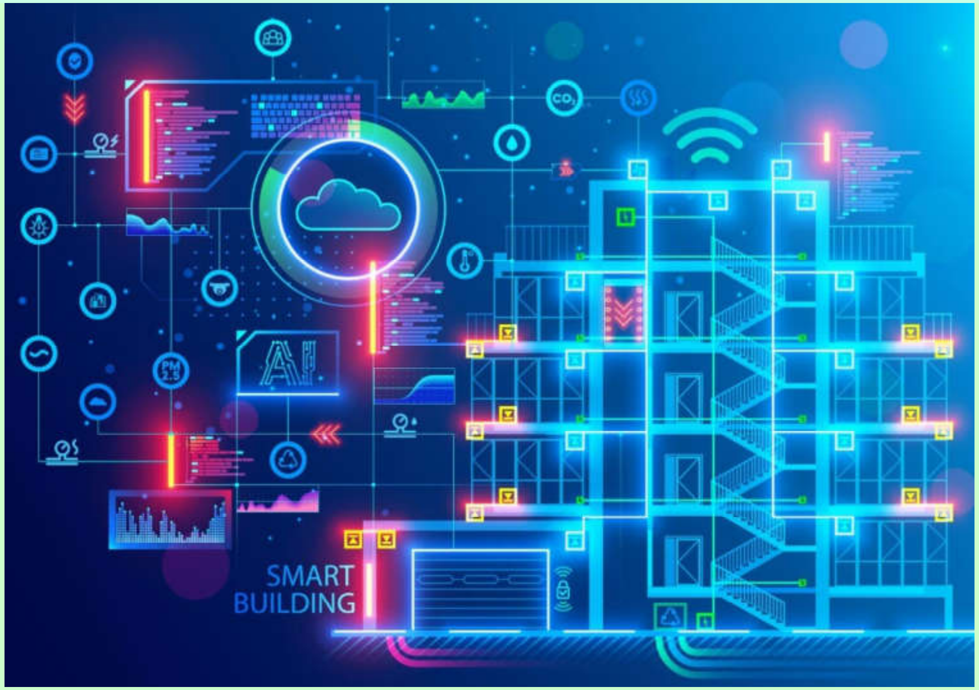


Smart HVAC Systems

智能大廈科技

Ir Dr. Sam C. M. Hui
Department of Mechanical Engineering
The University of Hong Kong
E-mail: cmhui@hku.hk

Aug 2025

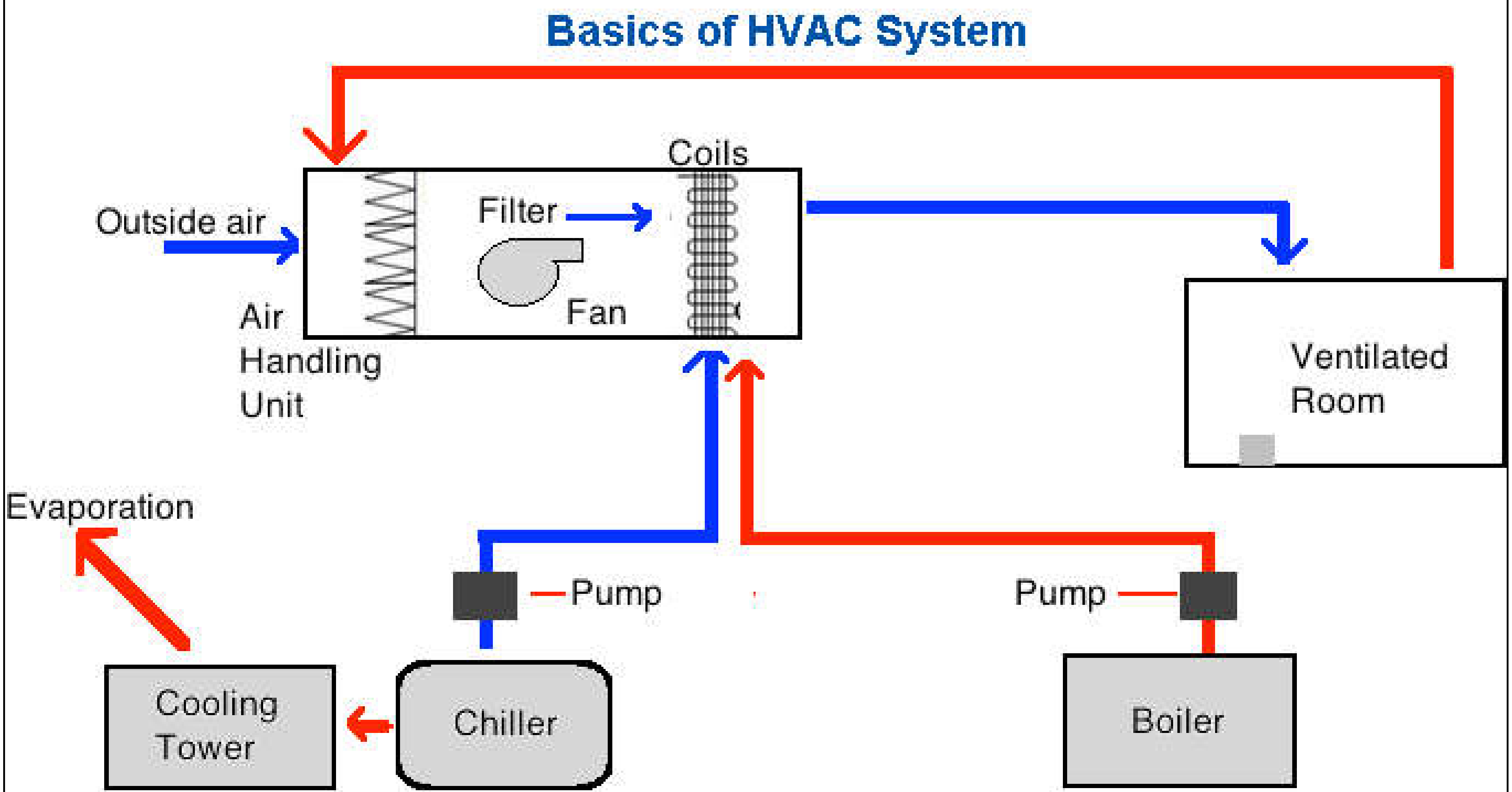
Contents

- Basic concepts
- HVAC controls
- Advanced HVAC control
- Central plant optimization
- Smart HVAC

Basic concepts

- Heating, ventilation & air conditioning (HVAC) systems
  - Control the temperature, humidity & purity of the air in an enclosed space to provide thermal comfort & acceptable indoor air quality (IAQ)
  - Can provide ventilation/air movement & maintain pressure relationships between spaces
  - System design should be within reasonable installation, operation & maintenance costs

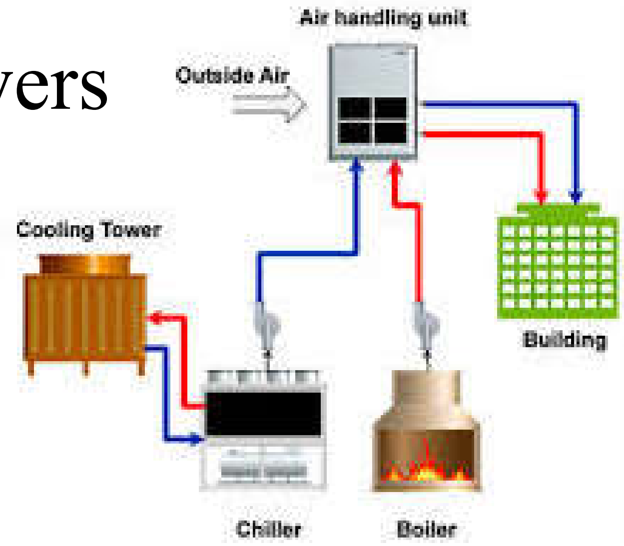
Basics of HVAC system & its components



(Source: https://www.pharmaguideline.com/2017/05/basics-of-hvac-system.html)

Basic concepts

- Key elements of HVAC systems:
  - Thermostat & sensors, controllers
  - Ventilation fans, air handling units, fan coil units
  - Air ductwork, air filters, dampers, VAV boxes
  - Air conditioner, chillers
  - Compressor, condenser, cooling towers
  - Pumps & piping, control valves
  - Boilers & furnace, heat exchanger



Basic concepts

- Key personnel for HVAC system projects:
  - HVAC system designer
    - Responsible for conceptual design, tendering, etc.
  - Controls vendor sales representative
    - Provide advice on control products & features

Design, plan, specification

  - Mechanical & electrical contractors
    - Installation of mechanical & electrical parts
  - Controls contractor
    - Details of control system + part of the installation

Installation

  - Facility managers & operators
    - Operation & maintenance

Operation, monitoring

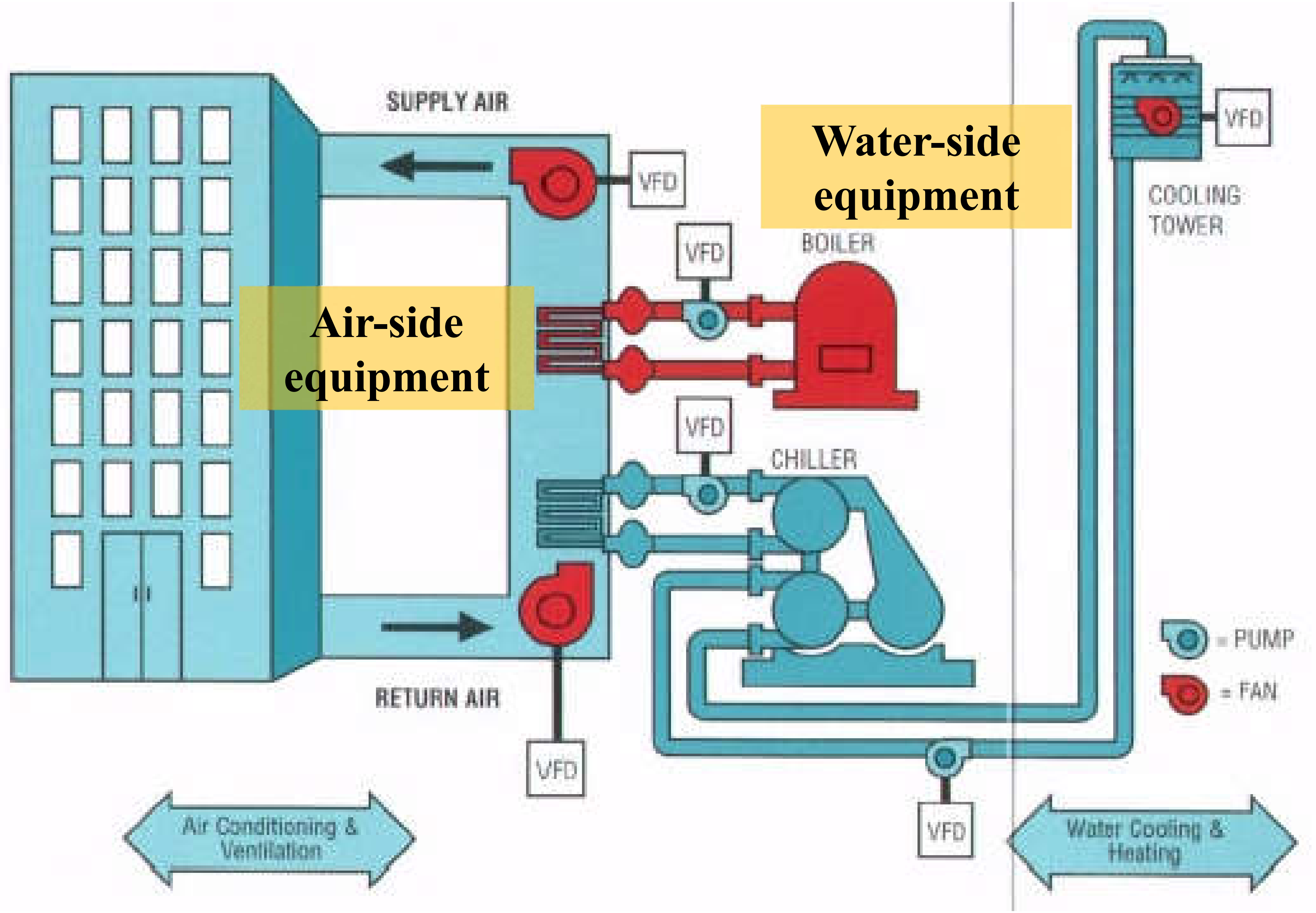
Using BAS to control major HVAC systems & equipment

[Source: Johnson Controls]

Basic concepts

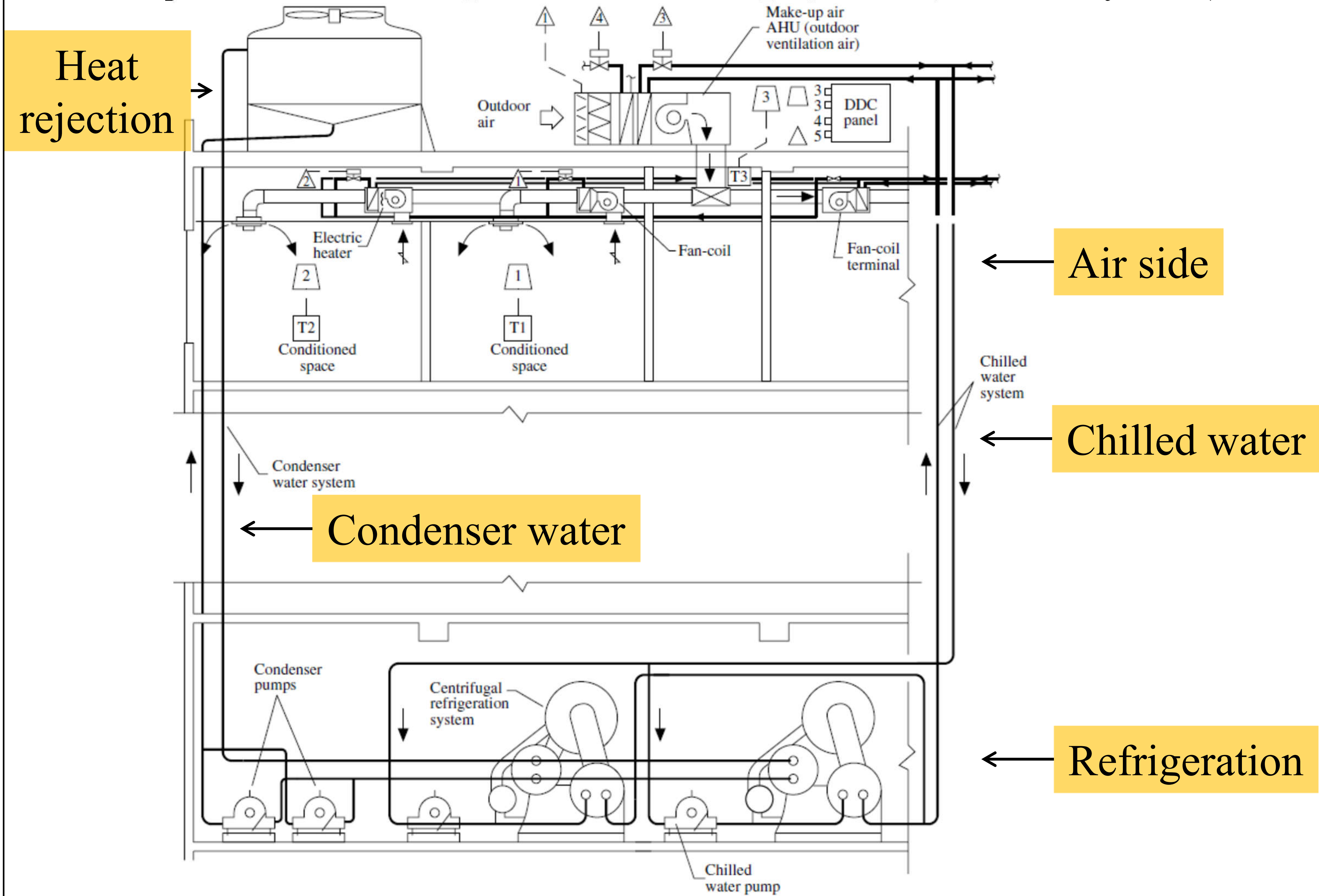
- HVAC sub-systems & components:
  - 1. Air-side (e.g. fans, air duct)
  - 2. Water-side (e.g. pumps, piping)
    - Chilled water, condenser water, seawater, etc.
  - 3. Refrigeration equipment
  - 4. Heat rejection (e.g. cooling towers)
  - 5. Controls
- Including centralised, partially centralised & local HVAC systems

Example of a centralised HVAC system



(Source: http://www.allhvacinfo.com/)

A space-conditioning air-conditioning system (fan-coil system)



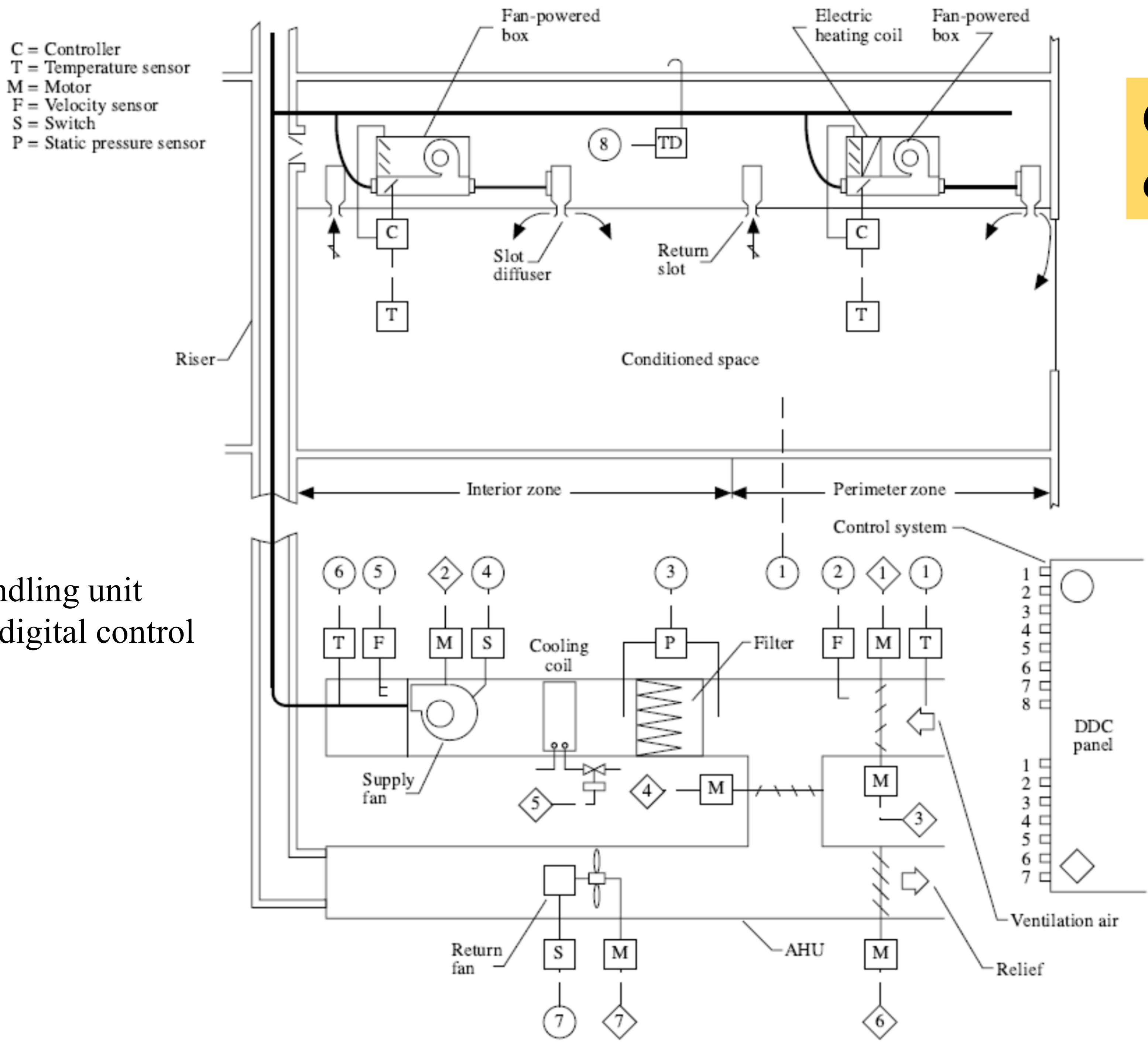
(Source: Wang, S. K., Lavan, Z. and Norton, P., 2000. *Air Conditioning and Refrigeration Engineering*)

HVAC sub-systems & components

Air side:	**Refrigeration side:**
1. Outdoor air intake (screen, louvers, dampers) 2. Preheater 3. Return air intake (dampers) 4. Filter 5. Cooling coil 6. Dehumidifier 7. Heating coil 8. Humidifier 9. Fan 10. Duct system 11. Air outlet 12. Air terminal (with outlet)	1. Refrigeration machine or chiller (compressor, condenser, cooler and refrigerant piping) **Water side:** 1. Pumps 2. Water piping **Heat rejection:** 1. Cooling tower **Heating side:** 1. Boiler & auxiliaries 2. Piping (hot water or steam)

Air-side & control sub-systems for a typical floor of a HVAC system

Control diagram

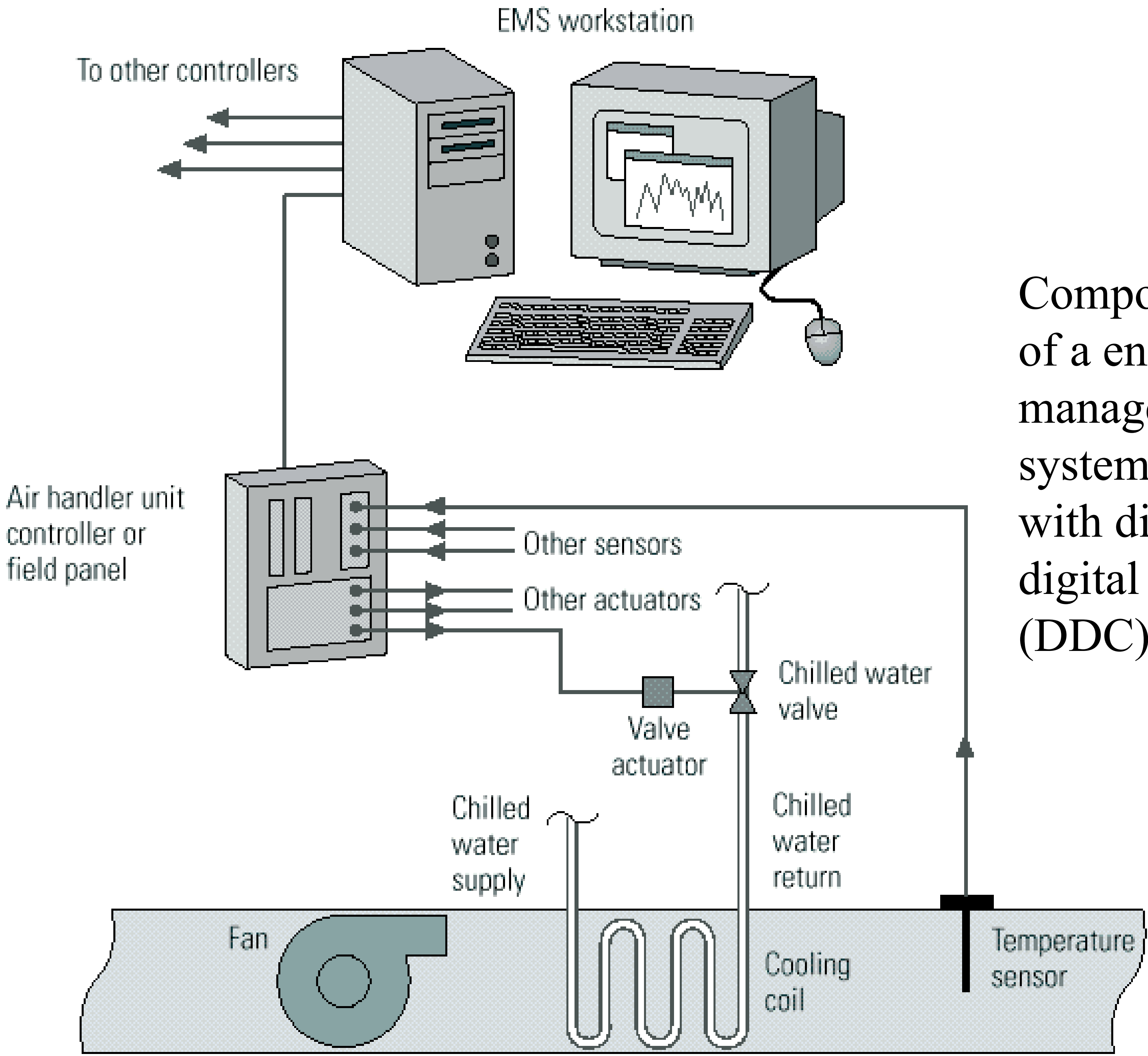


AHU = air handling unit
DDC = direct digital control

(Source: Wang, S. K., Lavan, Z. and Norton, P., 2000. *Air Conditioning and Refrigeration Engineering*)

HVAC controls

- Direct digital control (DDC) system
  - Microprocessor-based open or closed loop control of an output device based upon input data & a sophisticated control algorithm, typically proportional, integral & derivative (PID)
  - Complex strategies & energy management functions are available
  - Provide alarm & trending functions
  - Central diagnostic capabilities are also possible

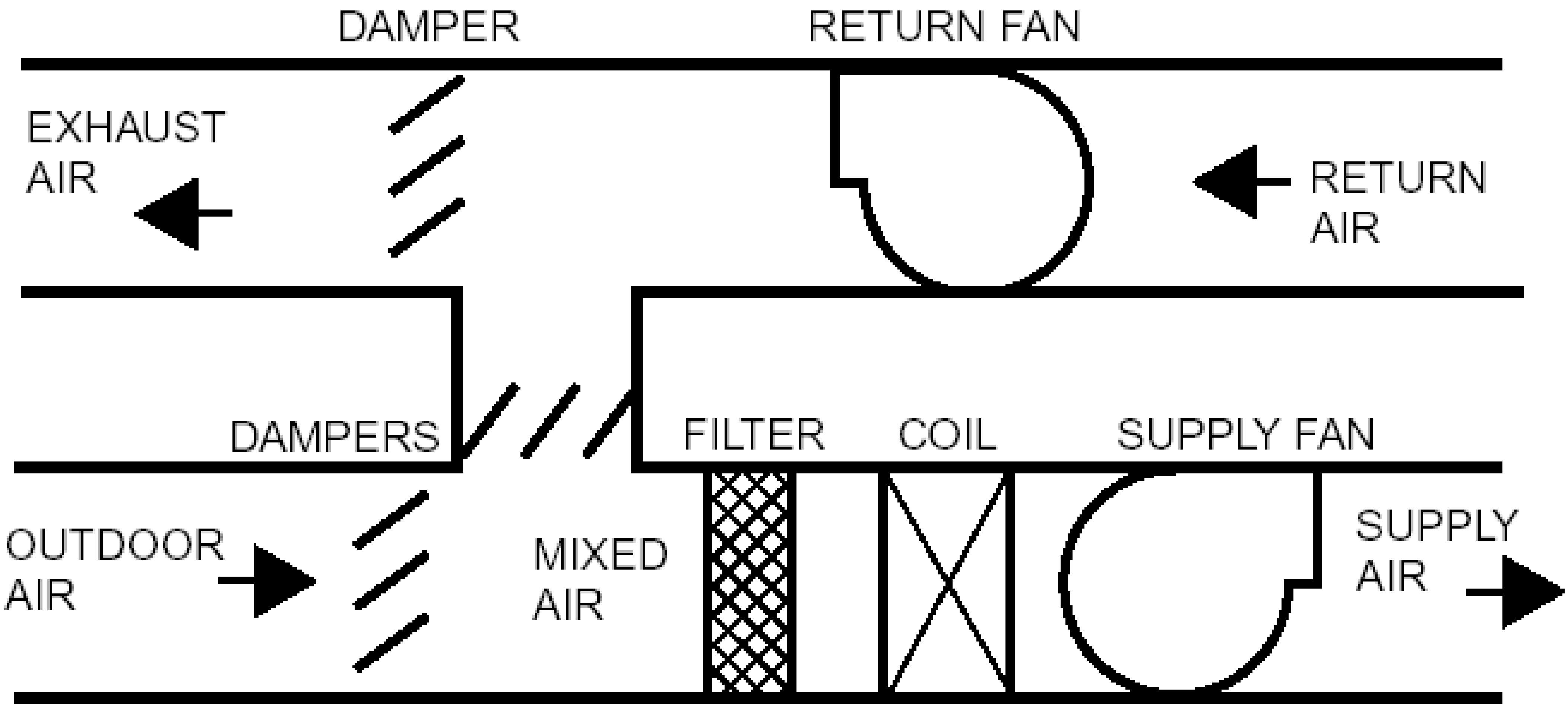


Components of a energy management system (EMS) with direct digital control (DDC)

HVAC controls

- Main control parameters:
  - Indoor air temperature/humidity, air velocity, air change rate, environmental emissions (CO_2, VOC), load factor, state of charge of storage, temperature of storage, heat loss time lag
- Controllable components:
  - Energy generation, energy storage, emission
- Technological interfaces:
  - Sensors, actuators, controllers, information & communication technology (ICT)

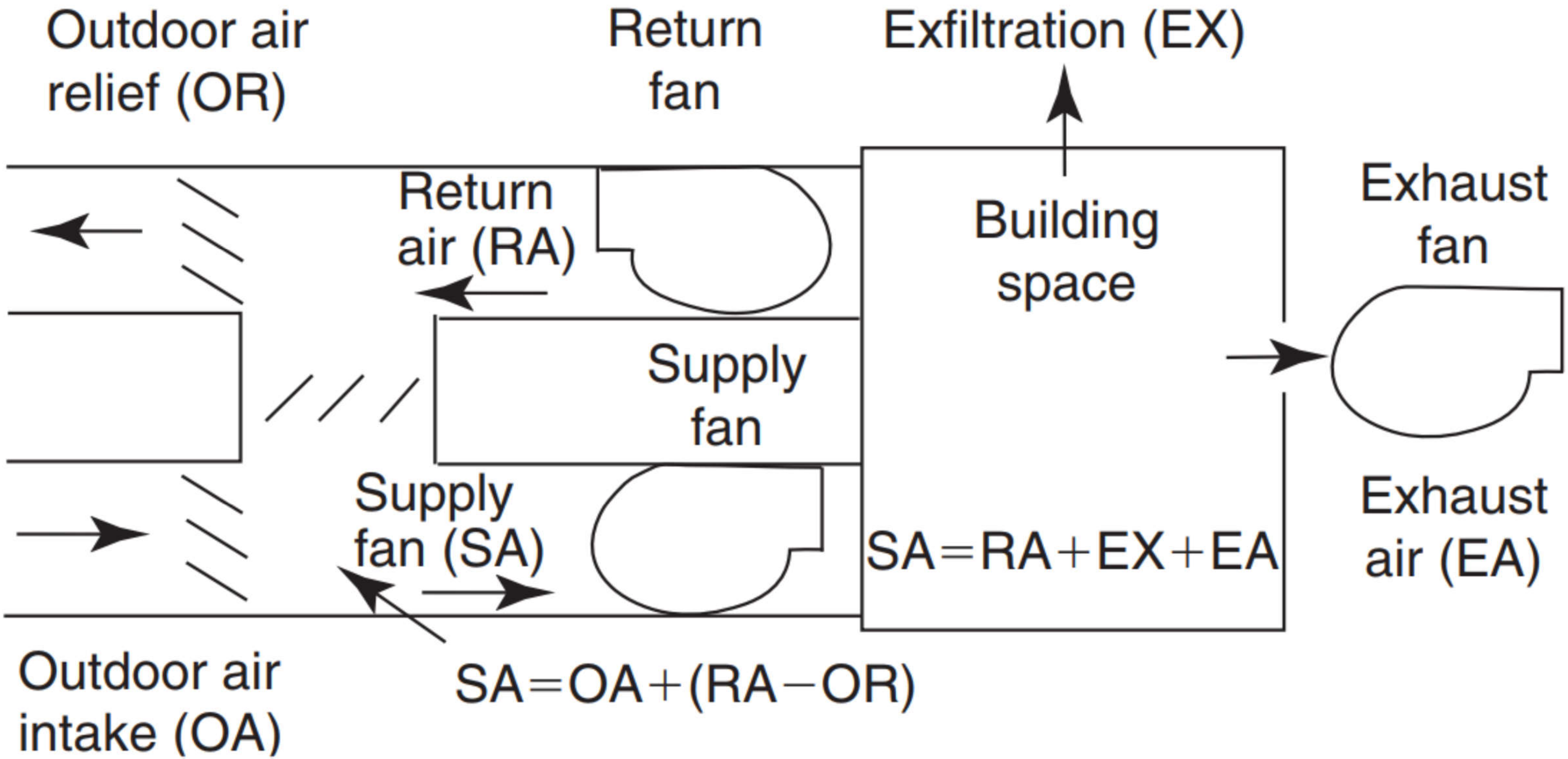
Schematic diagram of a typical constant air volume (CAV) system



Can you identify the components at the air handling unit (AHU) room?

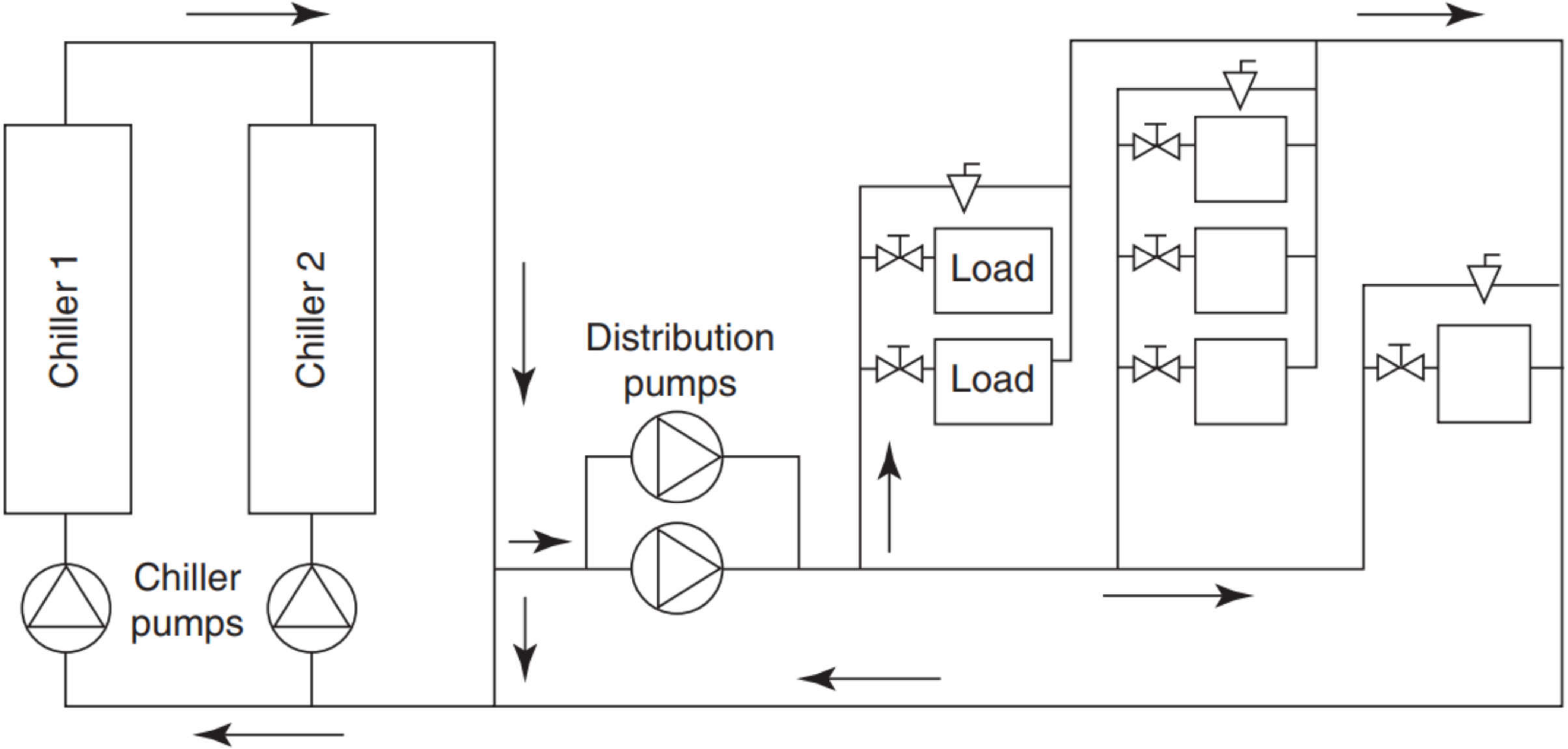
[Source: Honeywell, 1997. *Engineering Manual of Automatic Control for Commercial Buildings*]

Supply air (SA), return air (RA) & exhaust air (EA) relationships



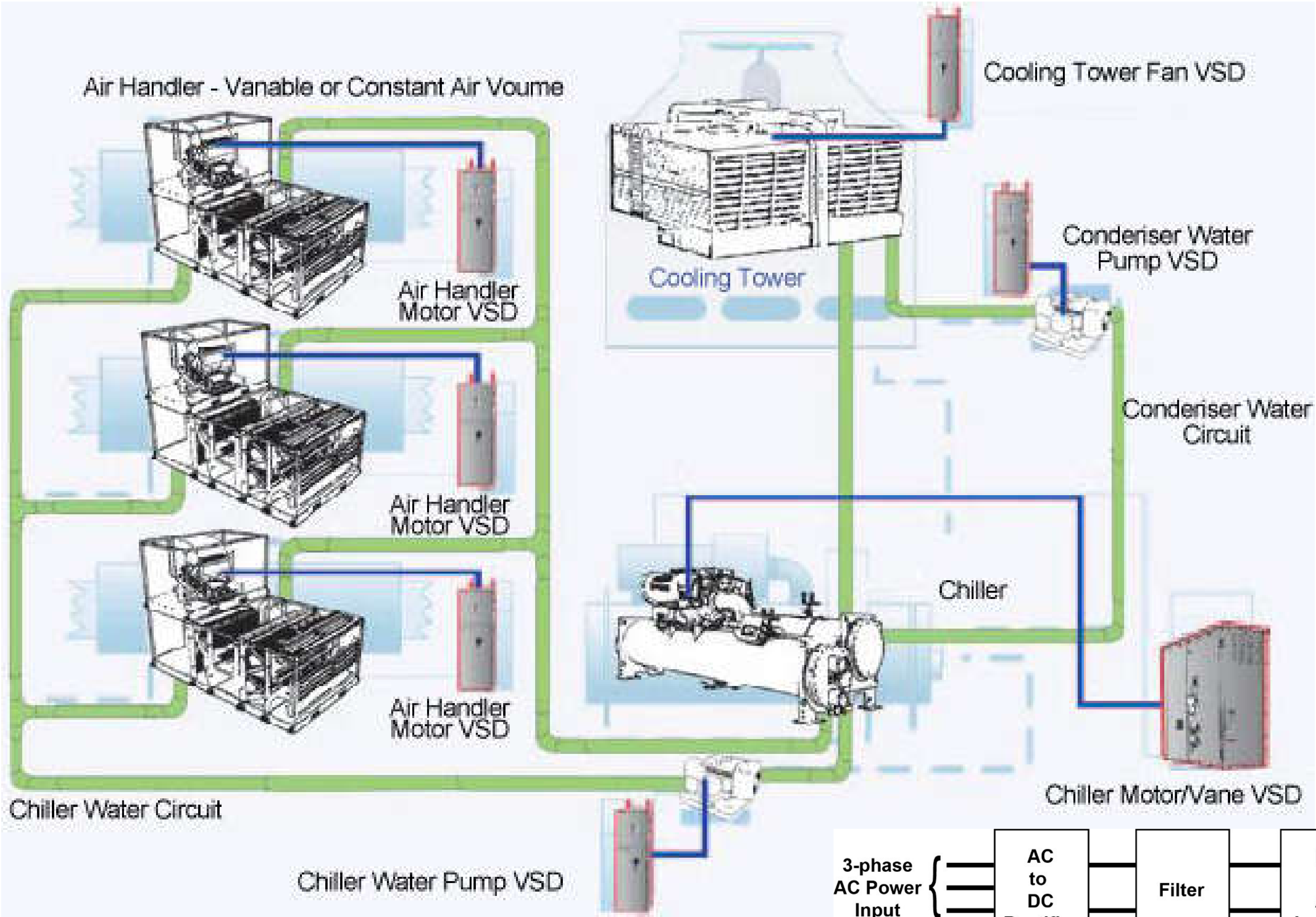
[Source: Montgomery, R. and McDowall, R., 2008. *Fundamentals of HVAC Control Systems*]

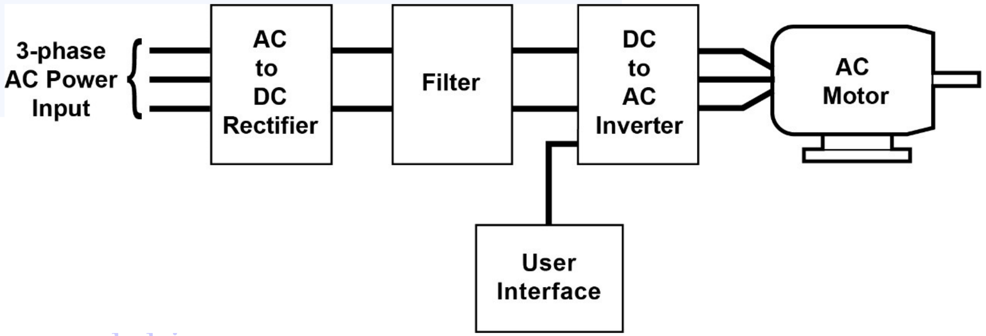
Chiller plant & primary secondary chilled water pumping system



[Source: Montgomery, R. and McDowall, R., 2008. *Fundamentals of HVAC Control Systems*]

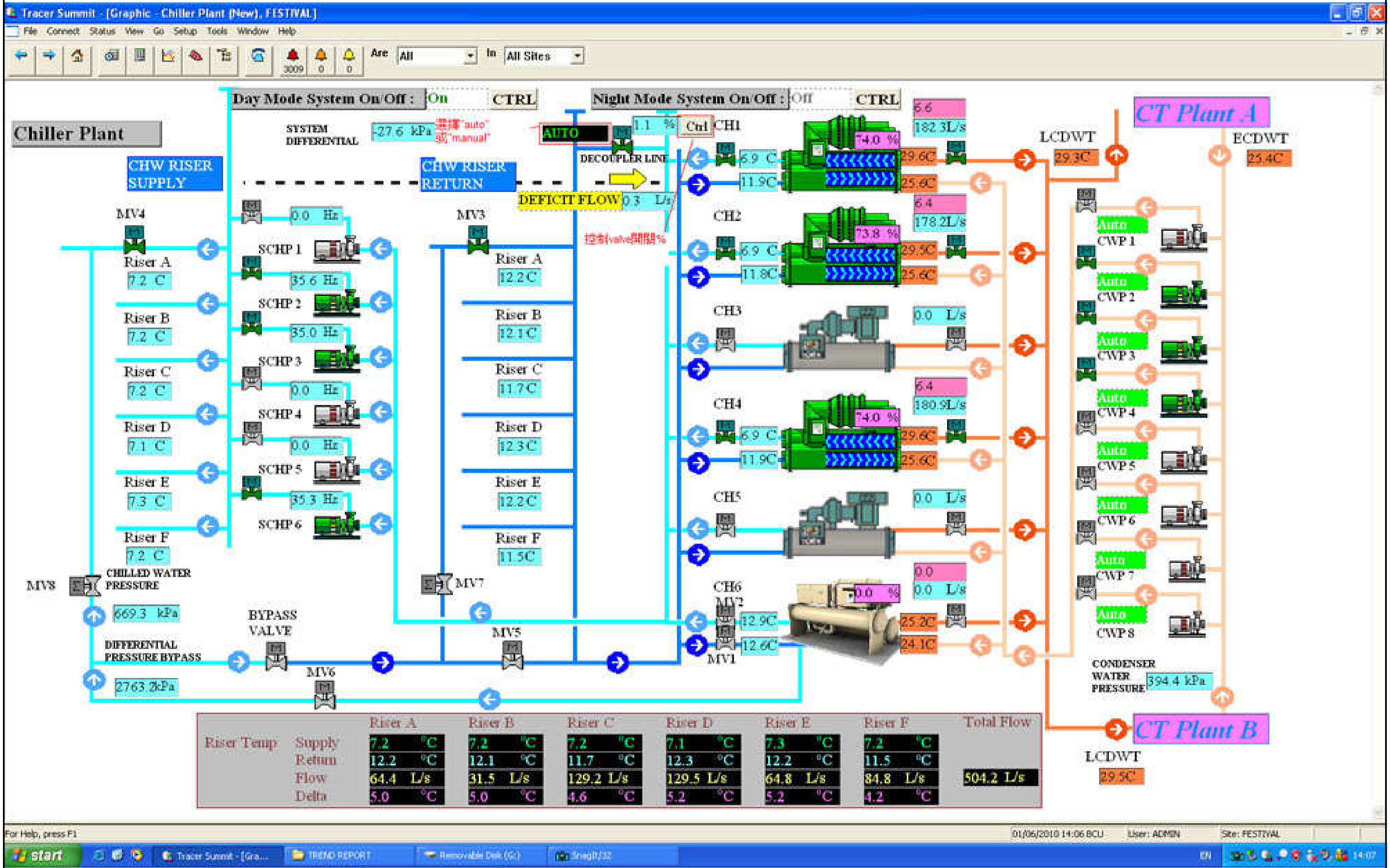
Variable speed drives (VSDs) in air-conditioning systems





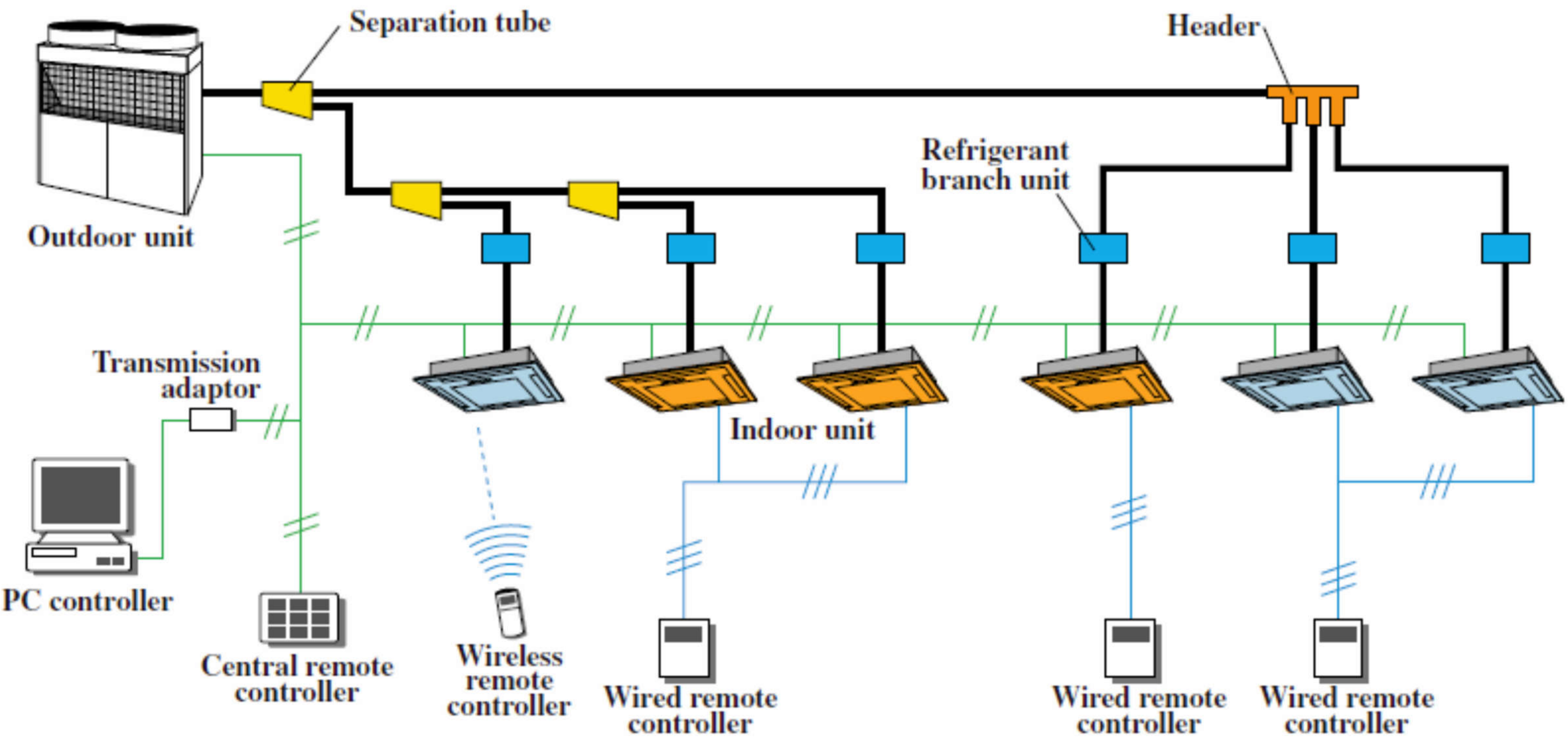
[Source: https://www.pnnl.gov/projects/om-best-practices/variable-speed-drives; https://www.emsd.gov.hk/energyland/en/appAndEquip/equipment/air_conditioning/vsd.html]

Example of chiller plant control interface



(Source: Trane)

Example of direct expansion (DX) based variable refrigerant flow (VRF) system --- refrigerant circuit & control communication devices

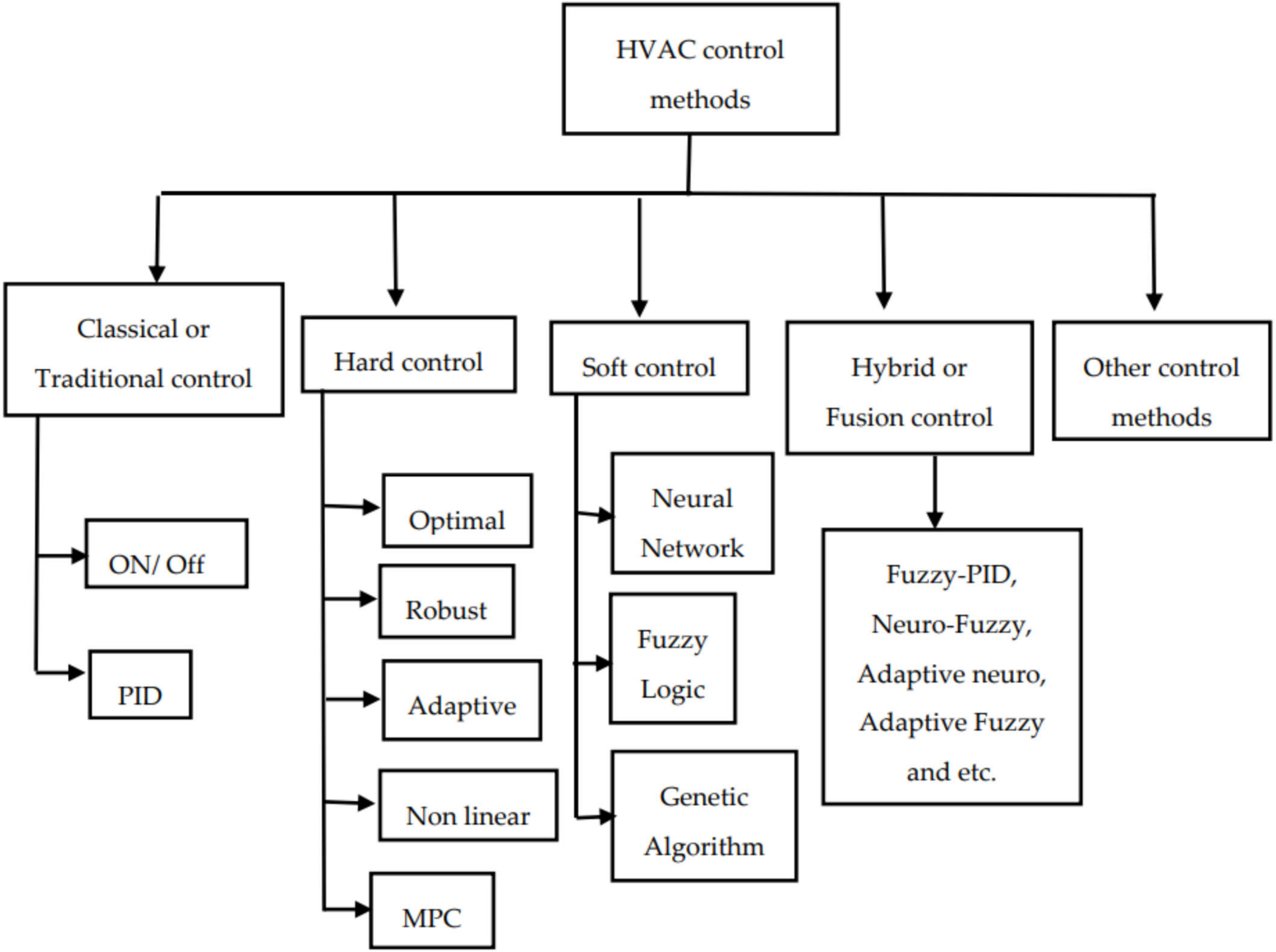


(Source: Fujitsu)

HVAC controls

- Classification of HVAC control strategies:
  - 1. Traditional
    - Sequence control: on/off control
    - Process control: proportional, integral, derivate (PID)
  - 2. Advanced
    - Soft computing: reinforcement learning (RL), artificial neural network (ANN), fuzzy logic (FL), agent-based
    - Hard computing: Auto-training PID, gain schedule, self-tuning, supervisory/optimal, model predictive
    - Hybrid: adaptive predictive (responsive to user, weather, grid, thermal mass)

Different control methods on HVAC systems

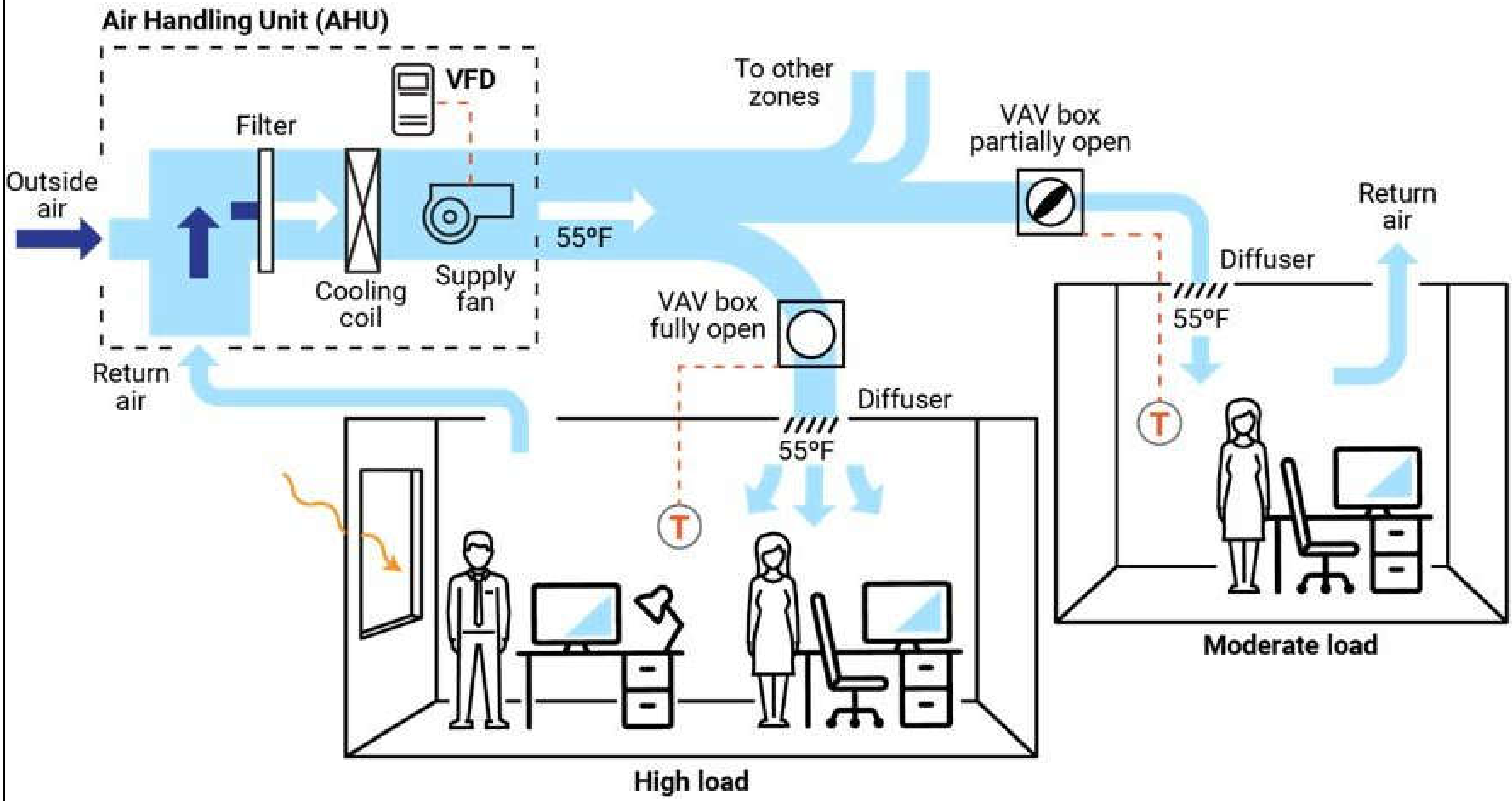


(Source: Behrooz F., Mariun N., Marhaban M. H., Radzi M. A. M. & Ramli A. R., 2018. Review of control techniques for HVAC systems—nonlinearity approaches based on fuzzy cognitive maps, *Energies*, 11 (3) 495. https://doi.org/10.3390/en11030495)

HVAC controls

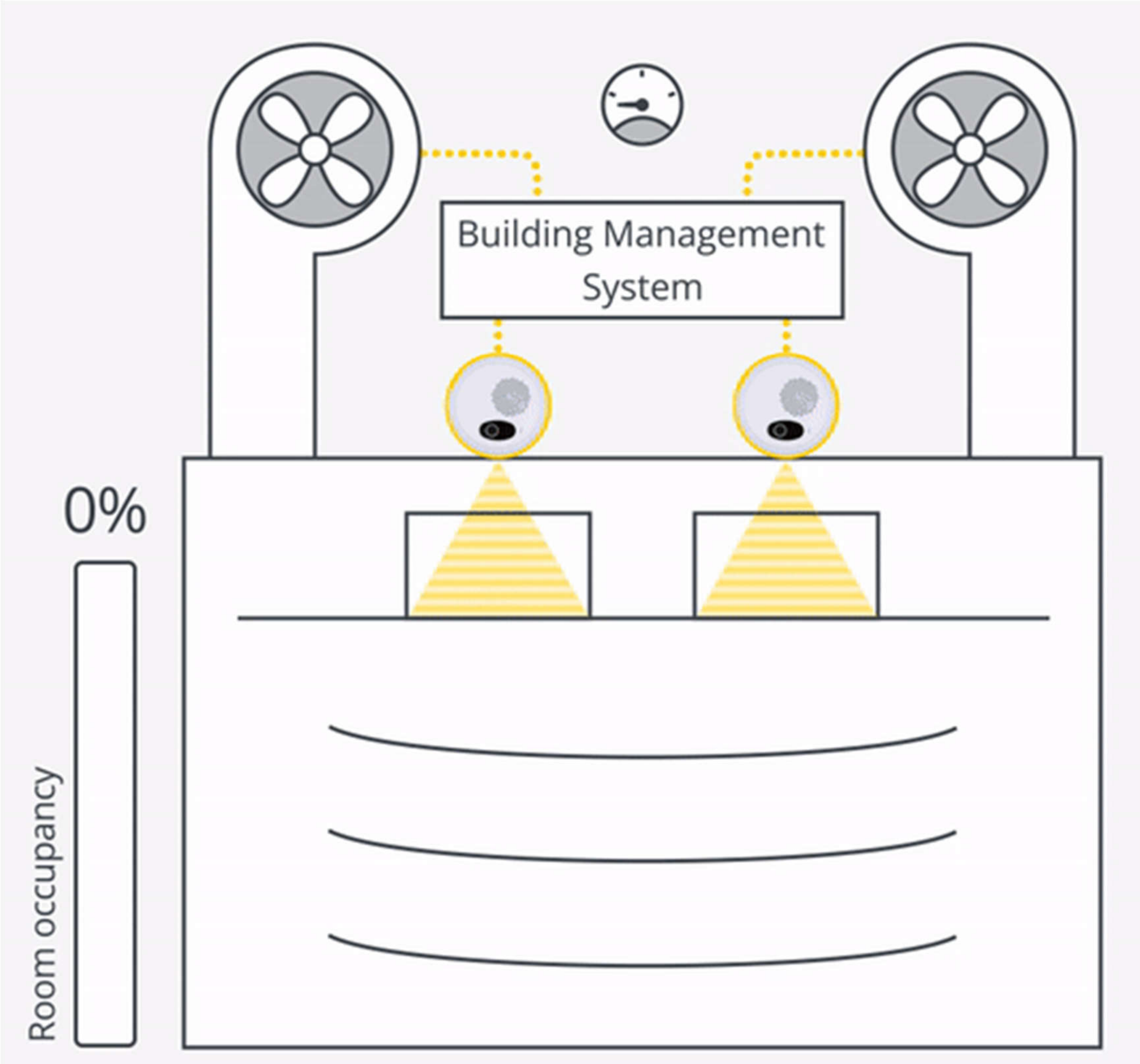
- HVAC indoor control applications:
  - Temperature & humidity monitoring & control
  - Carbon dioxide control (ventilation rate)
  - Exhaust fan control (thermostats or interlock)
  - Fume hood control (in laboratories)
  - Condensate management & control (on microbial)
  - Ventilation/outside air monitoring & control
  - Filtration monitoring & control

Operation of variable air volume (VAV) systems



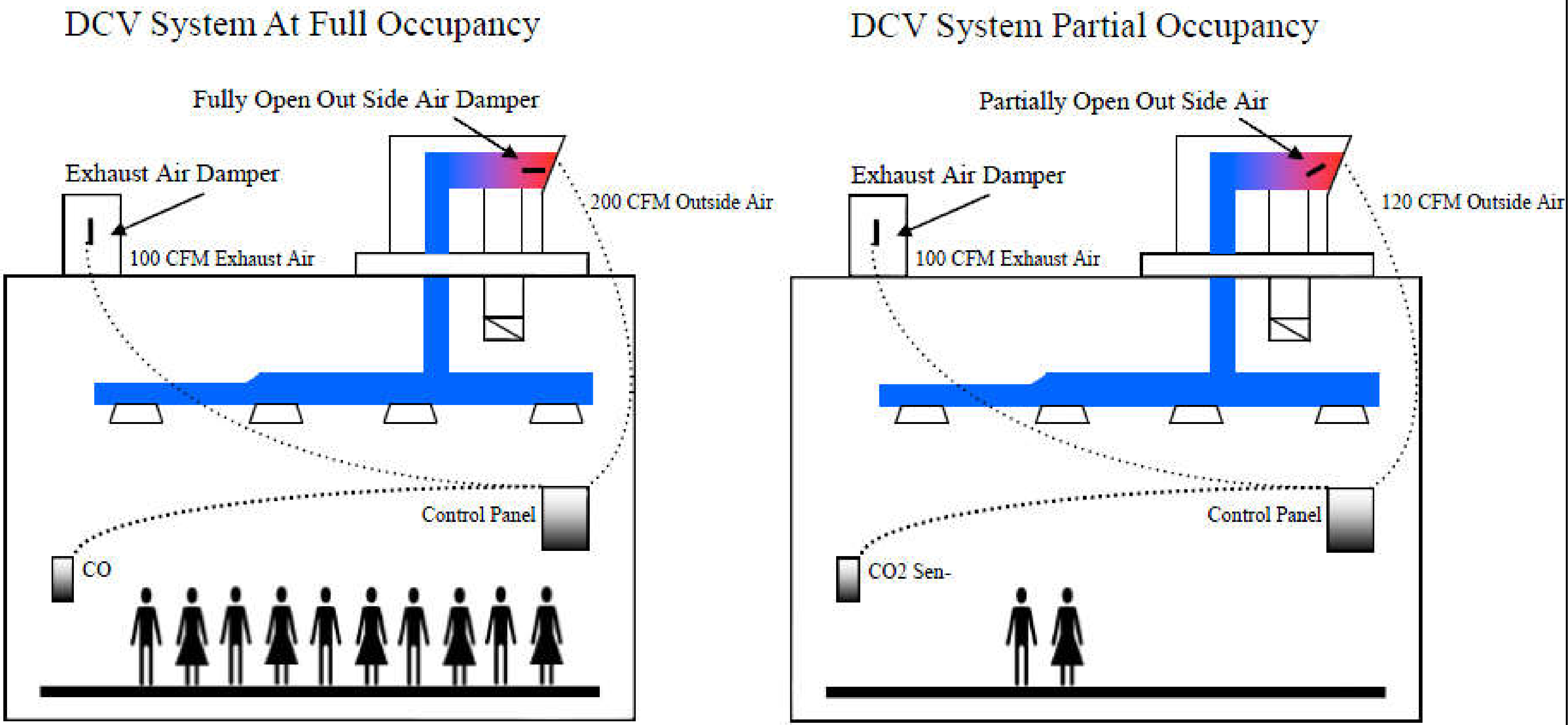
(Source: https://www.pnnl.gov/projects/om-best-practices/variable-air-volume-systems)

Smart building automation of HVAC systems with occupancy monitoring



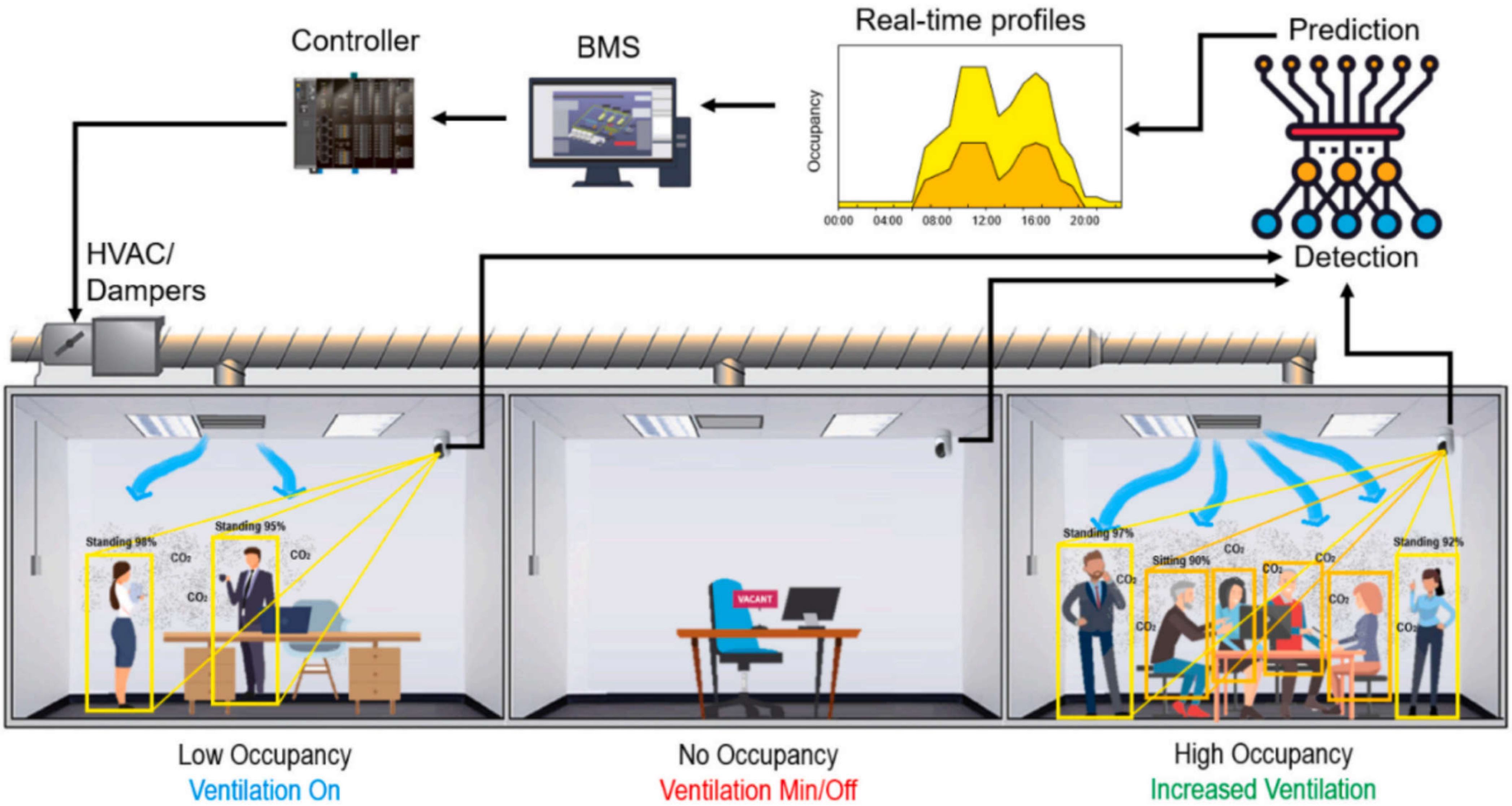
(Source: https://www.terabee.com/how-building-management-systems-are-changing-due-to-smart-building-automation/)

Demand control ventilation (DCV) control to adjust ventilation rate for full & partial occupancy



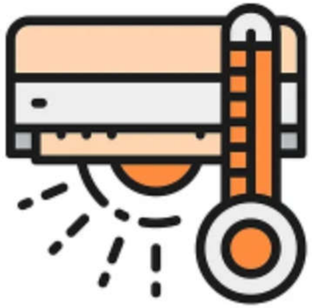
(Source: https://www.advancedcontrolsolutions.com/Demand-Control-Ventalation-and-Energy-Savings)

Vision-based approach framework for demand-based ventilation control



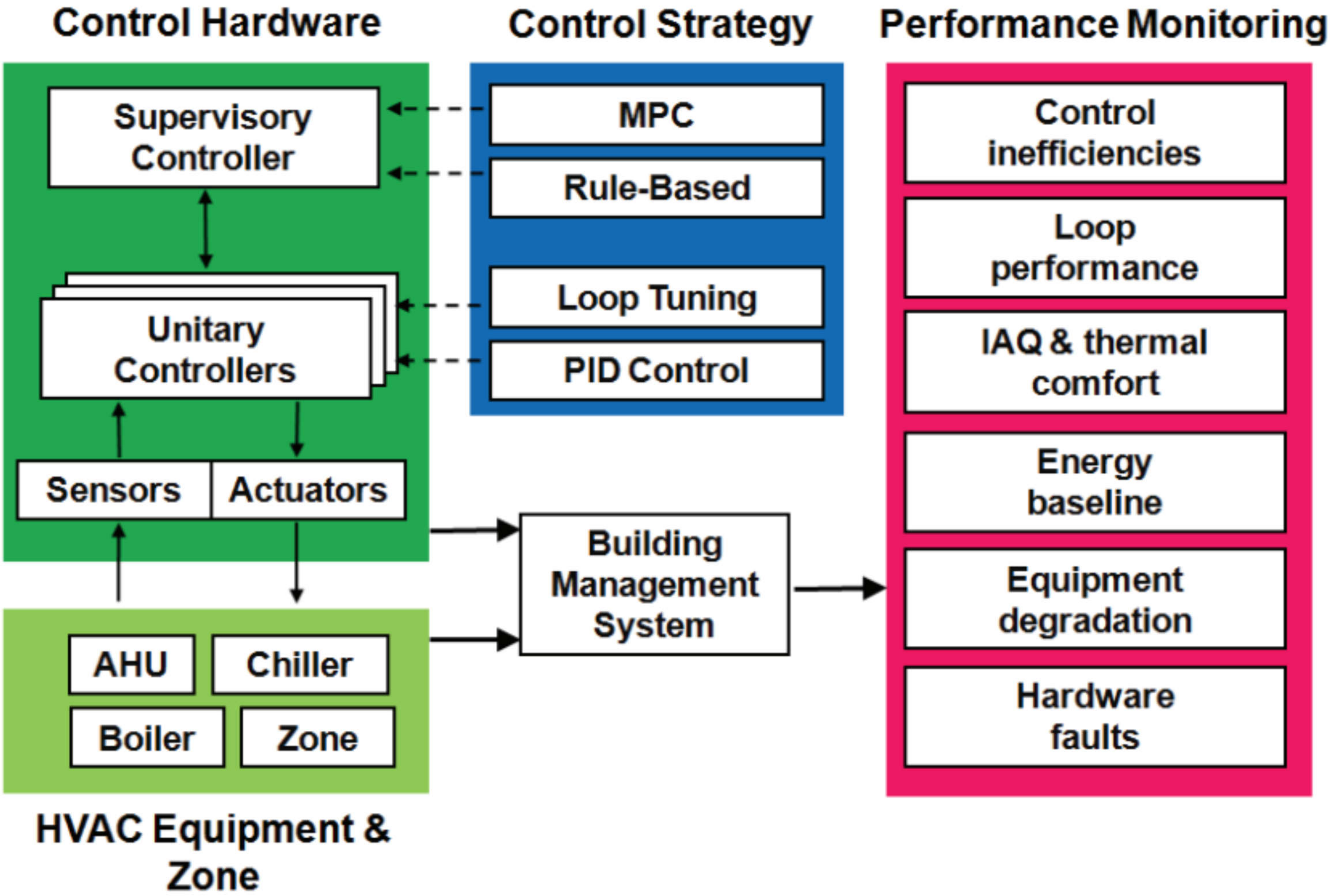
(Source: Wei S., Tien P. W., Chow T. W., Wu Y. & Calautit J. K., 2022. Deep learning and computer vision based occupancy CO2 level prediction for demand-controlled ventilation (DCV), *Journal of Building Engineering*, 56: 104715. https://doi.org/10.1016/j.jobe.2022.104715)

Advanced HVAC control



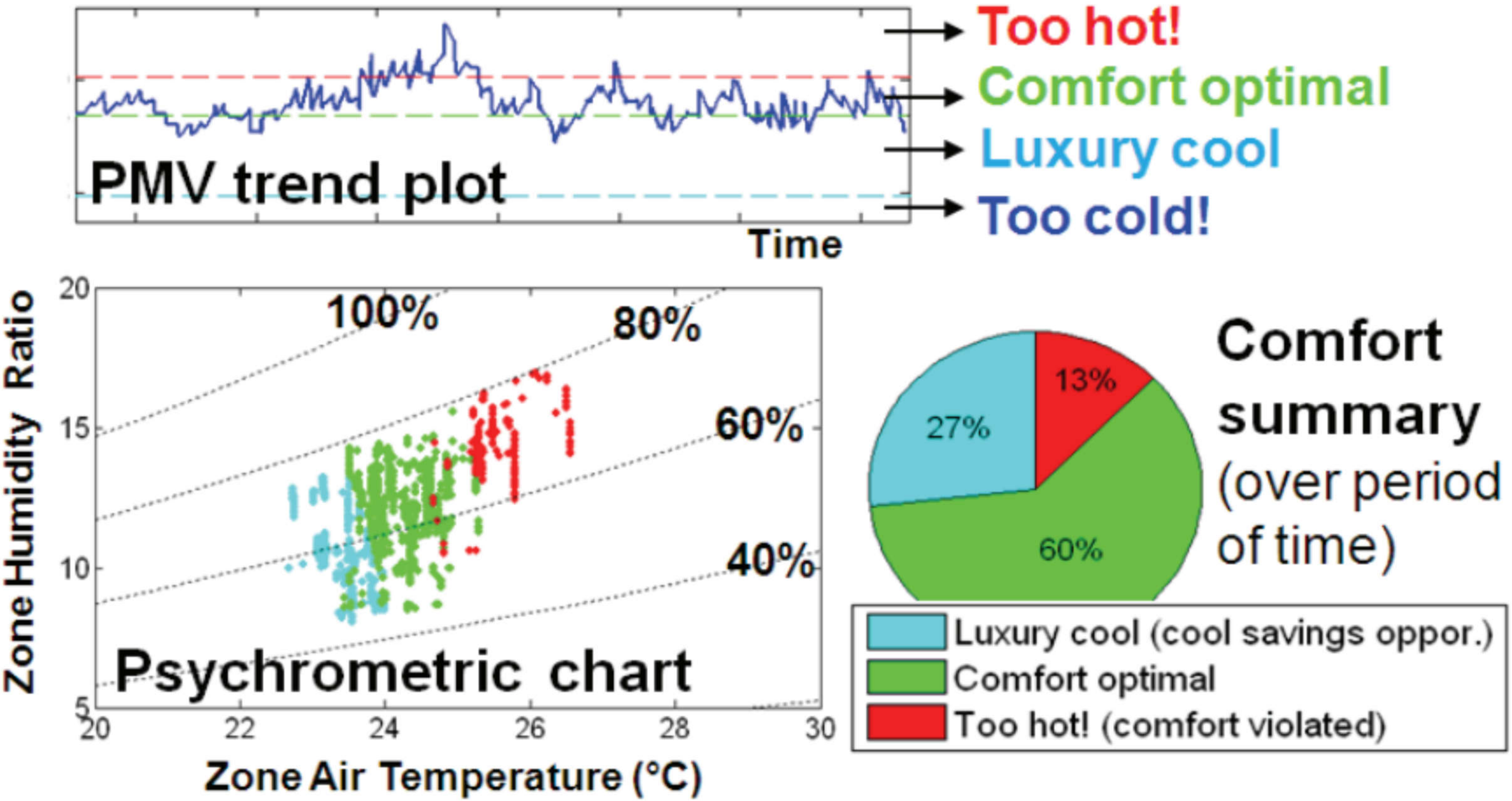
- Advanced HVAC control techniques:
  - 1. Performance monitoring
    - Quantify the performance of a particular control strategy, compare multiple control strategies among themselves & define a baseline for such comparisons
  - 2. Rule-based control strategies
    - Utilize various optimal setpoint resets, rules & other heuristics to reduce HVAC energy consumption
  - 3. Model-based predictive control (MPC)
    - Optimal control by modelling the relations between optimized variables, zone comfort & energy costs

Key elements of HVAC control systems



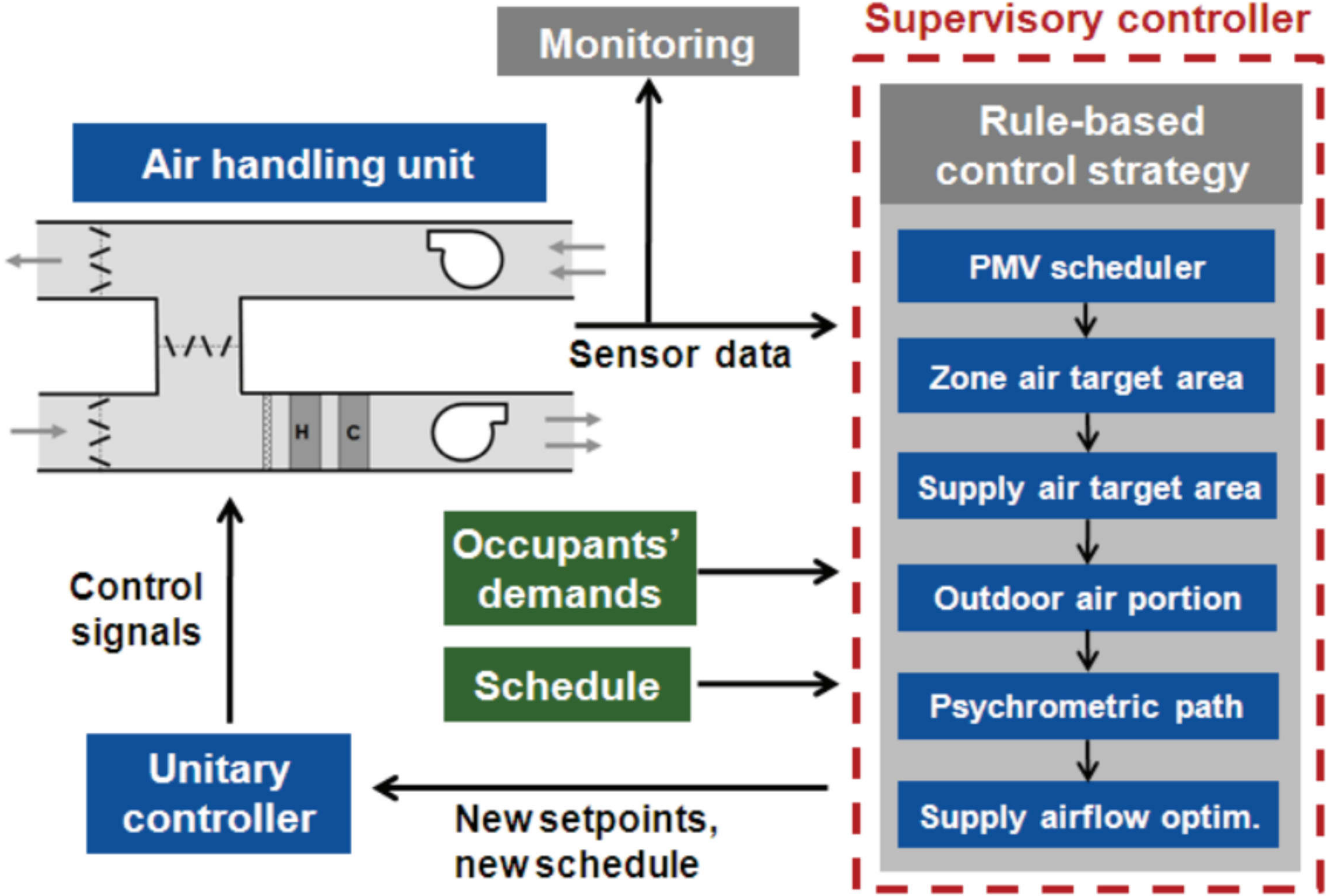
(Source: Mařík K., Rojíček J., Stluka P. & Vass J., 2011. Advanced HVAC control: theory vs. reality, *IFAC Proceedings Volumes*, 44 (1) 3108-3113. https://doi.org/10.3182/20110828-6-IT-1002.03085)

Visualization of thermal comfort for HVAC performance monitoring



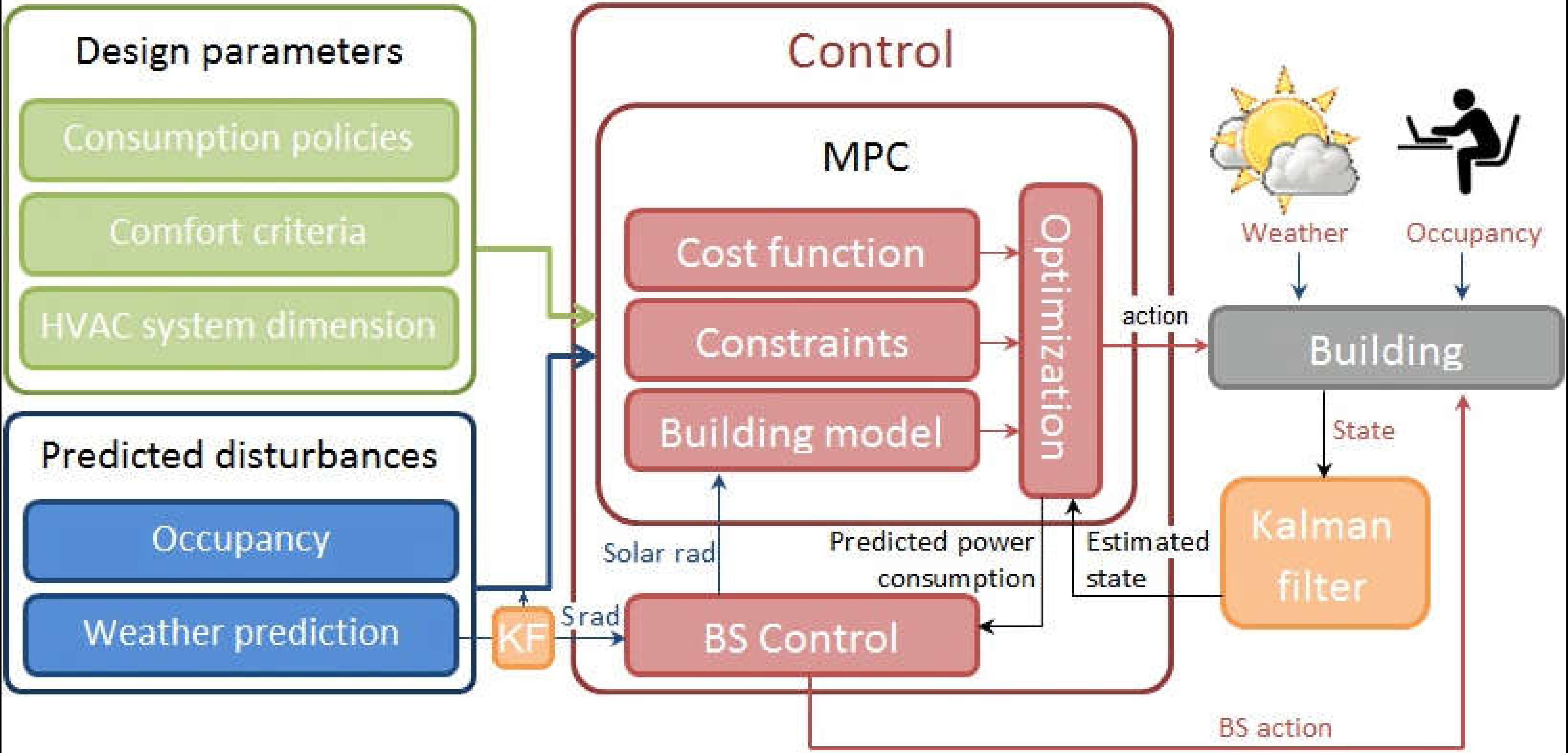
(Source: Mařík K., Rojíček J., Stluka P. & Vass J., 2011. Advanced HVAC control: theory vs. reality, *IFAC Proceedings Volumes*, 44 (1) 3108-3113. https://doi.org/10.3182/20110828-6-IT-1002.03085)

Example of a rule-based control strategy for air handling unit (AHU)



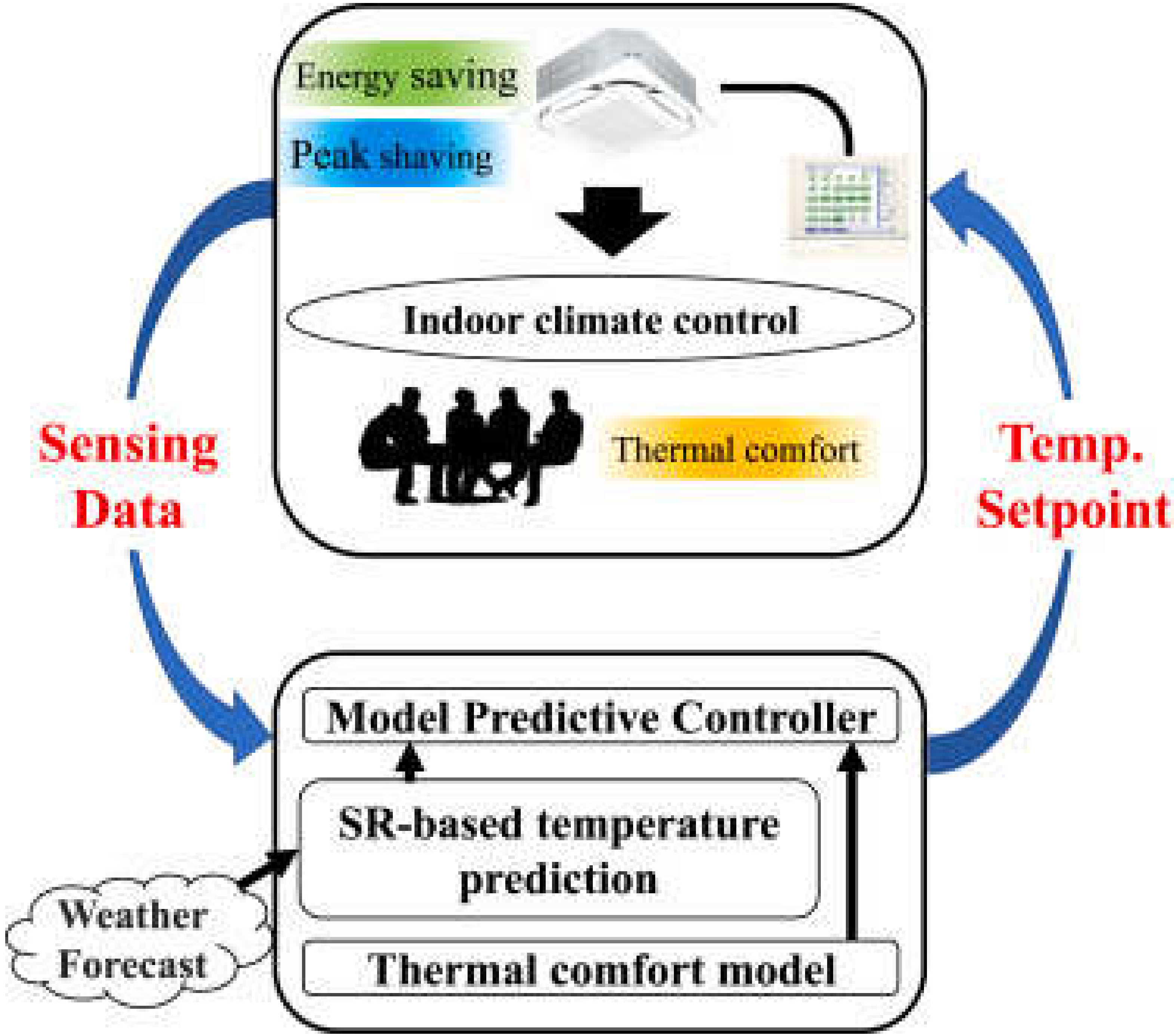
(Source: Mařík K., Rojíček J., Stluka P. & Vass J., 2011. Advanced HVAC control: theory vs. reality, *IFAC Proceedings Volumes*, 44 (1) 3108-3113. https://doi.org/10.3182/20110828-6-IT-1002.03085)

Model predictive control (MPC) scheme for the HVAC system with enhanced blind system control



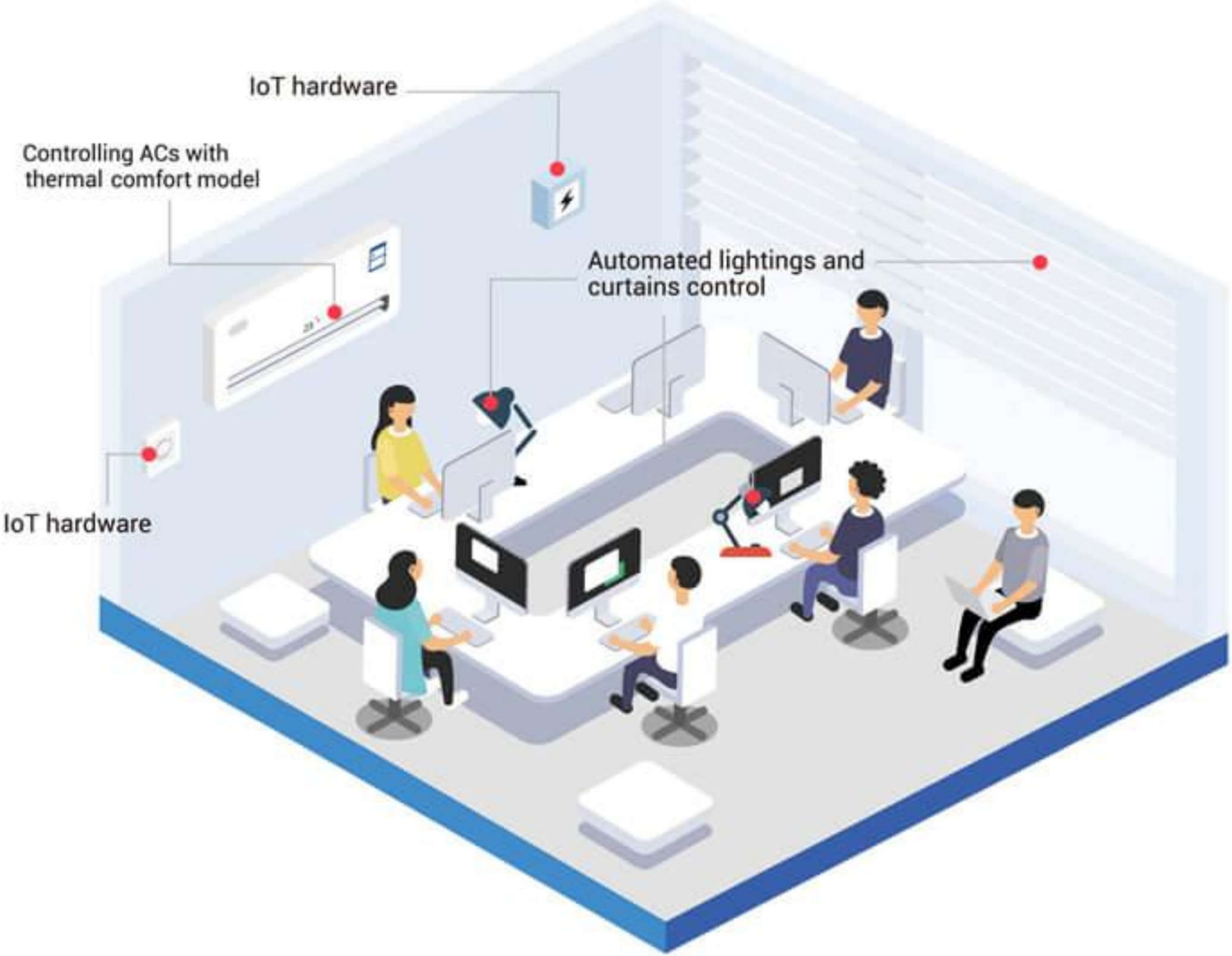
(Source: Carrascal-Lekunberri E., Garrido I., Van der Heijde B., Garrido A. J., Sala J. M. & Helsen L., 2017. Energy conservation in an office building using an enhanced blind system control, *Energies*, 10 (2) 196. https://doi.org/10.3390/en10020196)

Model predictive controller applied for HVAC indoor climate control



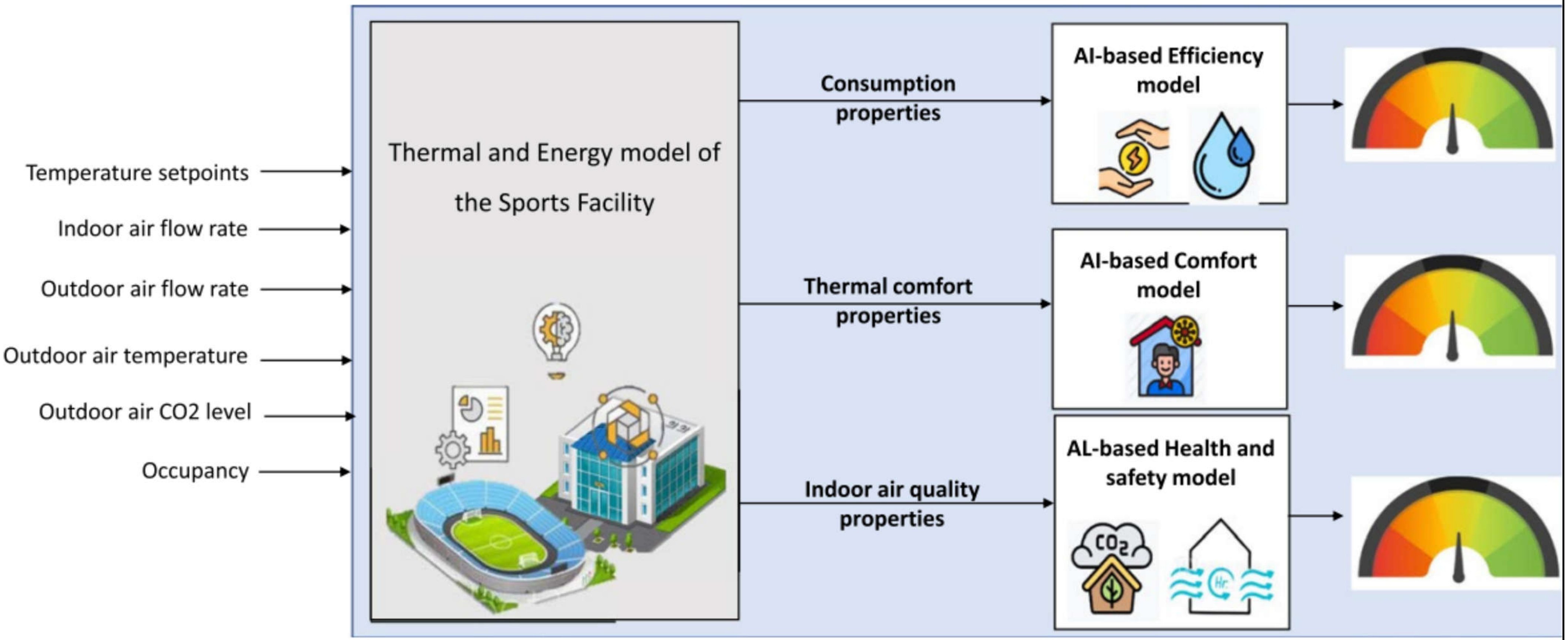
(Source: Zhao D., Watari D., Ozawa Y., Taniguchi I., Suzuki T., Shimoda Y. & Onoye T., 2023. Data-driven online energy management framework for HVAC systems: An experimental study, *Applied Energy*, 352: 121921. https://doi.org/10.1016/j.apenergy.2023.121921)

Smart HVAC control with thermal comfort model



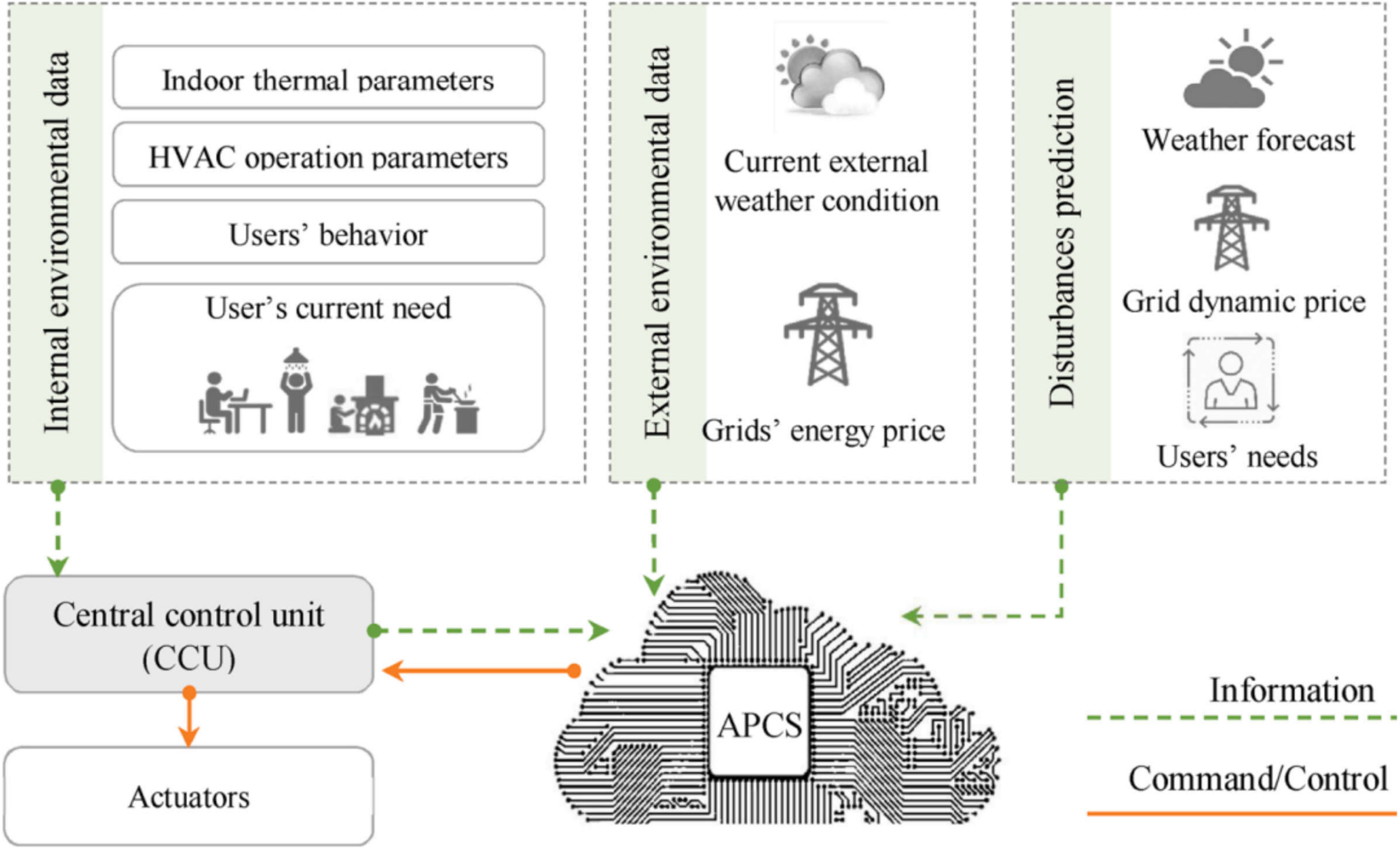
(Source: https://www.innovationhub.hk/article/smart-building-management-system)

Thermal & energy model of a sports facility to include properties of energy consumption, thermal comfort & indoor air quality



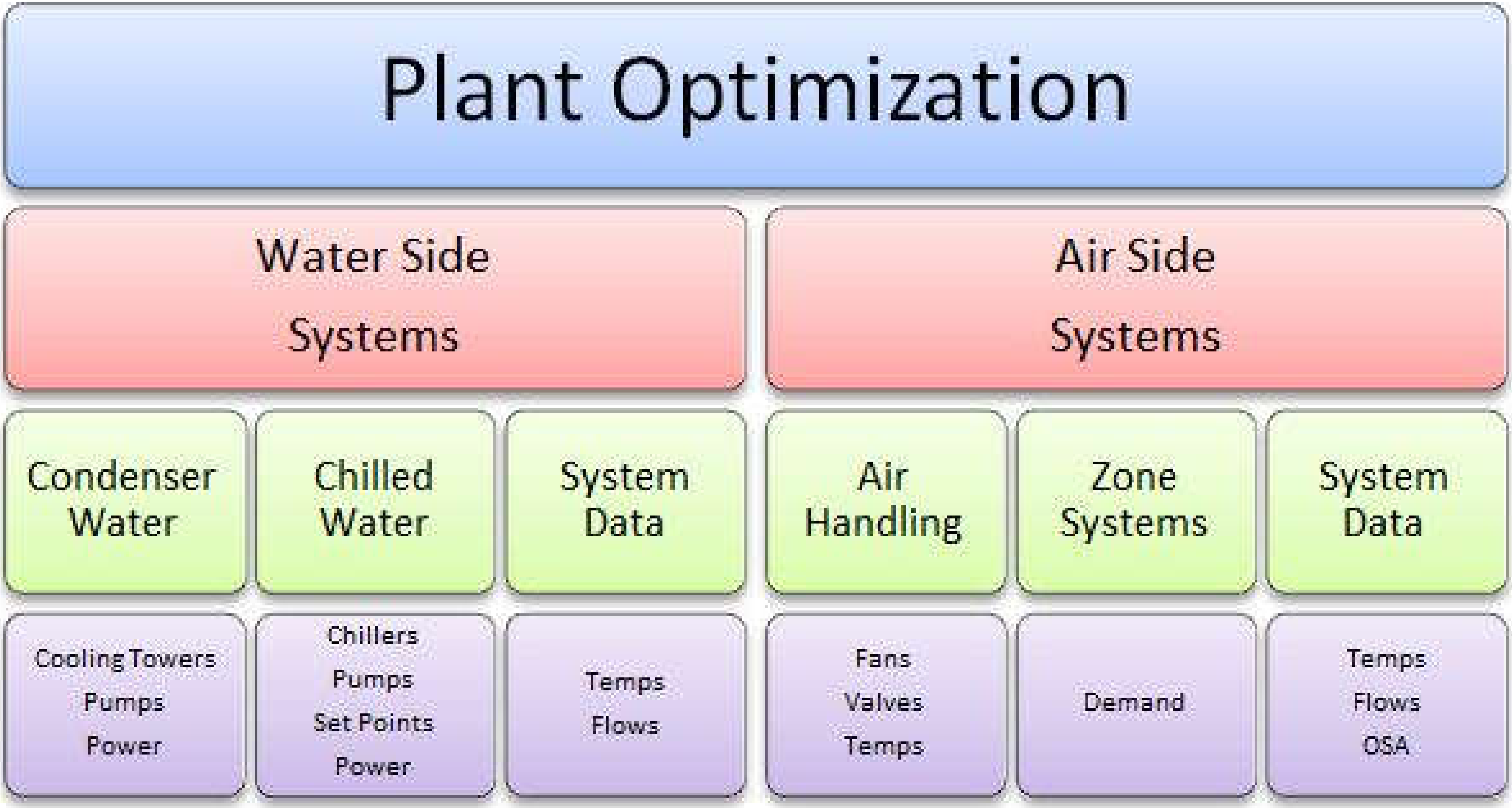
(Source: Himeur Y., Elnour M., Fadli F., Meskin N., Petri I., Rezgui Y., Bensaali F. & Amira A., 2022. AI-big data analytics for building automation and management systems: a survey, actual challenges and future perspectives, *Artificial Intelligence Review*, 56: 4929-5021. https://doi.org/10.1007/s10462-022-10286-2)

Adaptive-predictive control strategy (APCS) for HVAC systems in smart buildings



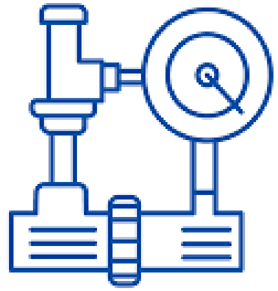
(Source: Gholamzadehmir M., Pero C. D., Buffa S., Fedrizzi R. & Aste N., 2020. Adaptive-predictive control strategy for HVAC systems in smart buildings – A review, *Sustainable Cities and Society*, 63: 102480. https://doi.org/10.1016/j.scs.2020.102480)

Major components of HVAC plant & system optimization



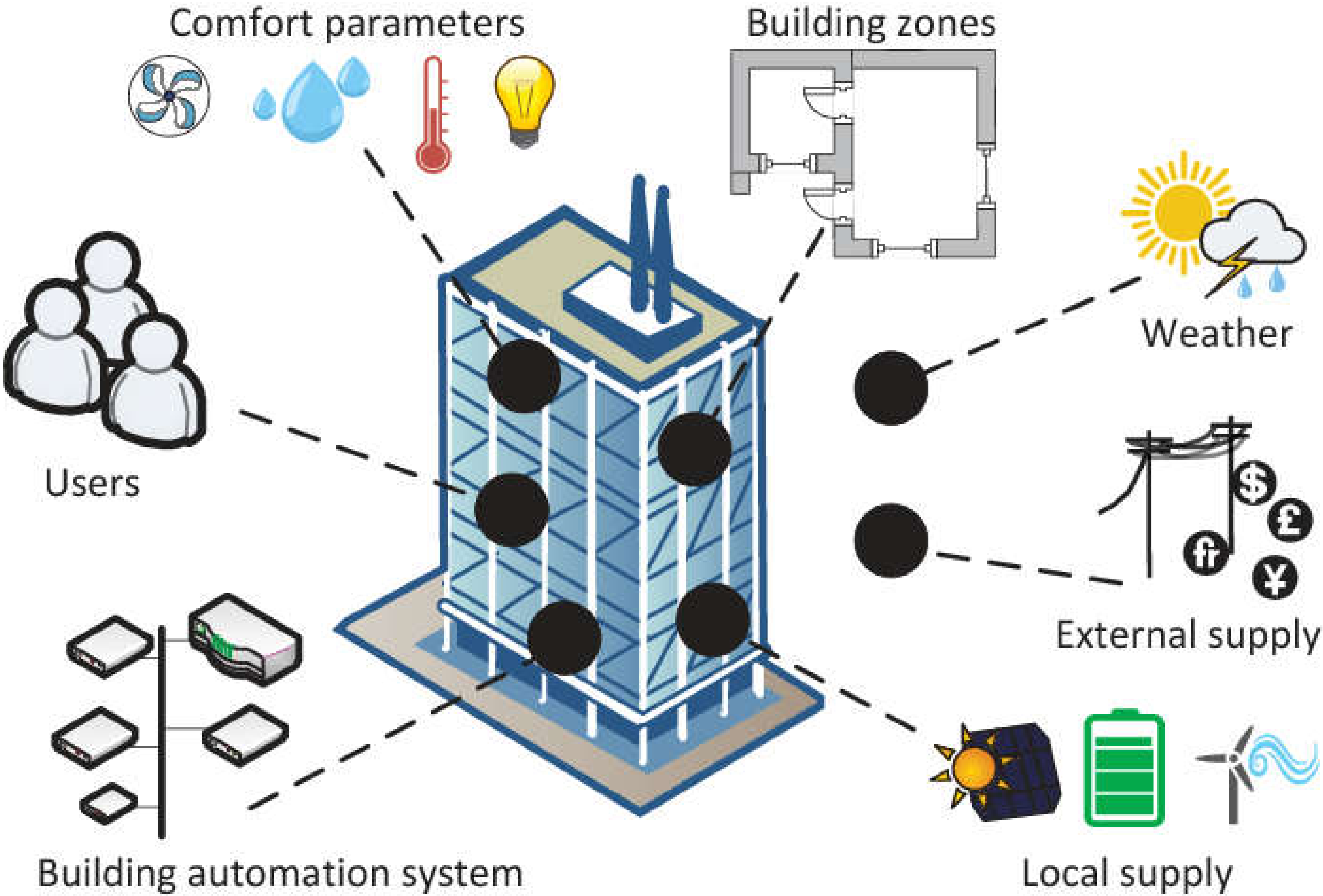
(Source: https://www.automatedbuildings.com/news/aug12/articles/climatec/120724035404climatec.html)

Central plant optimization



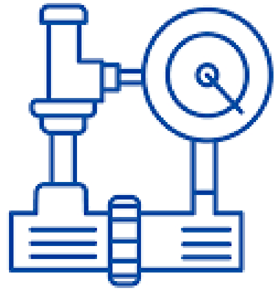
- In large buildings, a HVAC central plant is usually the primary source of cooling or heating, delivering thermal energy as chilled or hot water to HVAC systems
- Improving the efficiency of the generation & distribution of thermal energy reduces energy wastage at the source
- A small percentage improvement can produce large overall savings

Relevant influencing factors for optimization in building energy management system



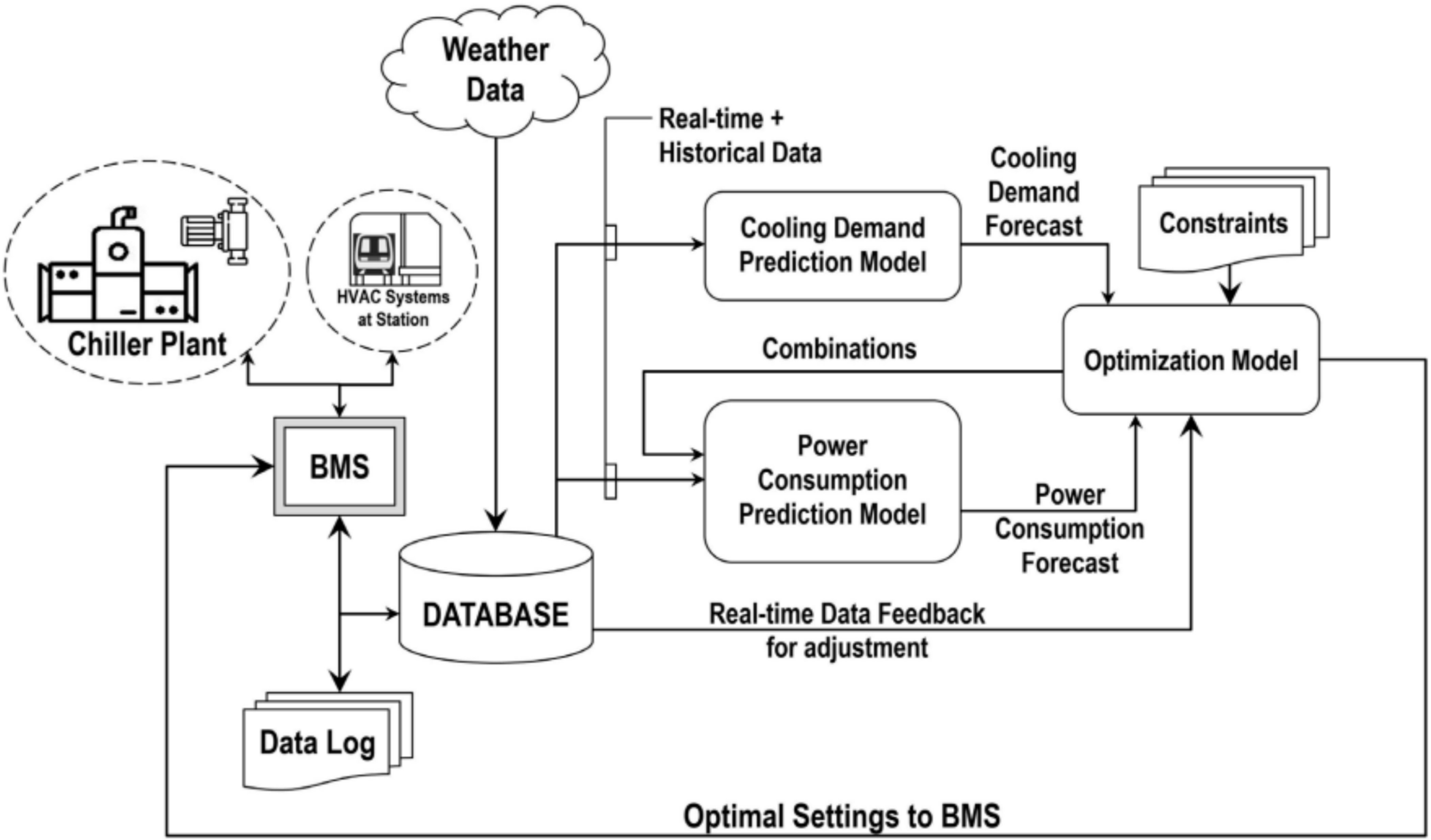
(Source: Schachinger D. & Kastner W., 2018. Context-aware optimization strategies for universal application in smart building energy management, In *2018 IEEE 16th International Conference on Industrial Informatics (INDIN)*, Porto, Portugal, 2018, pp. 478-483. http://doi.org/10.1109/INDIN.2018.8472000)

Central plant optimization



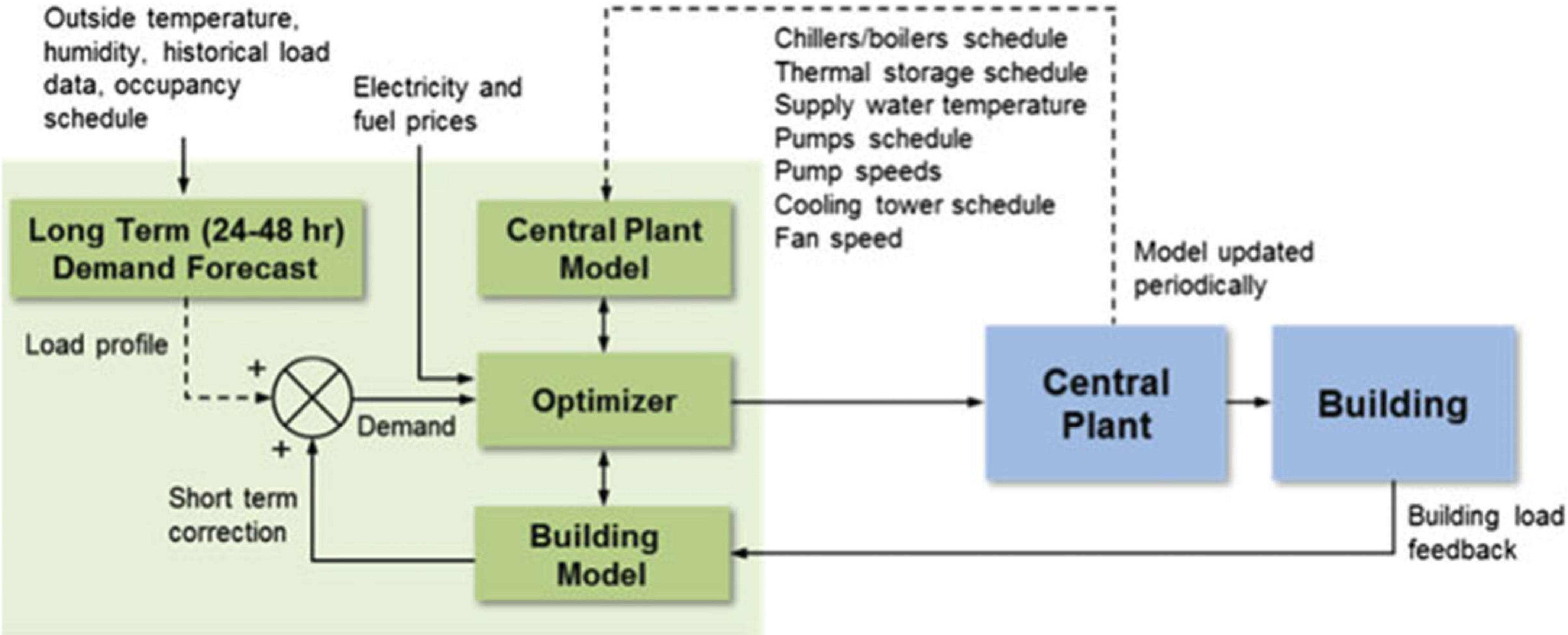
- Plant equipment efficiencies vary with load & external conditions
- Central plants have multiple chillers, boilers, & power generators, which may differ from each other in capacities & performance
  - The ability to select equipment & operate it at optimized points to minimize the total energy
- Modelling the load dynamics offers the additional benefits of predictive optimization

System architecture of a chiller plant optimisation



(Source: Suen A. T. Y., Ying D. T. W. & Choy C. T. L., 2021. Application of artificial intelligence (AI) control system on chiller plant at MTR station, *HKIE Transactions*, 29 (2) 90-97. https://doi.org/10.33430/V29N2THIE-2021-0032)

Optimization of HVAC central plant



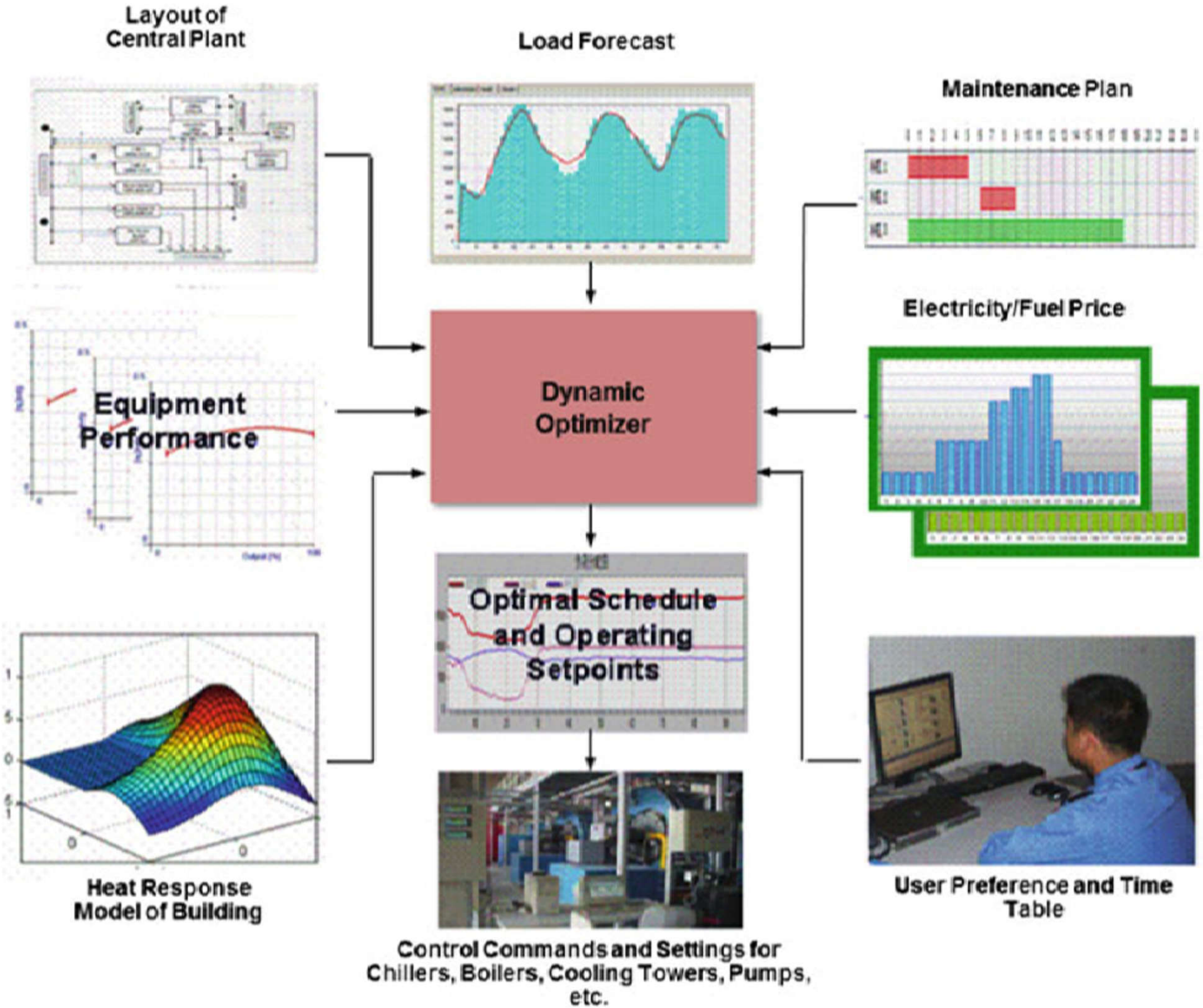
A <u>demand forecaster</u> predicts loads for the next 24 hours period based on the current weather, load history, & occupancy criteria.

A <u>dynamic load model</u> represents the building response to changes in energy supplied.

Based on the inputs of upcoming demand loads, central plant performance & building response, the <u>optimizer</u> solves the schedules & operating commands for the major equipment in the supply & distribution of chilled & hot water.

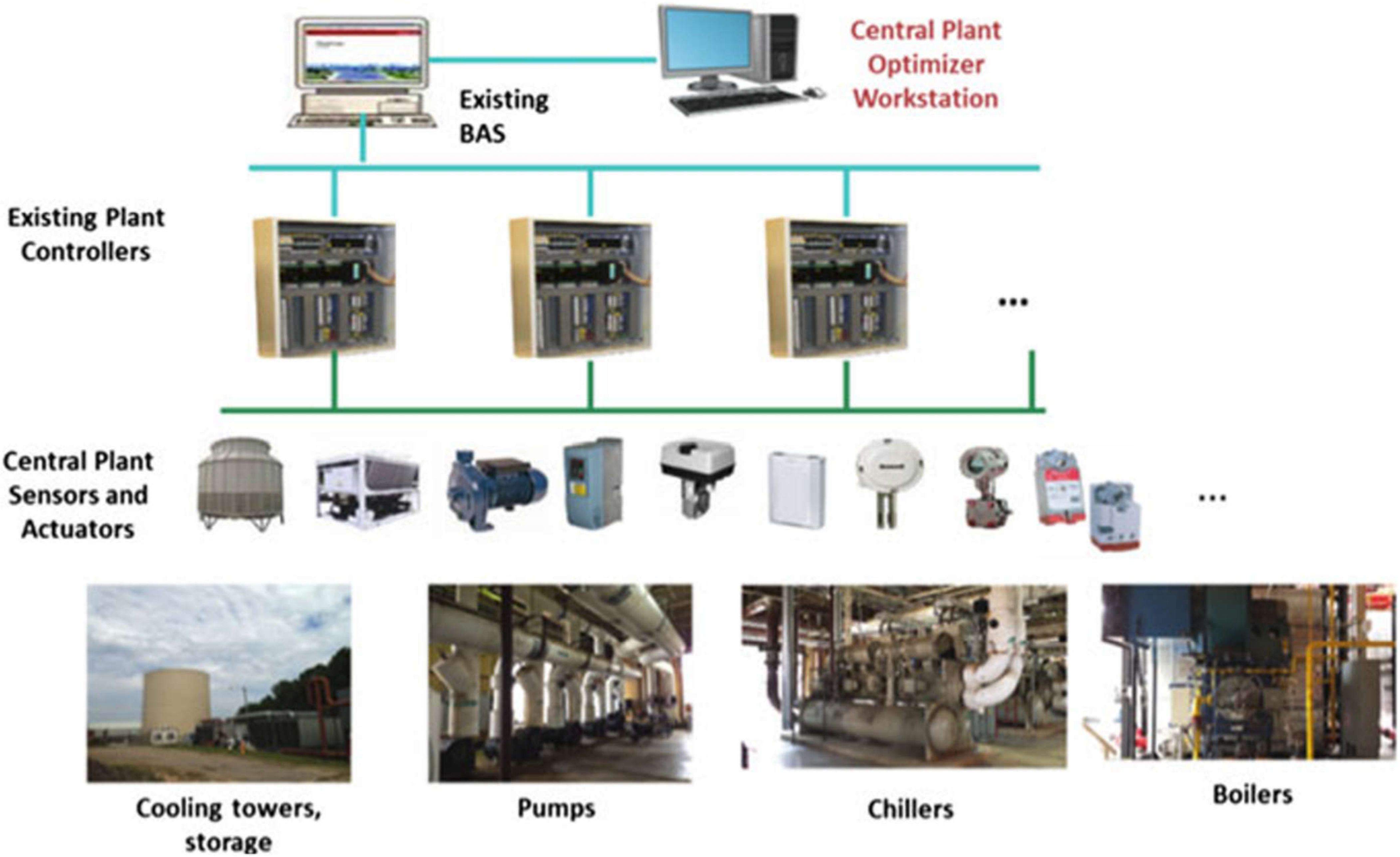
(Source: Wen J. T. & Mishra S., 2018. *Intelligent Building Control Systems A Survey of Modern Building Control and Sensing Strategies*)

Basic concept of a dynamic real-time supervisory optimizer



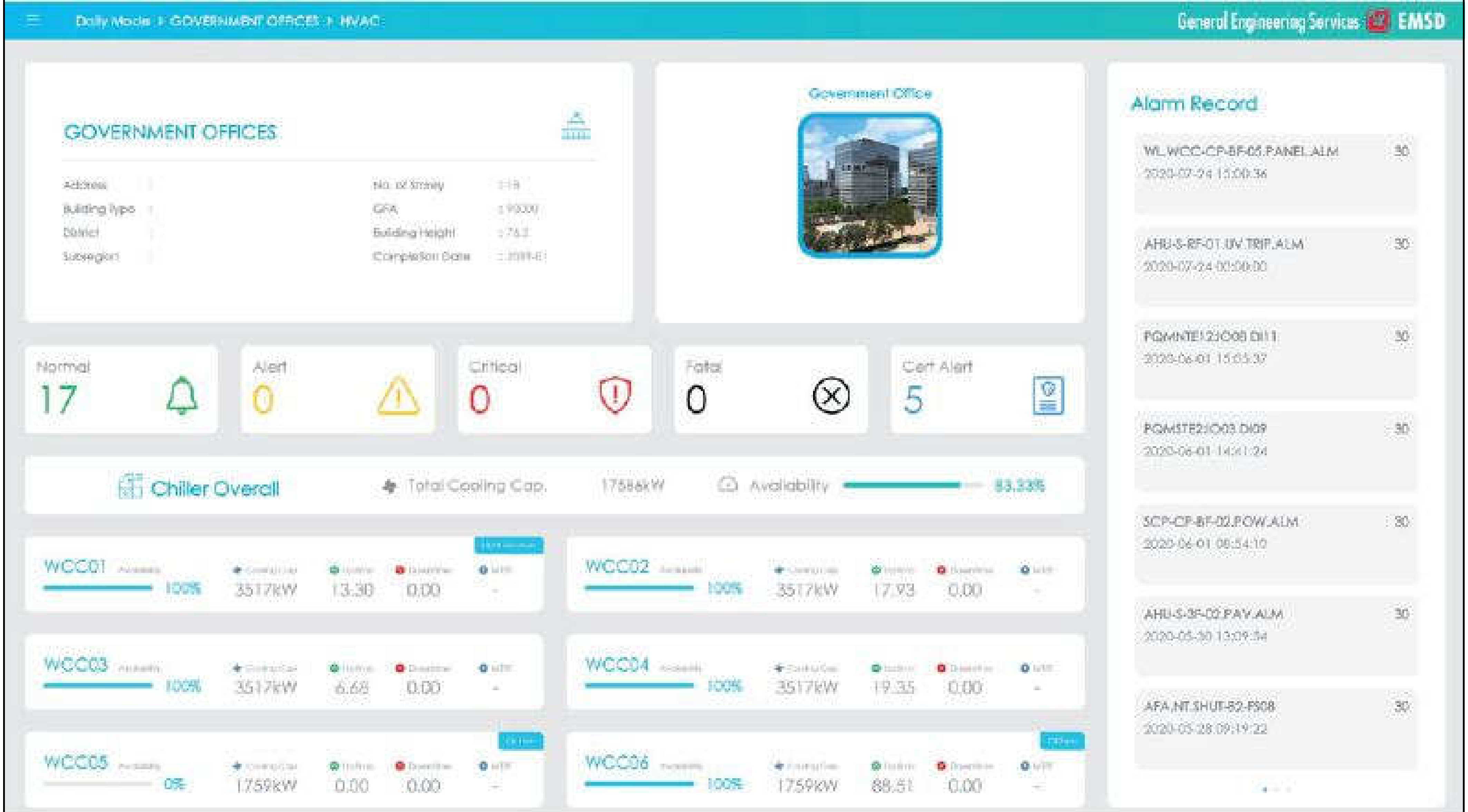
(Source: Wen J. T. & Mishra S., 2018. *Intelligent Building Control Systems A Survey of Modern Building Control and Sensing Strategies*)

HVAC control implementation of a real-time supervisory optimizer



(Source: Wen J. T. & Mishra S., 2018. *Intelligent Building Control Systems A Survey of Modern Building Control and Sensing Strategies*)

Dashboard showing the real-time monitoring of chiller plants

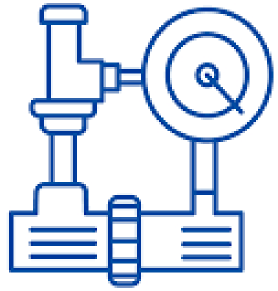


(Source: https://www.hkengineer.org.hk/issue/vol50-oct2022/feature_story/?id=17083)

Dashboard showing the real-time monitoring of chiller plants

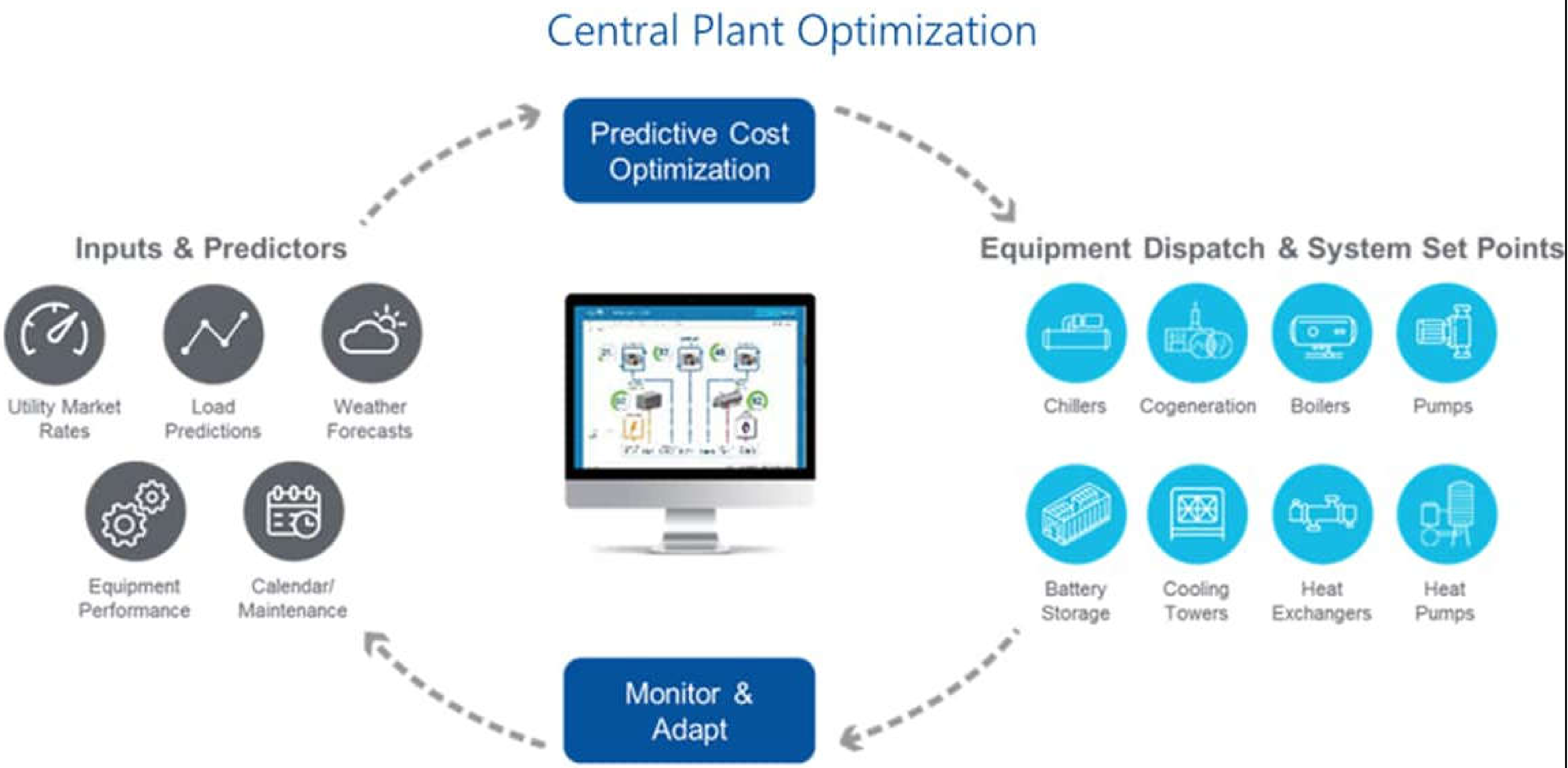
(Source: https://www.hkengineer.org.hk/issue/vol50-oct2022/feature_story/?id=17083)

Central plant optimization



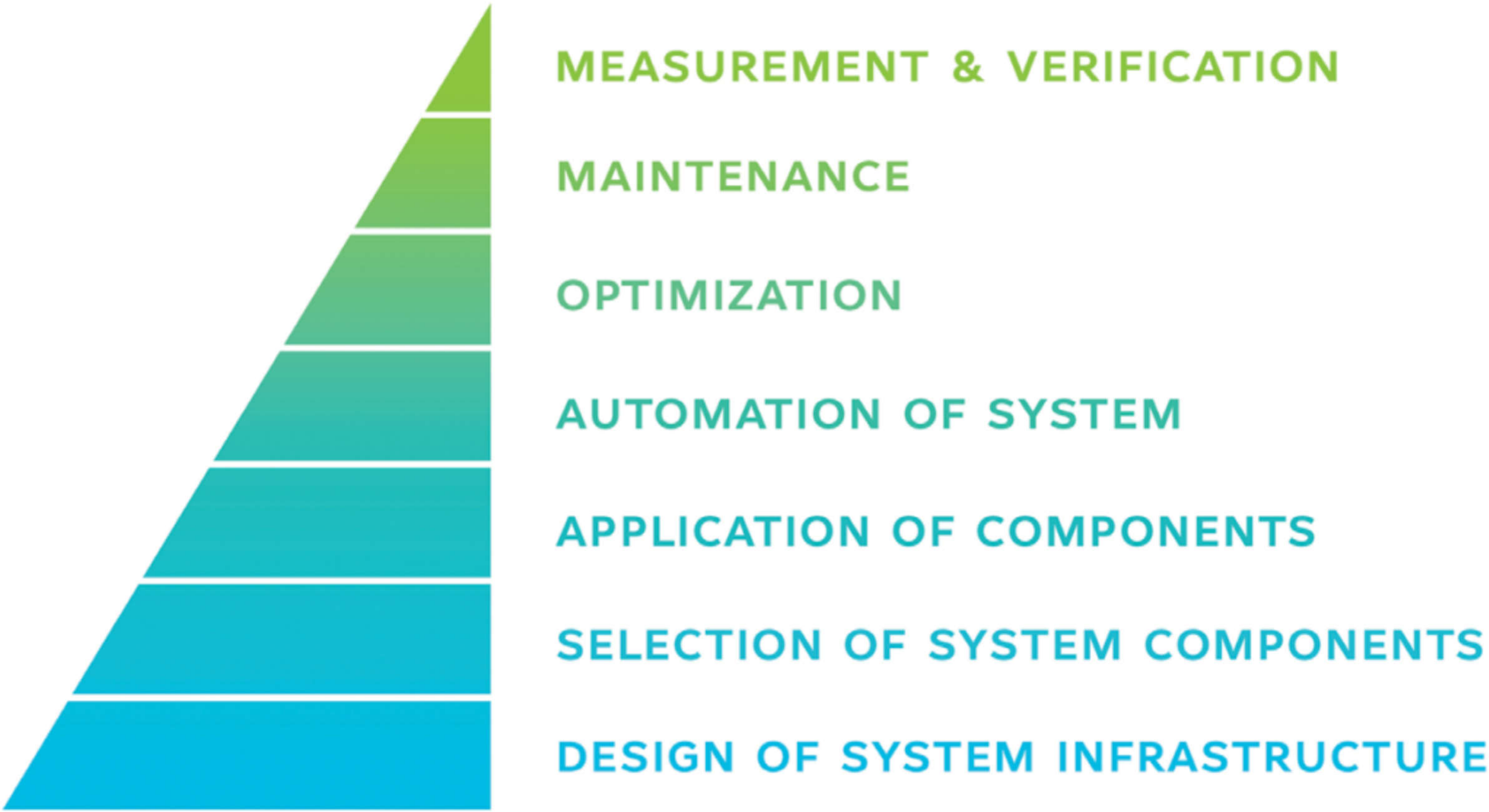
- Analysis of inputs for plant optimization
  - Equipment performance models (predictors)
  - Weather forecasts (for ambient conditions)
  - Load predictions (for hourly loads)
  - Utility pricing (demand chargers & tariffs)
  - Calendars & maintenance schedules (events)
- Help operators on both plant design & operating decisions to minimize lifecycle costs while delivering reliable services

HVAC central plant optimization using predictive algorithms to automatically make adjustments to minimize cost & energy



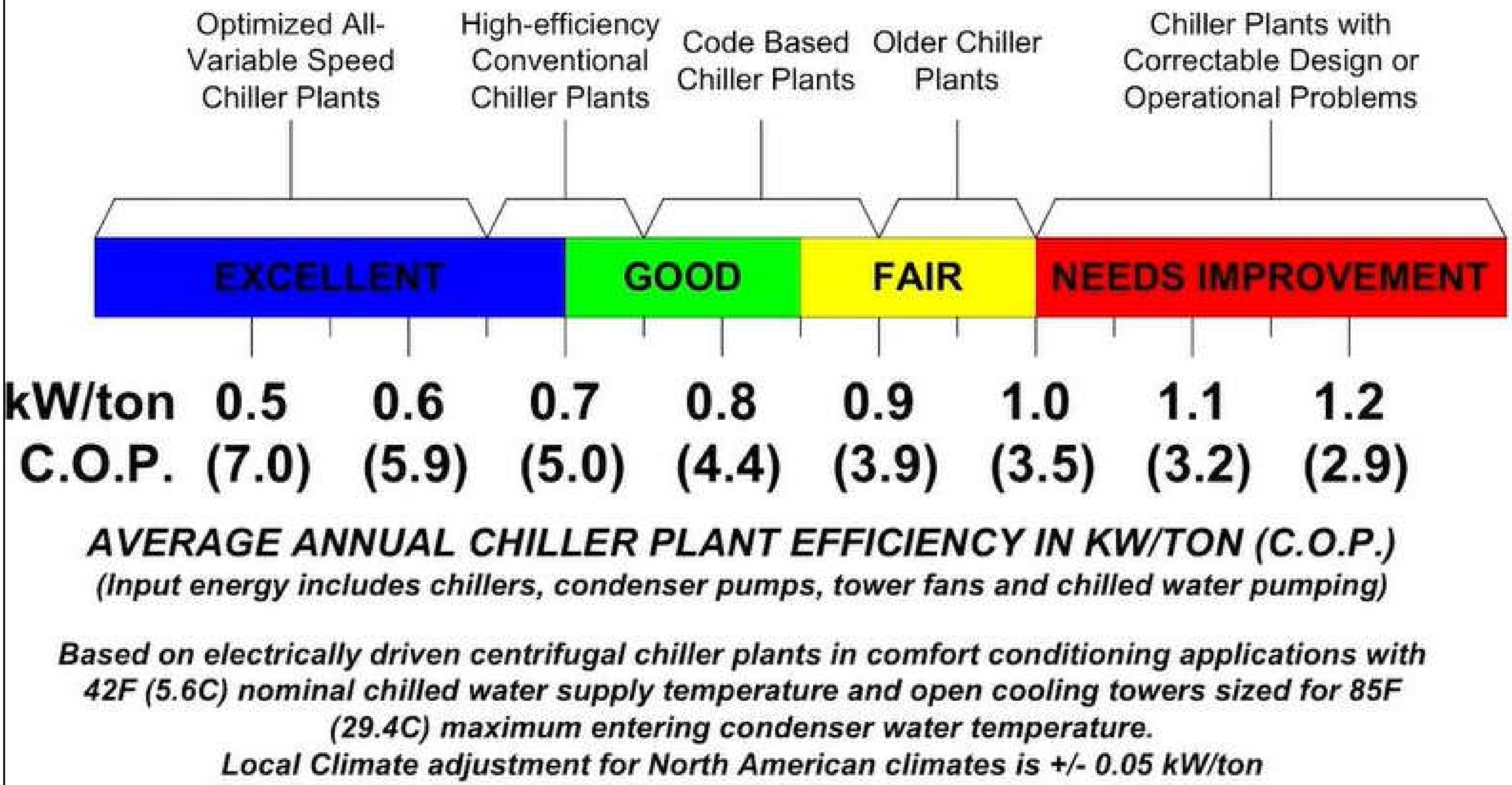
(Source: https://www.johnsoncontrols.com/en_au/digital-solutions/central-plant-optimization)

Achieving plant efficiency potential is determined by both the design & operating decisions



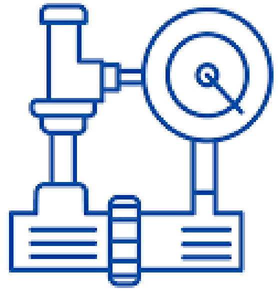
(Source: Seven Steps to Maximizing Central Plant Efficiency (Johnson Controls) https://www.johnsoncontrols.com/-/media/jci/be/united-states/services-and-support/optimization-and-retrofit-services/files/be_wp_centralplantoptimization.pdf)

Chiller plant energy use spectrum



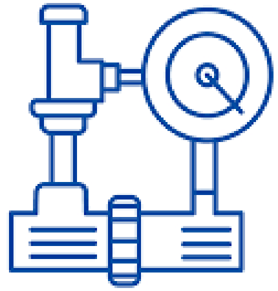
(Source: https://optimumenergyco.com/how-to-optimize-an-hvac-system/)

Central plant optimization



- Self-tuning methods for HVAC central plant
  - 1) Auto-tuning – software feature
  - 2) Adaptive techniques - recognize changing conditions, and choose different control settings based on the sensed condition
  - 3) Fuzzy logic control – the system monitors many inputs & performs a pseudo-logic operation on these data to assign a 'degree of control'
  - 4) Neural network – 'teach' the system how to react to given scenarios (like human brain)

Central plant optimization

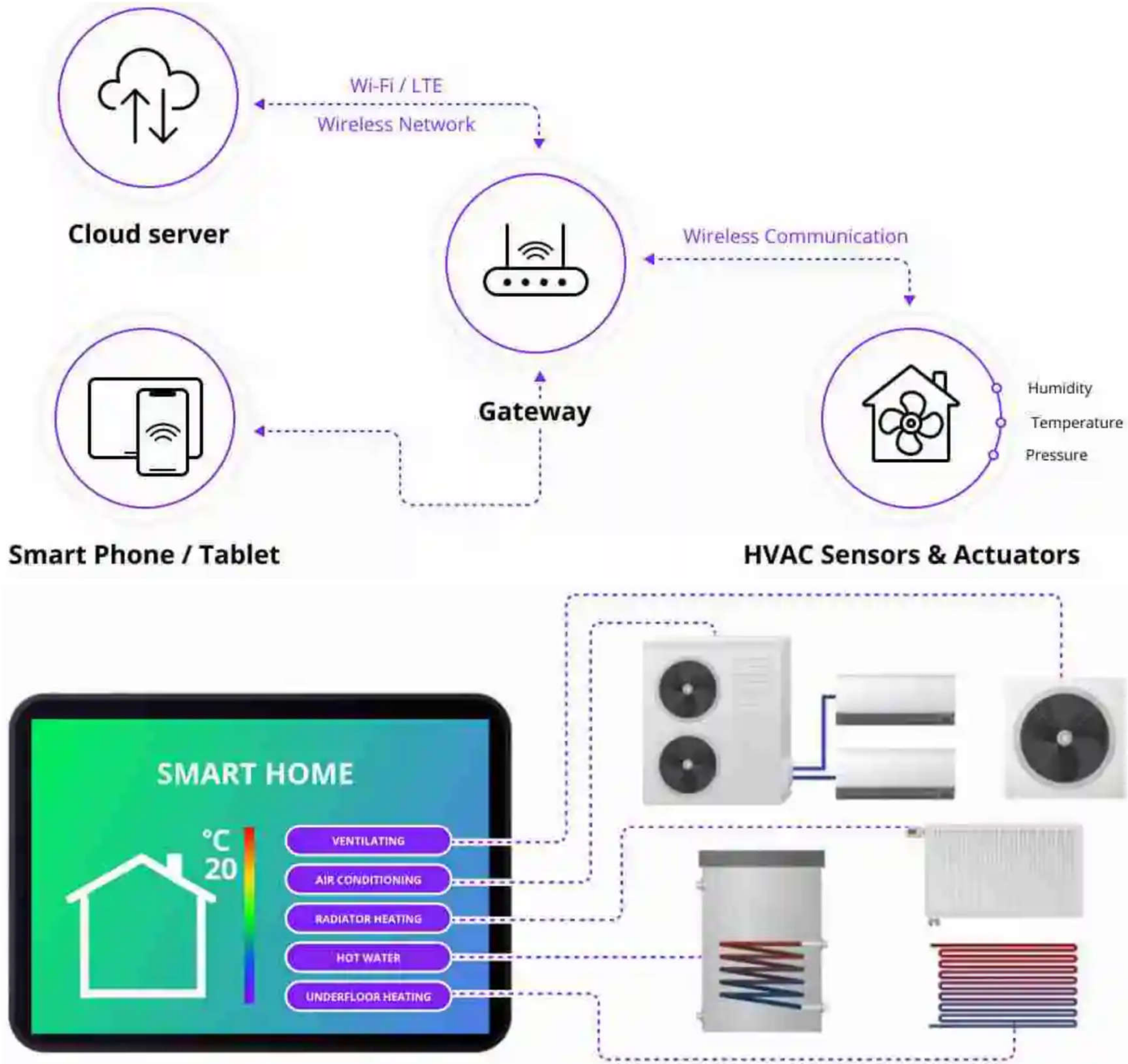


- Chiller optimization via AI/big data analytics
  - AI self-learning to identify energy saving opportunities automatically
  - Equipment fault detection & diagnosis
- Process of applying AI on HVAC:
  - 1. Data collection (BMS, IoT, weather patterns)
  - 2. Machine learning with AI models
  - 3. Fault detection, capacity prediction, automatic control

Smart HVAC

- Smart HVAC systems
  - HVAC systems that can improve efficiency, control & overall performance with advanced technologies & components, e.g.
    - Sensors that collect the data
    - Network hub that receives, stores & analyses the information
    - Controllers that regulate the HVAC activity
    - User interface & remote control (e.g. smart phone)
  - By optimizing energy consumption, smart HVAC makes our building & facilities more sustainable

Components & main features of a smart HVAC system



(Source: https://euristiq.com/smart-hvac-systems/)

Smart HVAC

- Smart HVAC at home
  - Allow the homeowner to control the indoor environmental conditions to achieve an ideal comfort level & better energy efficiency

  - HVAC sensors:

    - Environmental sensors: monitor the condition & alert the homeowner if any problems (e.g. air duct leaks, dirty air filters & poor HVAC efficiency)
    - Occupancy sensors: detect the presence of people & automatically adjust the HVAC controls or airflow

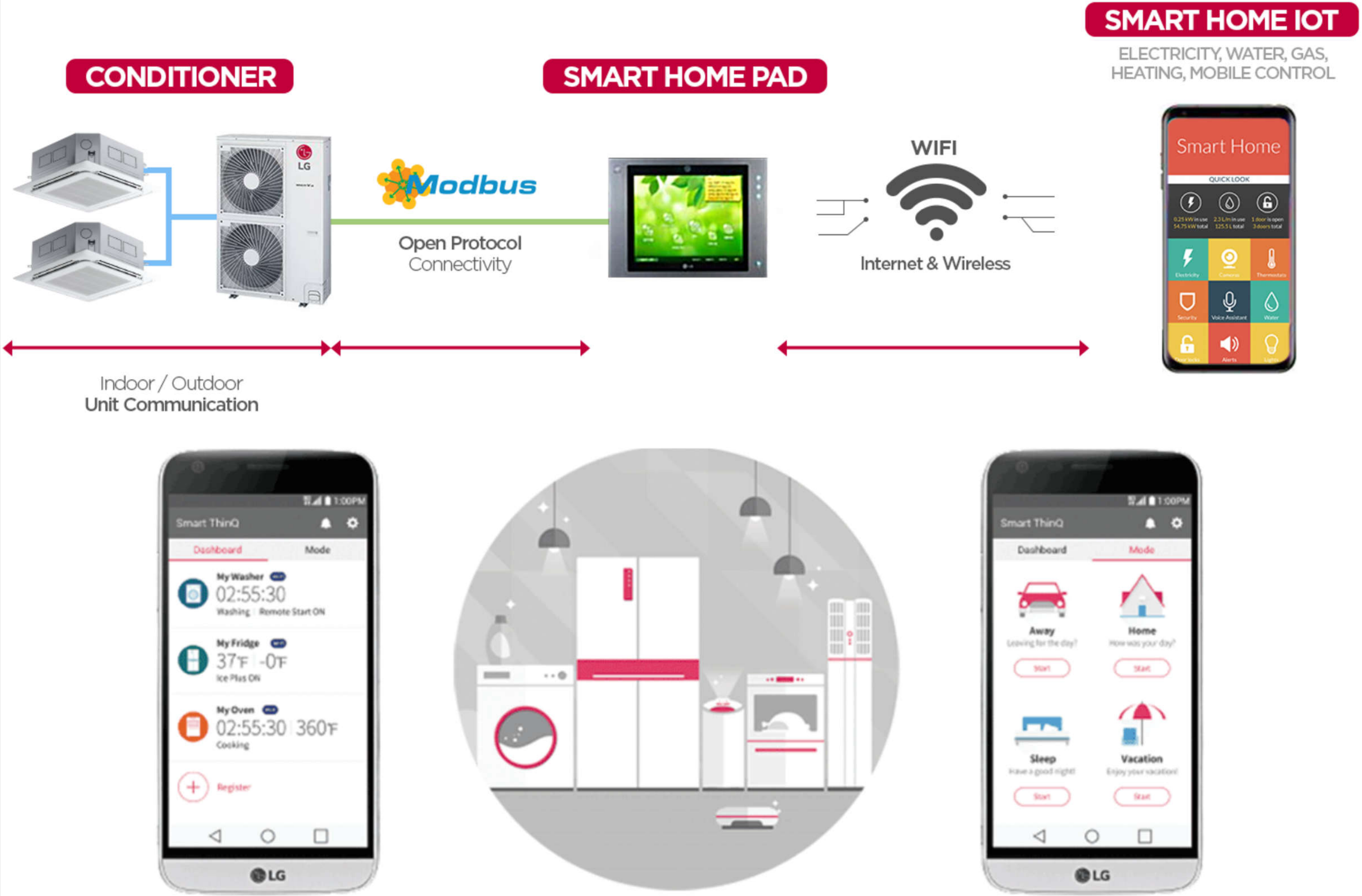
  - Remote control & scheduling, voice control

Smart HVAC

- Smart thermostat
  - A wireless device that automatically adjusts heating & cooling temperature settings for optimal performance or remotely through smartphone
  - Learn your temperature preferences & establish a schedule that automatically adjusts to energy-saving temperatures when you are asleep or away
  - Geofencing allows smart thermostat to know when people on the way home and automatically adjusts temperature to their liking

(Further information: https://en.wikipedia.org/wiki/Smart_thermostat)

Smart HVAC in the smart home



(Source: https://www.lghvacstory.com/smart-hvac-in-the-smart-home-part-1-of-2/)

Comparison of communication interface for smart HVAC

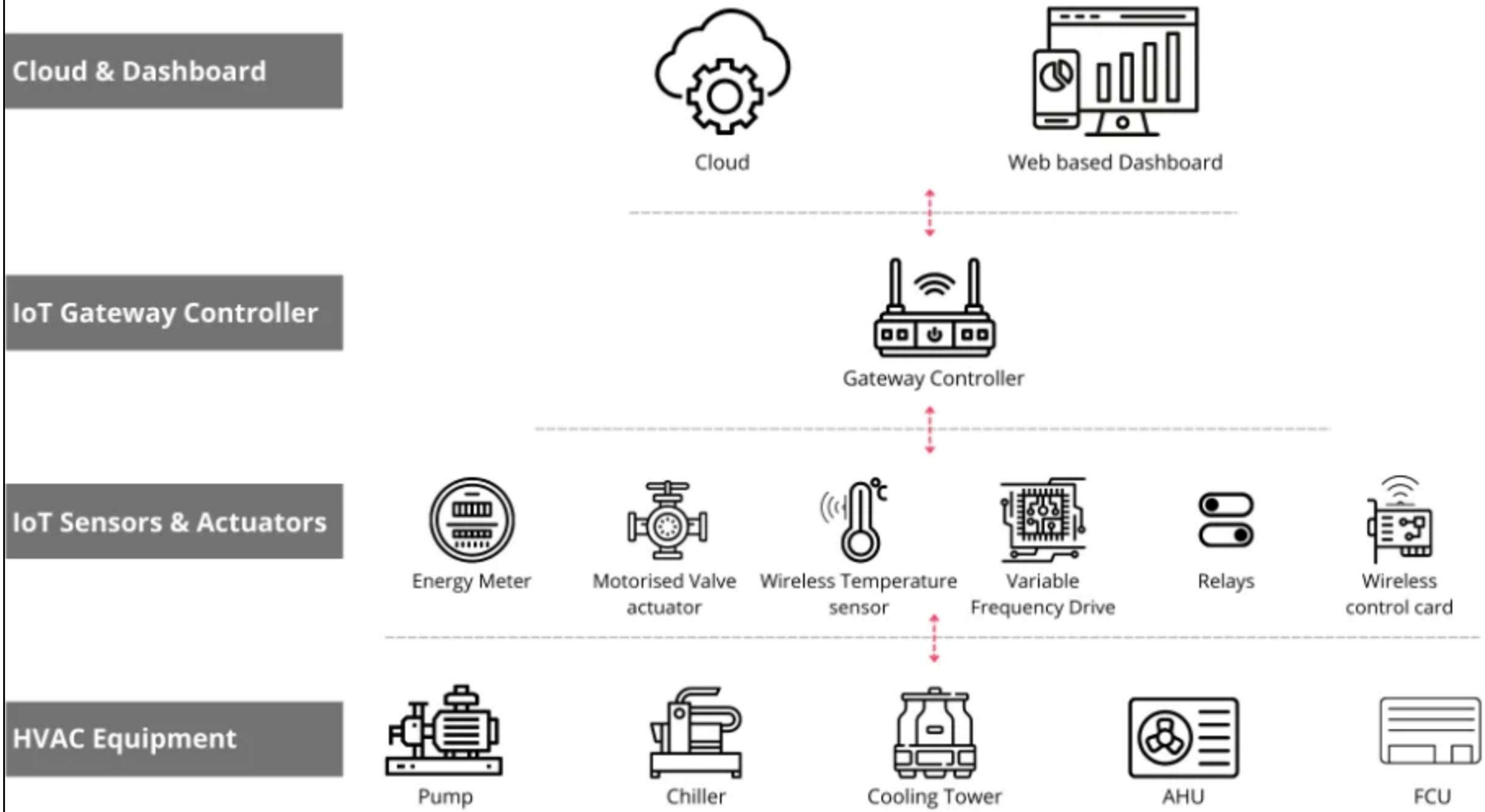
IoT Protocol	Key Features	Suitable For	Bandwidth Efficiency	Interoperability	Application Scale
MQTT	Lightweight, publish-subscribe messaging, low overhead	Resource-constrained devices, limited bandwidth networks	High	Good	Small to large scale
BACnet	Standardized protocol for building automation and control systems	Building automation, seamless integration in commercial buildings	Moderate	Excellent	Medium to large scale
Zigbee	Low-power wireless, reliable communication	Home automation, small-scale smart HVAC applications	Moderate	Good	Small to medium scale
Modbus	Widely used serial communication protocol, robust	Industrial environments, smart HVAC integration	High	Good	Small to large scale
Wi-Fi	High-speed wireless communication	LANs, internet connectivity, remote monitoring	High	Good	Small to large scale

(Source: https://www.dusuniot.com/blog/smart-hvac-iot-technology-and-innovative-design/)

Smart HVAC

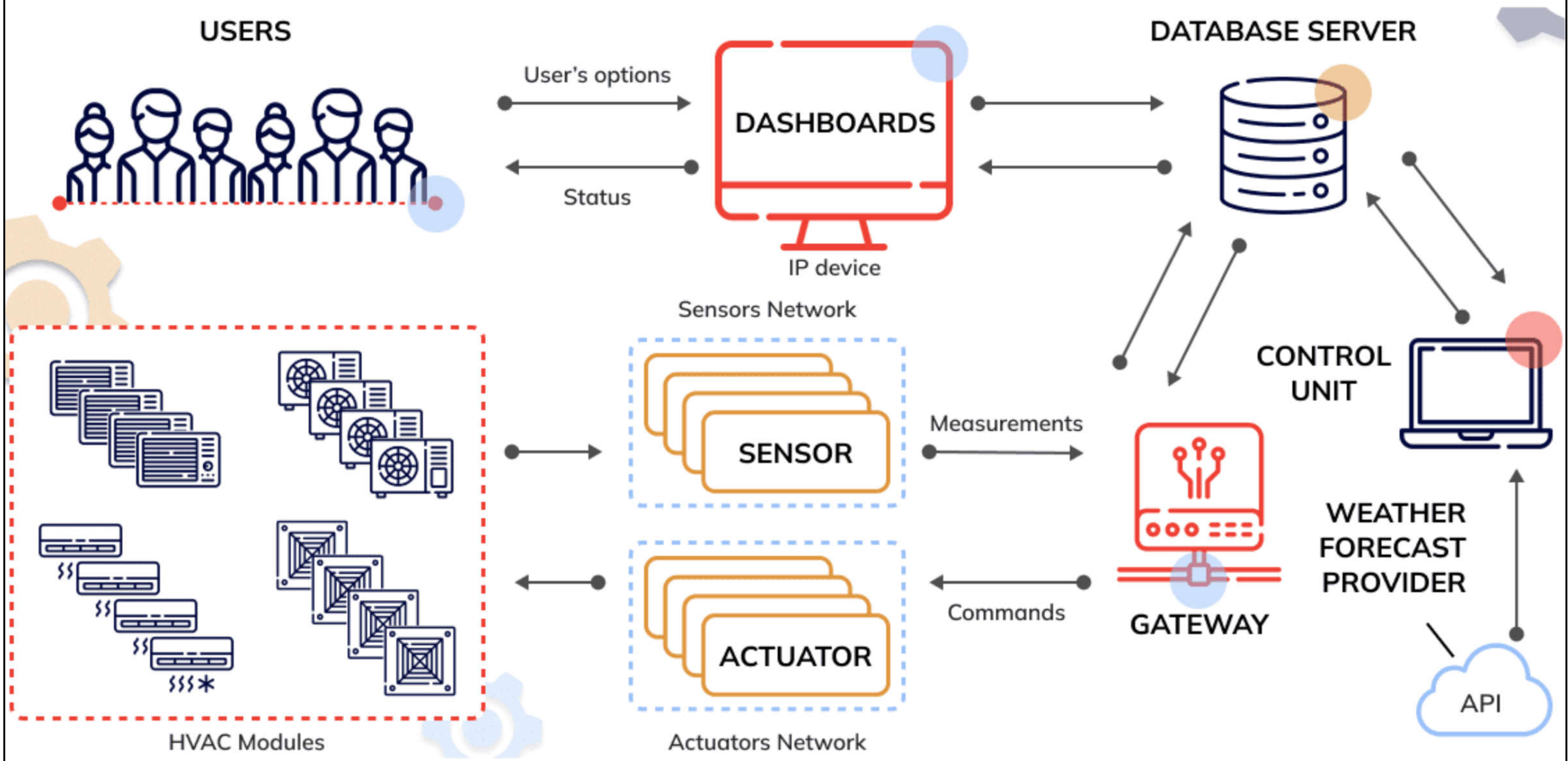
- Smart HVAC for large buildings
  - Cloud service, dashboards & data analytics
  - Real-time monitoring of system performance
  - Use of IoT, AI & machine learning algorithms
  - Automated fault detection & diagnostics (AFDD)
    - Predictive tools to identify faulty equipment & nodal pain points to avoid system failure & costly downtime
  - Integration with lighting controllers, power meters & other building systems

Basic concept & architecture of smart HVAC



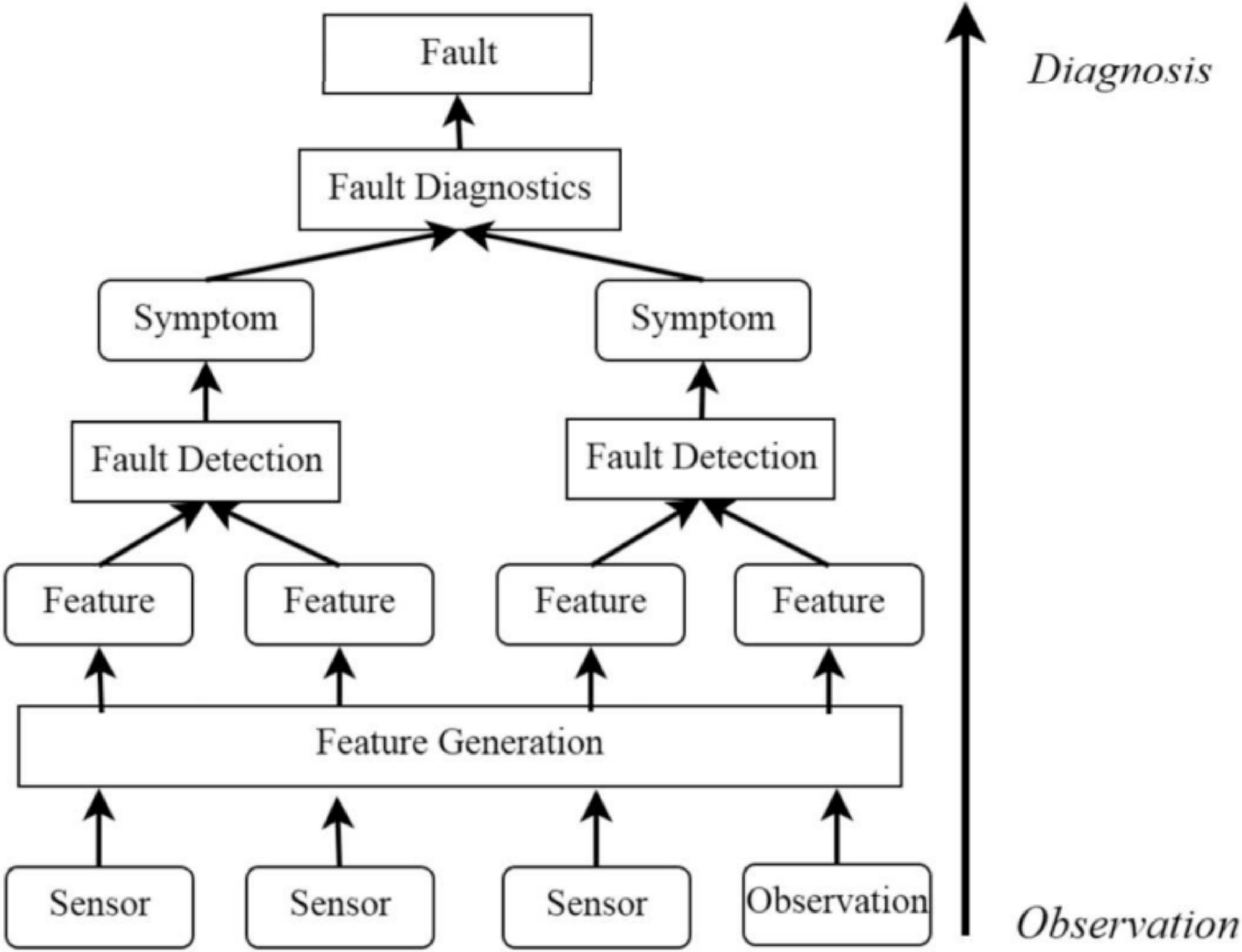
(Source: https://www.dusuniot.com/blog/smart-hvac-iot-technology-and-innovative-design/)

Remote monitoring & control of smart HVAC systems



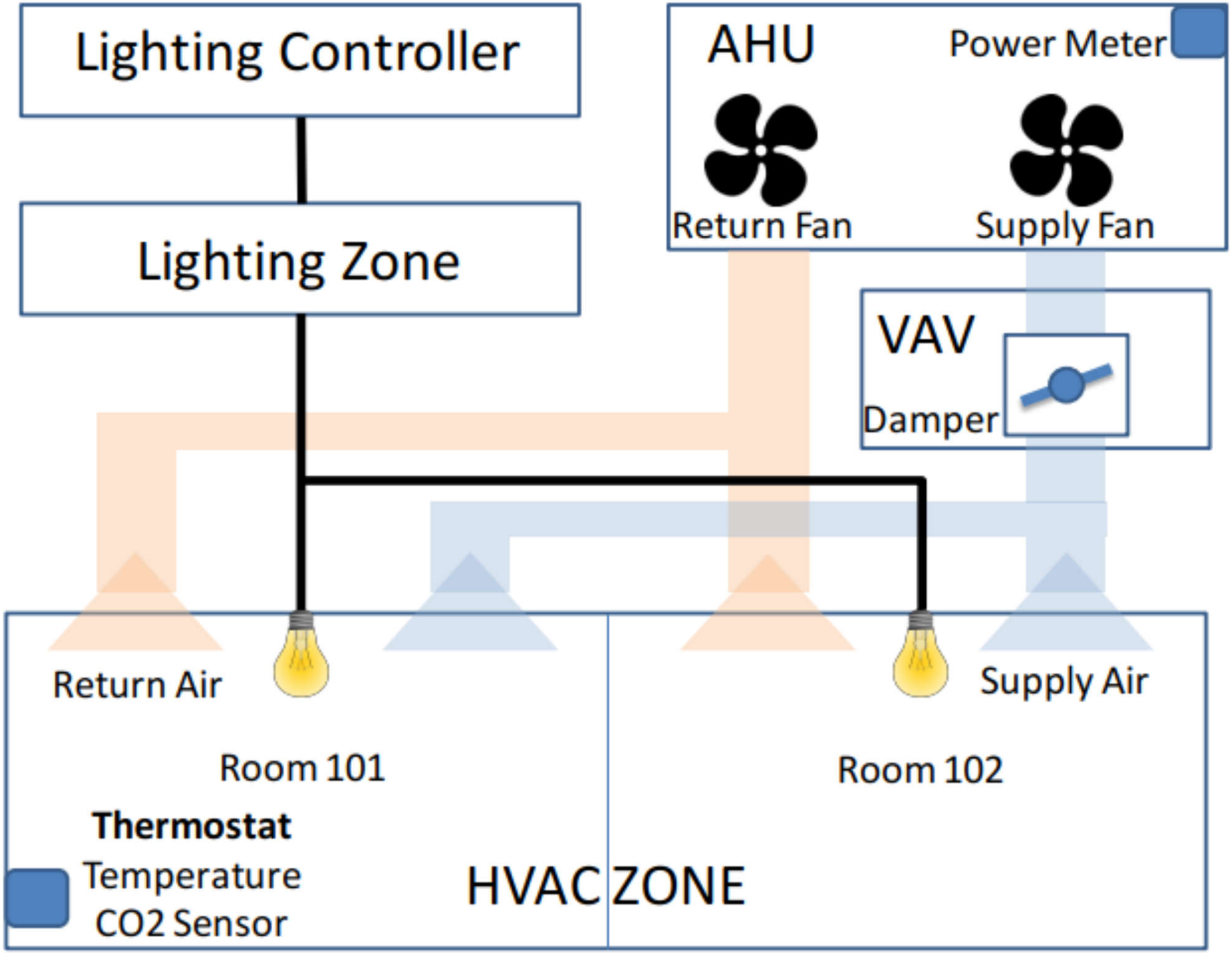
(Source: https://intellisoft.io/how-to-benefit-from-an-iot-solution-for-hvac-tips-tricks/)

Basic concepts of automated fault detection & diagnostics (AFDD)



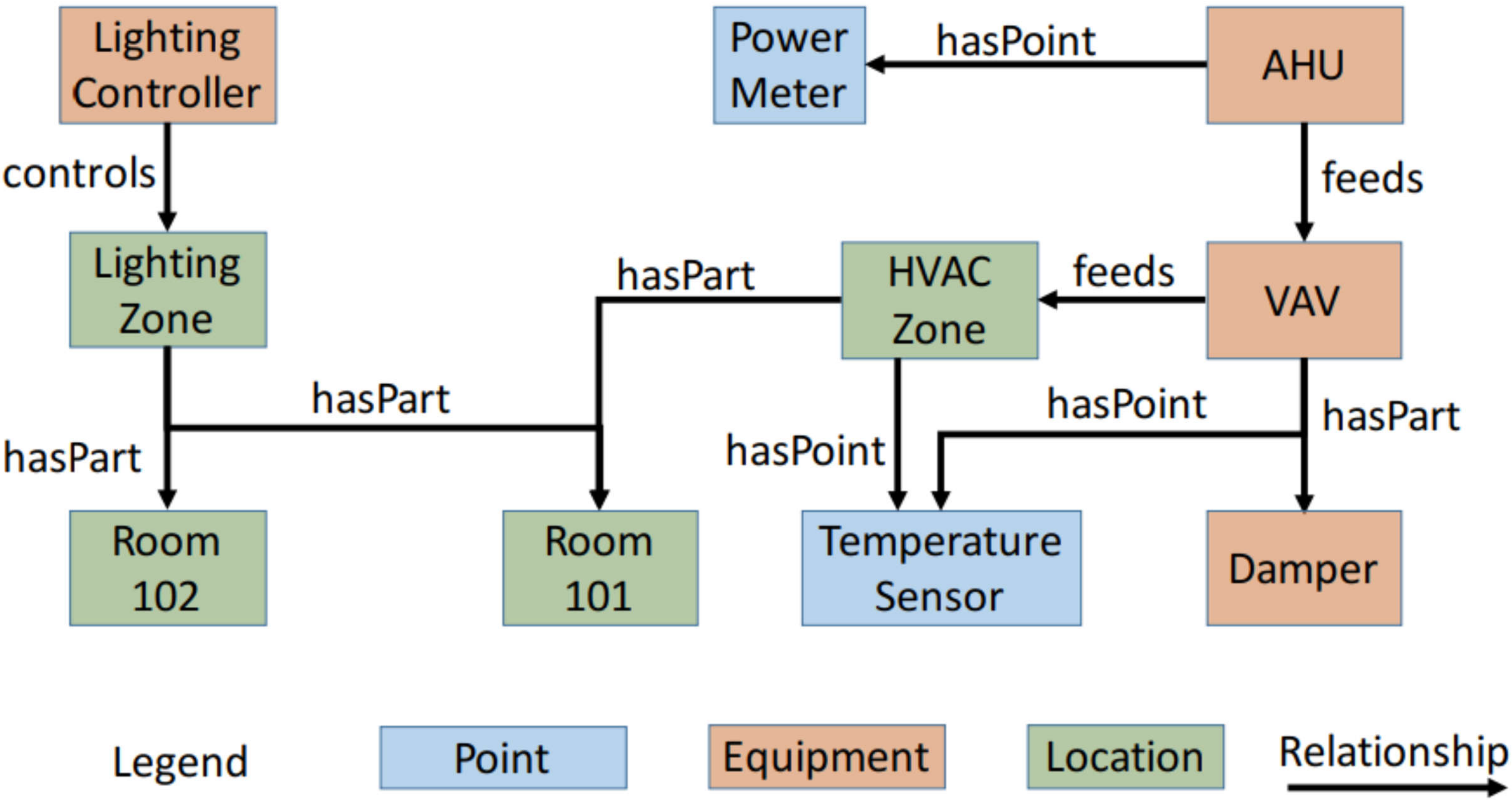
(Source: Shi Z. & O'Brien W., 2019. Development and implementation of automated fault detection and diagnostics for building systems: A review, *Automation in Construction*, 104: 215-229. https://doi.org/10.1016/j.autcon.2019.04.002)

An example building with components of lighting & HVAC systems



(Source: Bhattacharya A., 2016. *Enabling Scalable Smart-Building Analytics*, PhD Thesis in Computer Science, University of California, Berkeley. https://escholarship.org/uc/item/66d3c6rt)

Basic components & relationships for the example building



(Source: Bhattacharya A., 2016. *Enabling Scalable Smart-Building Analytics*, PhD Thesis in Computer Science, University of California, Berkeley. https://escholarship.org/uc/item/66d3c6rt)

Further reading

- Basic HVAC Controls
  https://mepacademy.com/basic-hvac-controls/
- Optimize chiller efficiency with artificial intelligence
  https://www.theclimatedrive.org/action-library/optimise-chiller-efficiency-with-artificial-intelligences
- 5 Benefits of Smart HVAC
  https://www.greencitytimes.com/smart-hvac/