Liu, Ruixue, Michael Fraylich, and Brian R. Saunders. “Thermoresponsive Copolymers: From Fundamental Studies to Applications.” Colloid and Polymer Science 287, no. 6 (June 2009): 627–43. https://doi.org/10.1007/s00396-009-2028-x.

22. Mota-Rojas, Daniel, Cristiane Gonçalves Titto, Ana De Mira Geraldo, Julio Martínez-Burnes, Jocelyn Gómez, Ismael Hernández-Ávalos, Alejandro Casas, et al. “Efficacy and Function of Feathers, Hair, and Glabrous Skin in the Thermoregulation Strategies of Domestic Animals.” Animals 11, no. 12 (December 6, 2021): 3472. https://doi.org/10.3390/ani11123472.

23. Pan, Lan, and L.M. Chu. “Energy Saving Potential and Life Cycle Environmental Impacts of a Vertical Greenery System in Hong Kong: A Case Study.” Building and Environment 96 (February 2016): 293–300. https://doi.org/10.1016/j.buildenv.2015.06.033.

24. Pu, Shirui, Jia Fu, Yutian Liao, Lurong Ge, Yihao Zhou, Songlin Zhang, Shenlong Zhao, et al. “Promoting Energy Efficiency via a Self- Adaptive Evaporative Cooling Hydrogel.” Advanced Materials 32, no. 17 (April 2020): 1907307. https://doi.org/10.1002/adma.201907307.

25. Rotilio, Marianna, Gianni Di Giovanni, Federica Cucchiella, Pierluigi De Berardinis, and Caterina Amici. “Temporary Building Construction to Make Cities More Sustainable: An Innovative ‘Square Box’ Proposal.” Journal of Cleaner Production 372 (October 2022): 133657. https://doi.org/10.1016/j.jclepro.2022.133657.

26. Tesler, Alexander B., Zhizhi Sheng, Wei Lv, Yi Fan, David Fricke, Kyoo-Chul Park, Jack Alvarenga, Joanna Aizenberg, and Xu Hou. “Metallic Liquid Gating Membranes.” ACS Nano 14, no. 2 (February 25, 2020): 2465–74. https://doi.org/10.1021/acsnano.9b10063.

27. Tsitsilianis, Constantinos. “Responsive Reversible Hydrogels from Associative ‘Smart’ Macromolecules.” Soft Matter 6, no. 11 (2010): 2372. https://doi.org/10.1039/b923947b.

29. Walter, Mario, Kristin Lengsfeld, David Borschewski, Stefan Albrecht, Philipp Kölsch, Thorsten Pretsch, Martin Krus, and Susanne Lehmann-Brauns. “Shape Memory Polymer Foam for Autonomous Climate-Adaptive Building Envelopes.” Buildings 12, no. 12 (December 15, 2022): 2236. https://doi.org/10.3390/buildings12122236.

30. Wang, Xiaoyuan, David James Young, Yun-Long Wu, and Xian Jun Loh. “Hydrogel-Based 3D Scaffolds for Stem Cell Culturing and Differentiation.” In Biodegradable Thermogels, edited by Xian Jun Loh and David James Young, 145–61. The Royal Society of Chemistry, 2018. https://doi.org/10.1039/9781788012676-00145.

31. Wei, Barbara Ang Ting. “PASSIVE ATMOSPHERIC WATER HARVESTING: BIOINSPIRED DESIGNS & THERMO-RESPONSIVE HYDROGELS,” n.d.

32. Xue, Kun, Sing Shy Liow, Anis Abdul Karim, Zibiao Li, and Xian Jun Loh. “Beyond Thermogels – Other Forms of Noncovalently Formed Polymeric Hydrogels.” In Biodegradable Thermogels, edited by Xian Jun Loh and David James Young, 162–82. The Royal Society of Chemistry, 2018. https://doi.org/10.1039/9781788012676-00162.