Optimization of HVAC Systems

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

Feb 2024

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- Basic concepts
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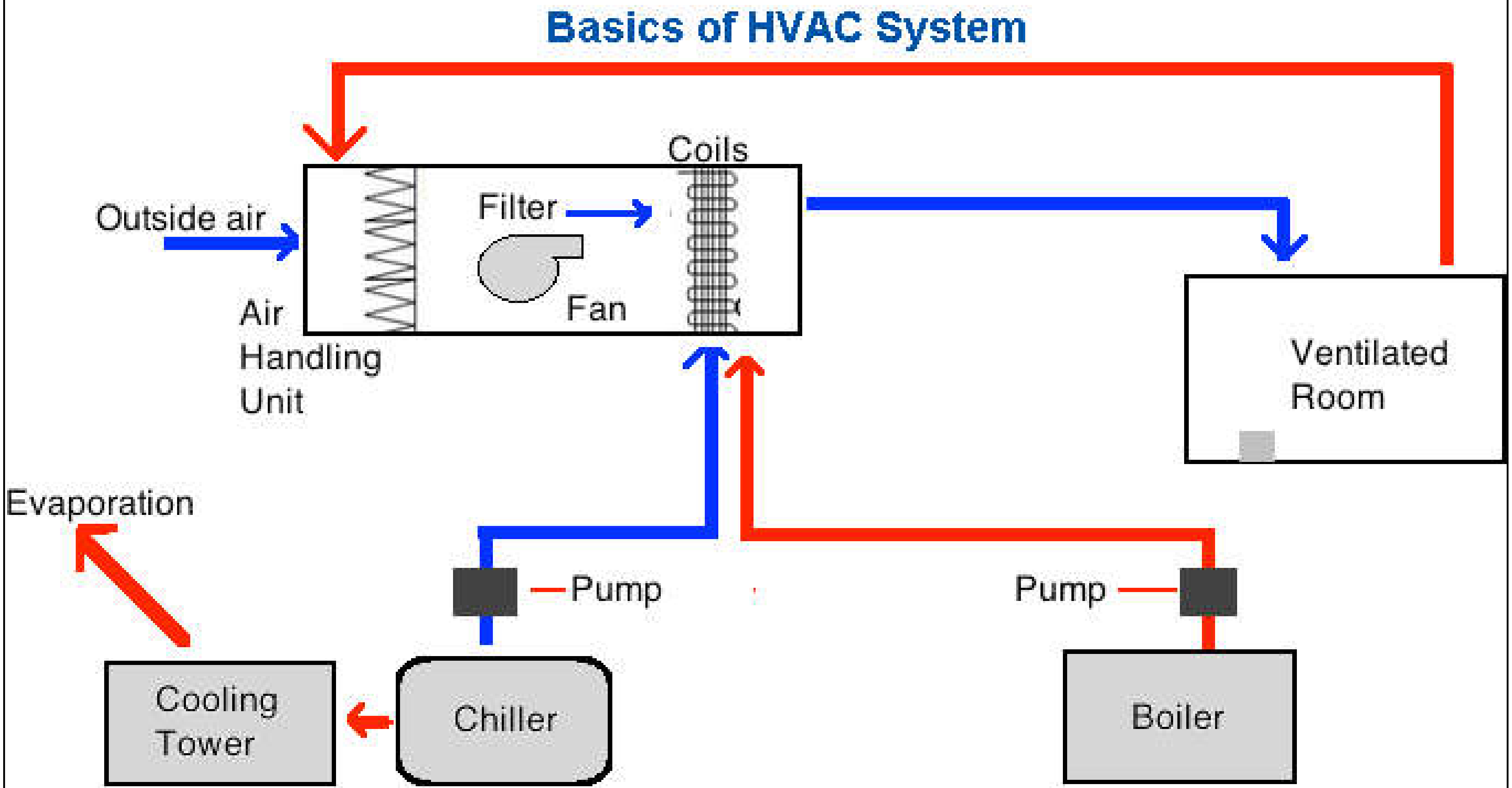
Basic concepts

- 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

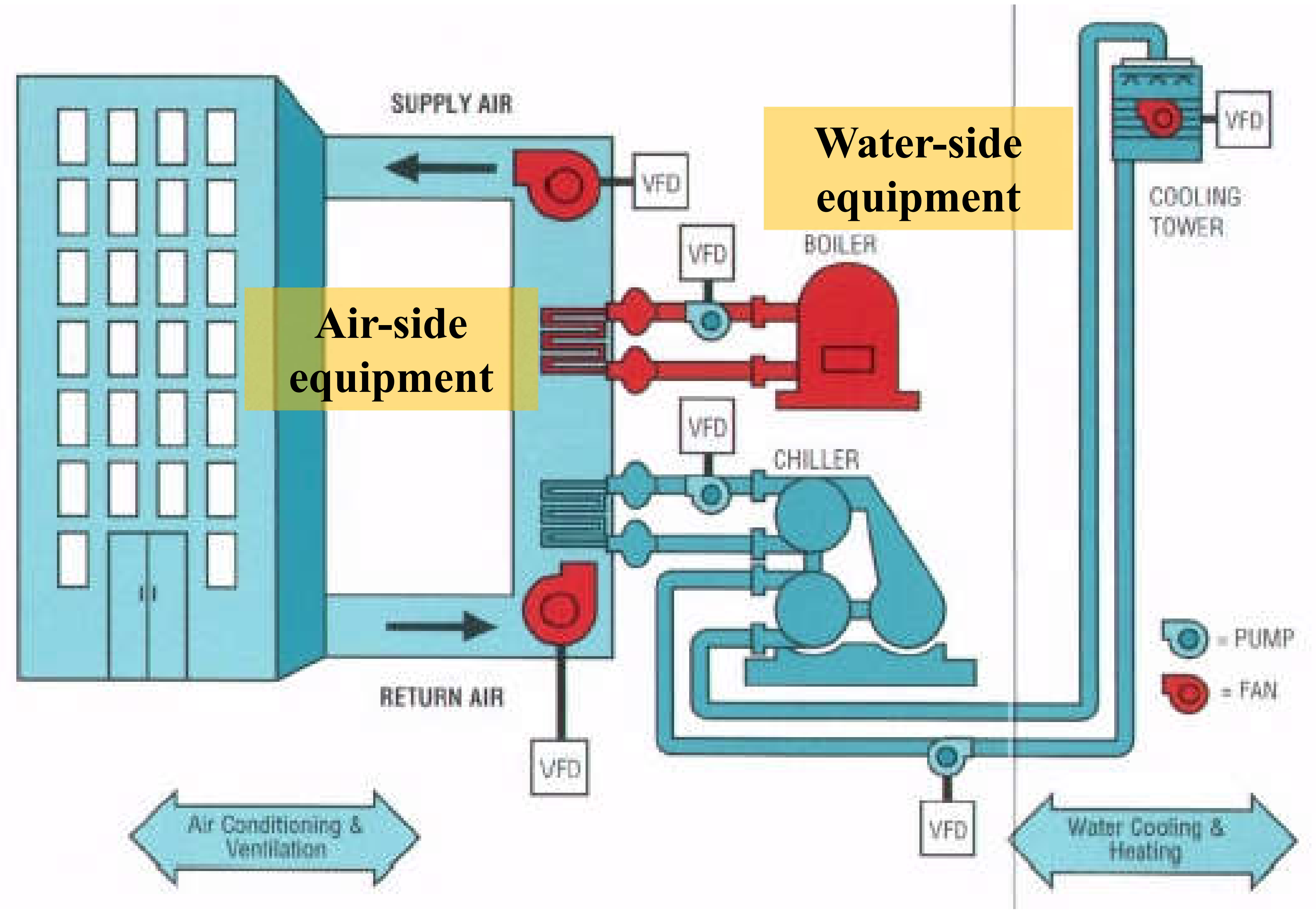
Using BAS to control major HVAC systems & equipment

[Source: Johnson Controls]

Basic concepts

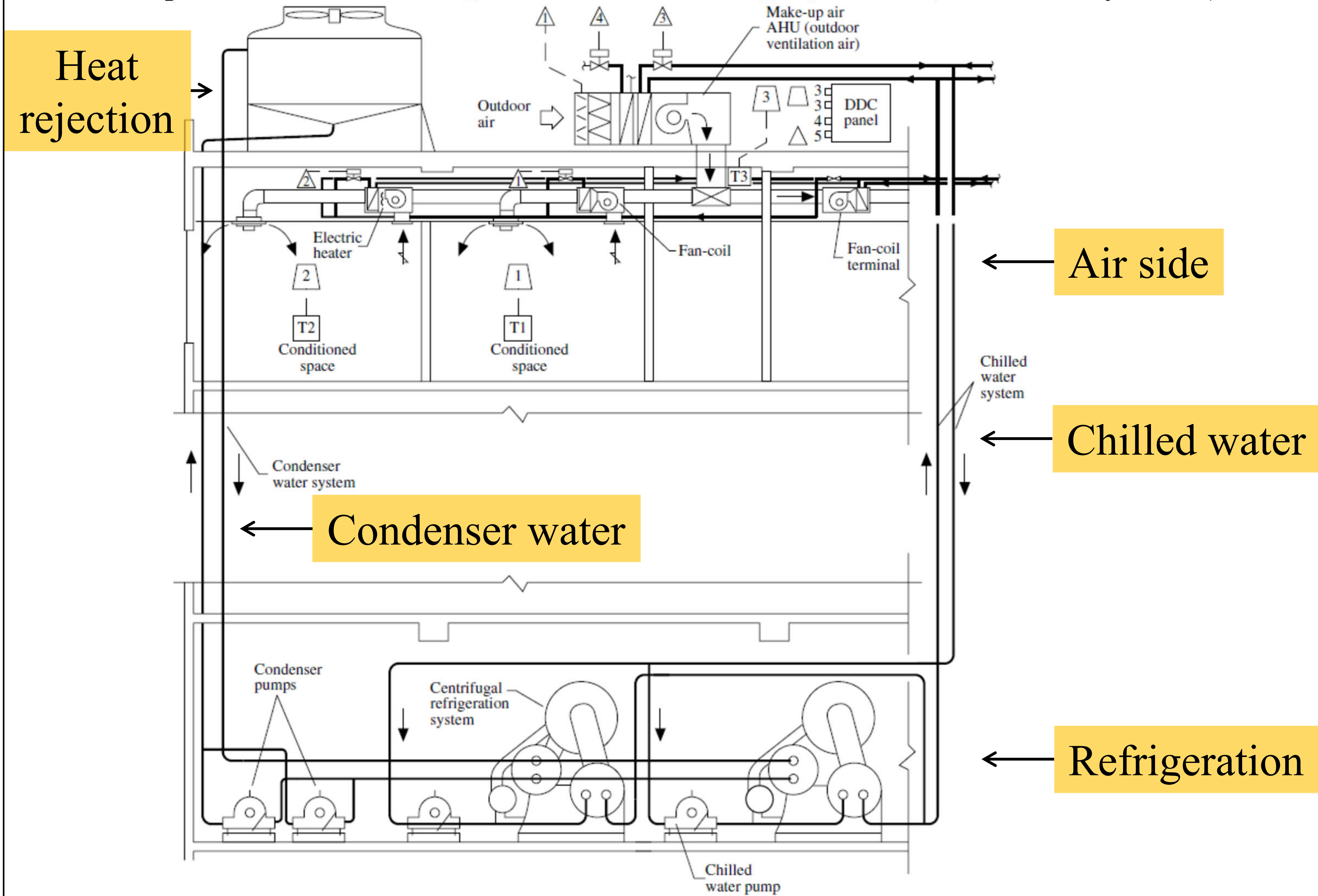
- HVAC sub-systems & components:
  - 1. Air-side (e.g. fans, air duct)
  - 2. Water-side (e.g. pumps, piping)
    - Chilled water, condenser water, seawater, etc.
  - 3. Refrigeration equipment
  - 4. Heat rejection (e.g. cooling towers)
  - 5. Controls
- Including centralised, partially centralised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

Example of a centralised HVAC system



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

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

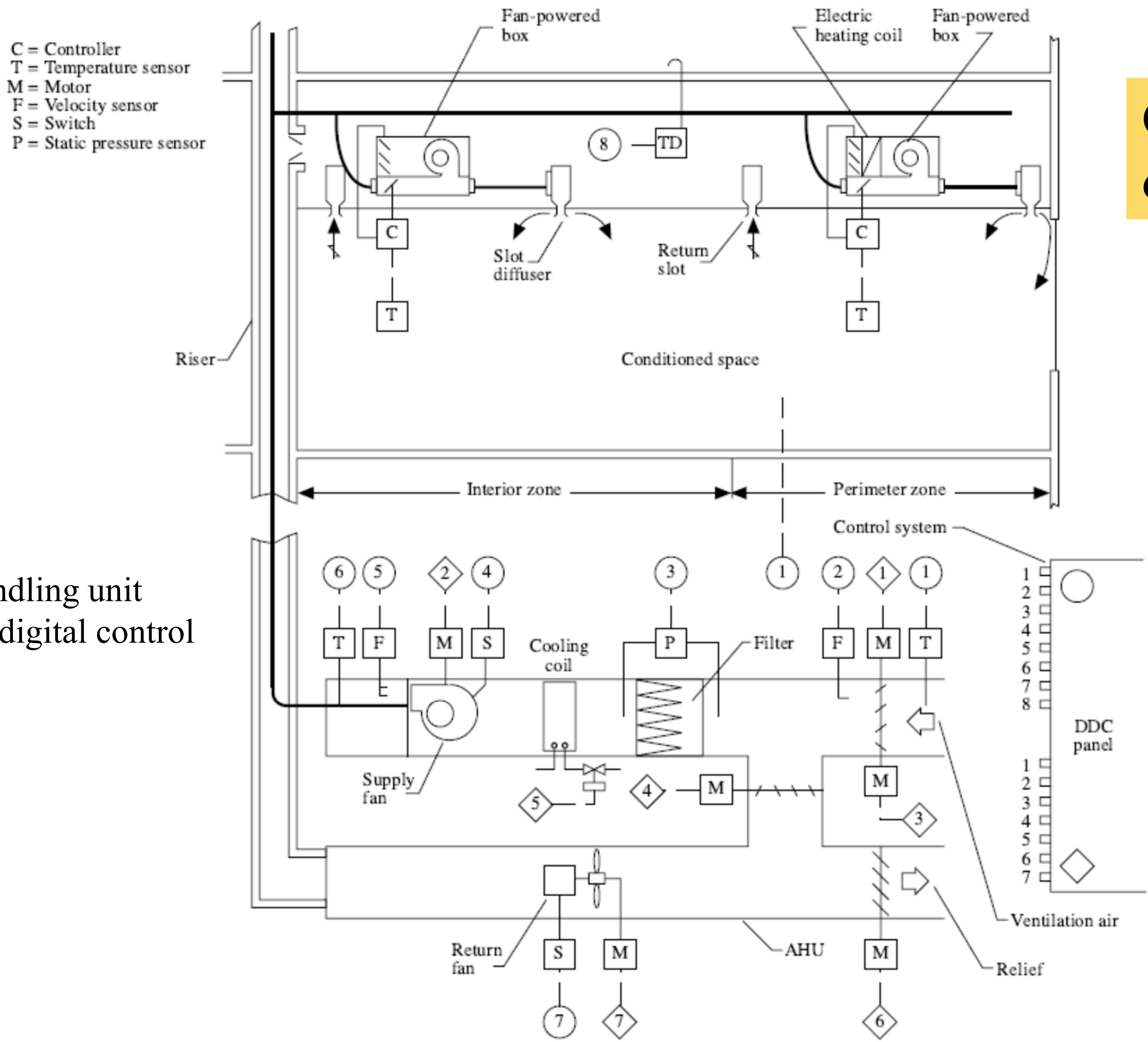


(Source: Wang, S. K., Lavan, Z. and Norton, P., 2000. *Air Conditioning and Refrigeration Engineering*)

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



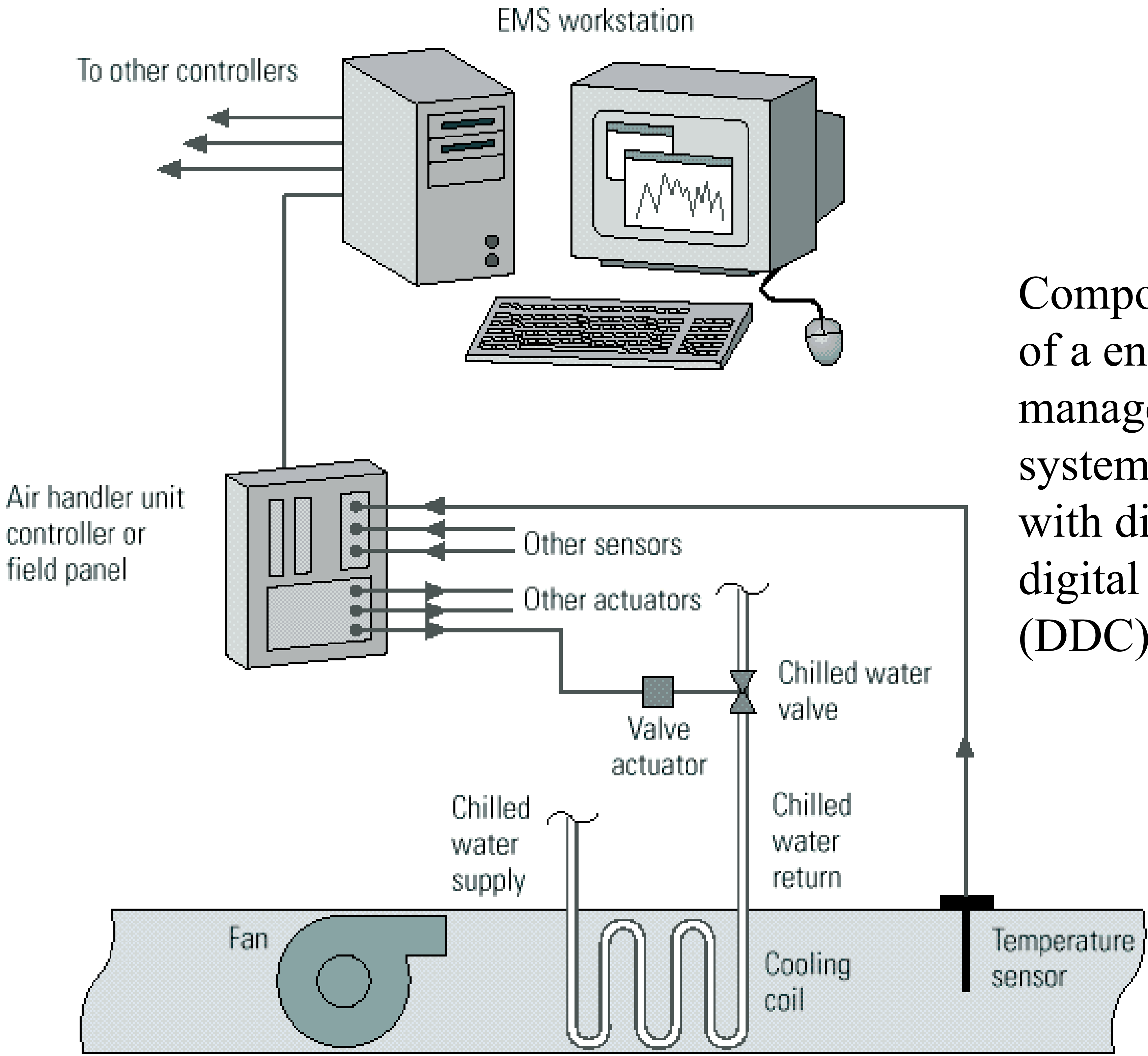
Control diagram

AHU = air handling unit
DDC = direct digital control

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

HVAC DDC system

- 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

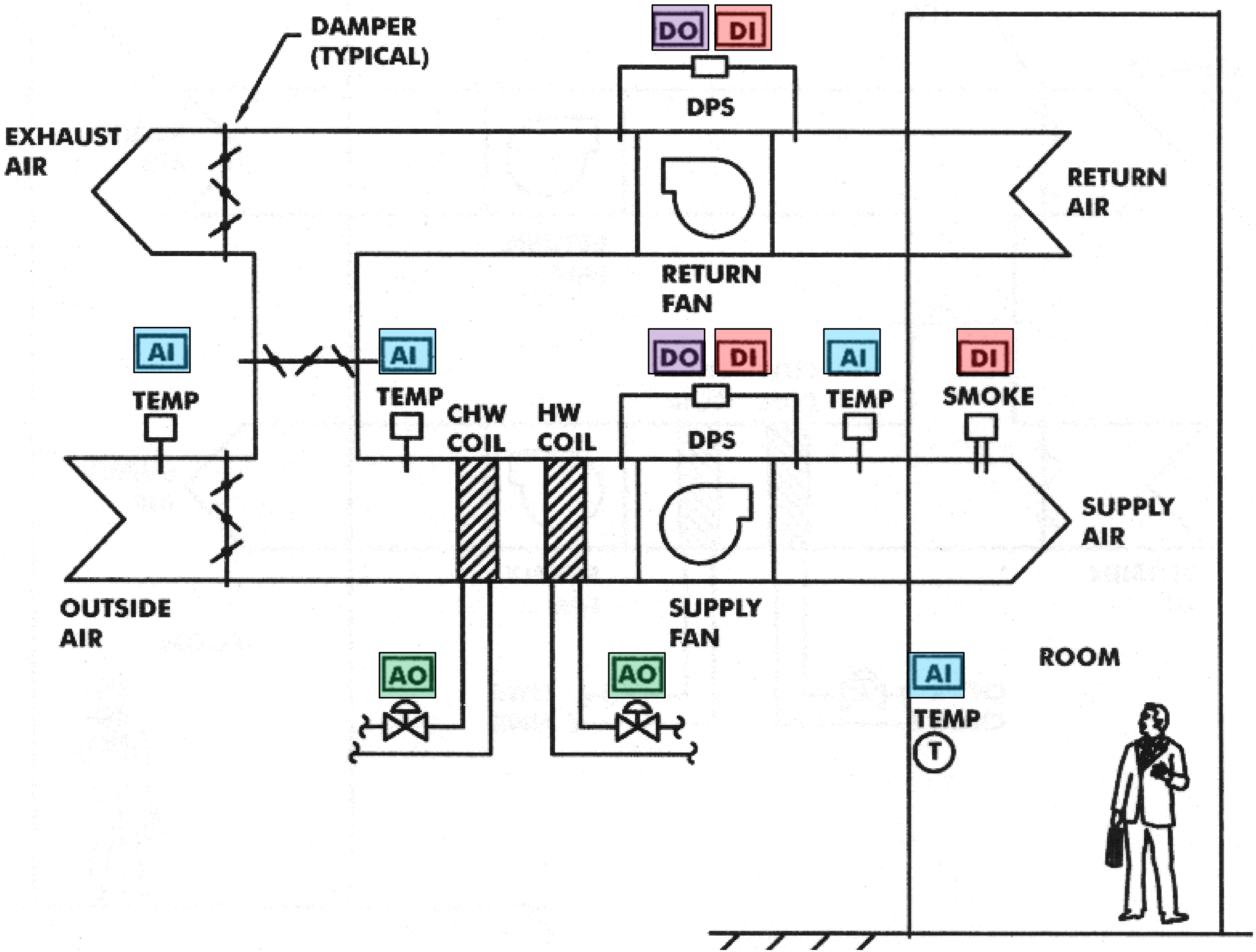


Components of a energy management system (EMS) with direct digital control (DDC)

HVAC DDC system

- Design an effective direct digital control (DDC) system
  - Simplicity & effective technical communication
- Types of DDC signals:
  - Digital output (DO), e.g. command to open a valve
  - Digital input (DI), e.g. status signal from a fan
  - Analogue input (AI), e.g. room temperature
  - Analogue output (AO), e.g. command to modulate a control valve

Control point designations for a constant volume single zone AHU



[Source: Shadpour, F., 2001. *The Fundamentals of HVAC Direct Digital Control*]

An example of a DDC point list

Point List					
Point	**DO**	**DI**	**AI**	**AO**	**Remarks**
Supply fan	1	1			
Return fan	1	1			
Duct temperature sensors			3		
Chilled and hot water valves				2	
Room temperature sensor			1		
Smoke detector		1			
Total	2	3	4	2	

Table 1-1: An example of a point list. The purpose of a point list is to identify the total number of each point category.

[Source: Shadpour, F., 2001. *The Fundamentals of HVAC Direct Digital Control*]

Example of point list for a variable air volume (VAV) terminal unit

	Hardware Points				Software Points						
Point Name	**AI**	**AO**	**BI**	**BO**	**AV**	**BV**	**Loop**	**Sched**	**Trend**	**Alarm**	**Show On Graphic**
Zone Temp	x								x		x
Zone Setpoint Adjust	x										x
Airflow	x								x		x
Zone Damper		x									x
Zone Override			x						x		x
Airflow Setpoint					x				x		x
Heating Mode						x			x		
Schedule								x			
Heating Setpoint									x		x
Cooling Setpoint									x		x
High Zone Temp										x	
Low Zone Temp										x	
Totals	**3**	**1**	**1**	**0**	**1**	**1**	**0**	**1**	**7**	**2**	**8**

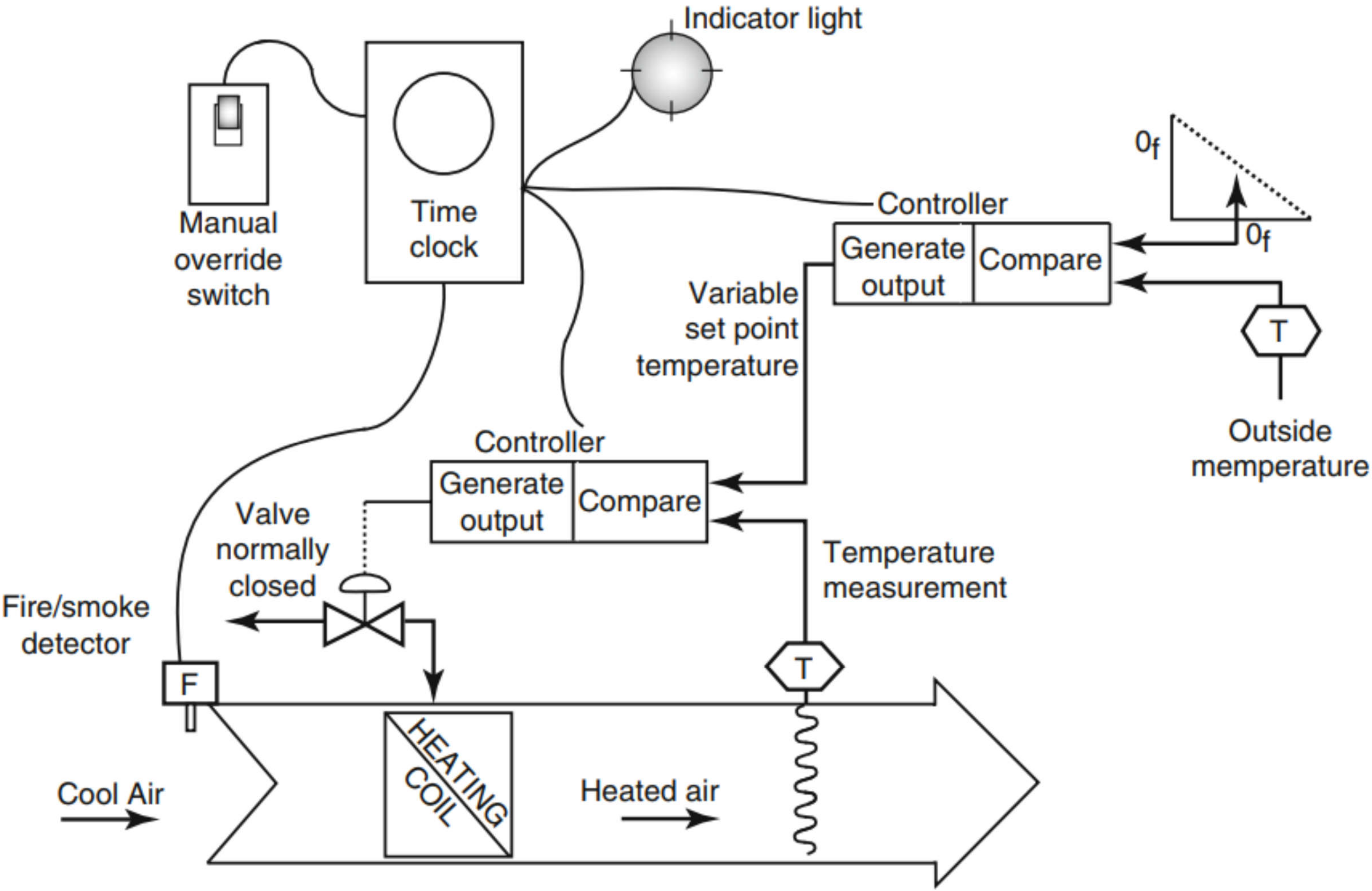
Total Hardware (5) **Total Software (12)**

AI = Analogue input
AO = Analogue output
BI = Binary (Digital) input
BO = Binary (Digital) output

AV = Analogue value
BV = Binary value
Sched = Schedule
Trend = Trend log

(Source: https://guidelines.vancouver.ca/guidelines-technical-direct-digital-control-systems-hvac.pdf)

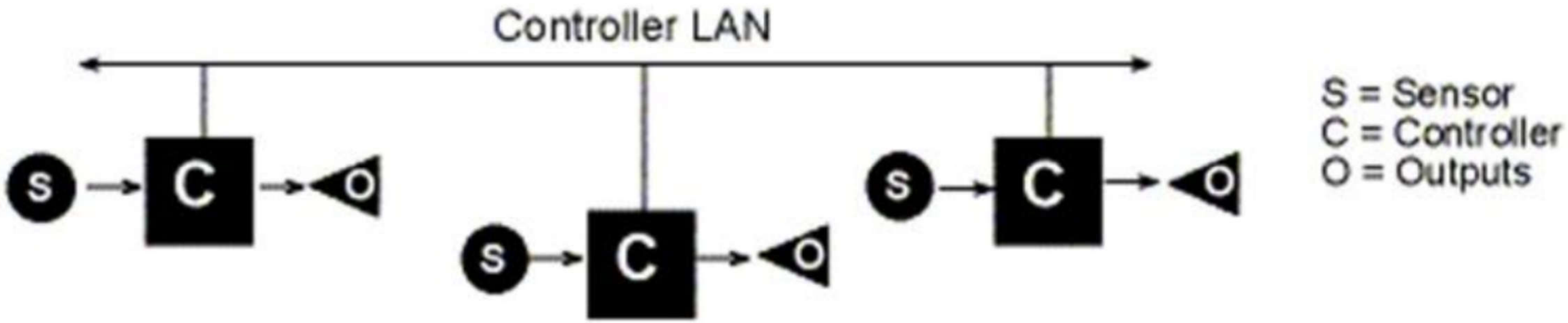
DDC control for an air heater with outdoor reset



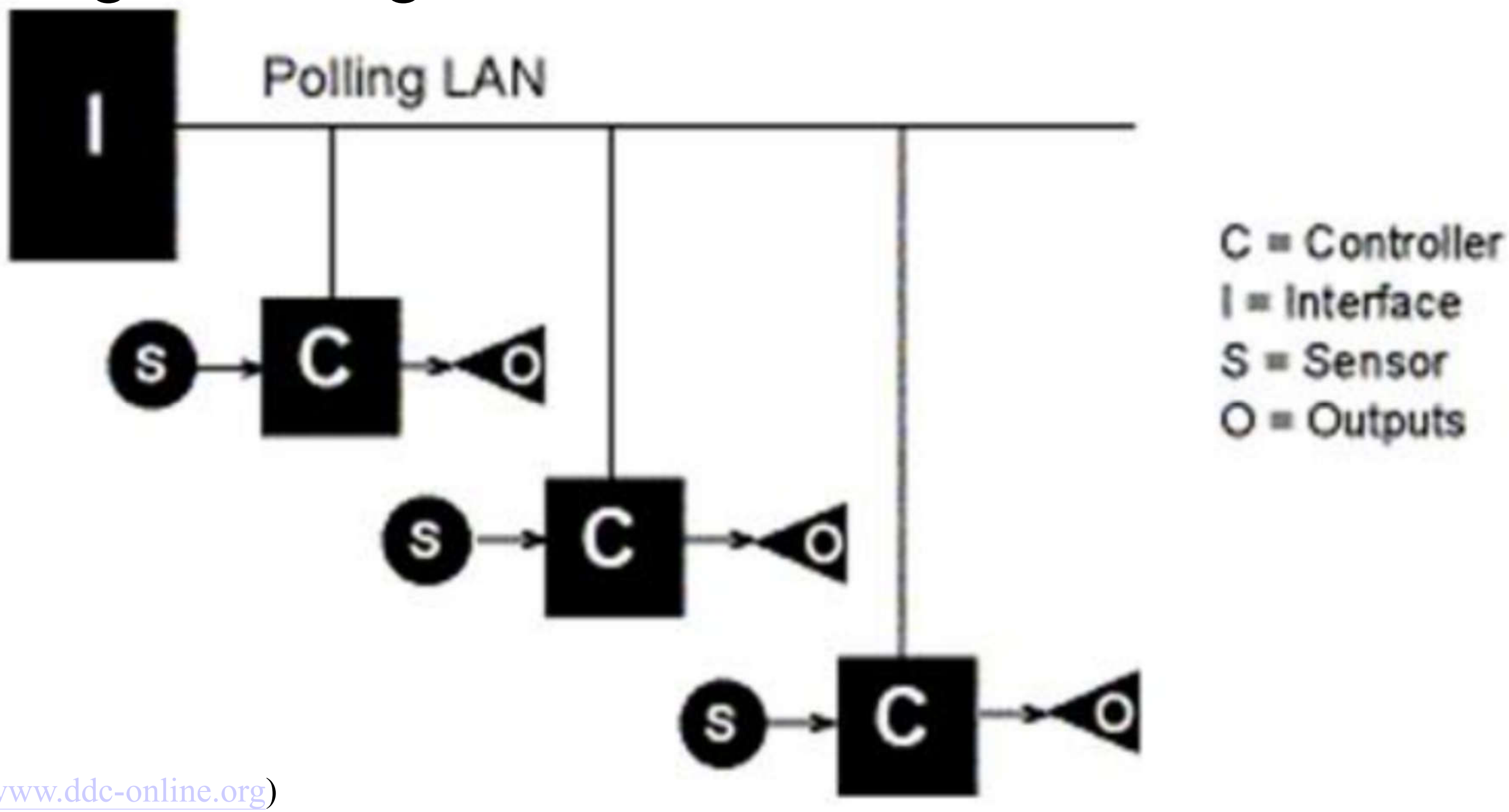
[Source: McDowall R. & Montgomery R., 2011. *Fundamentals of HVAC Control Systems*]

DDC networks – LAN configurations

(a) Peer-to-peer LAN diagram

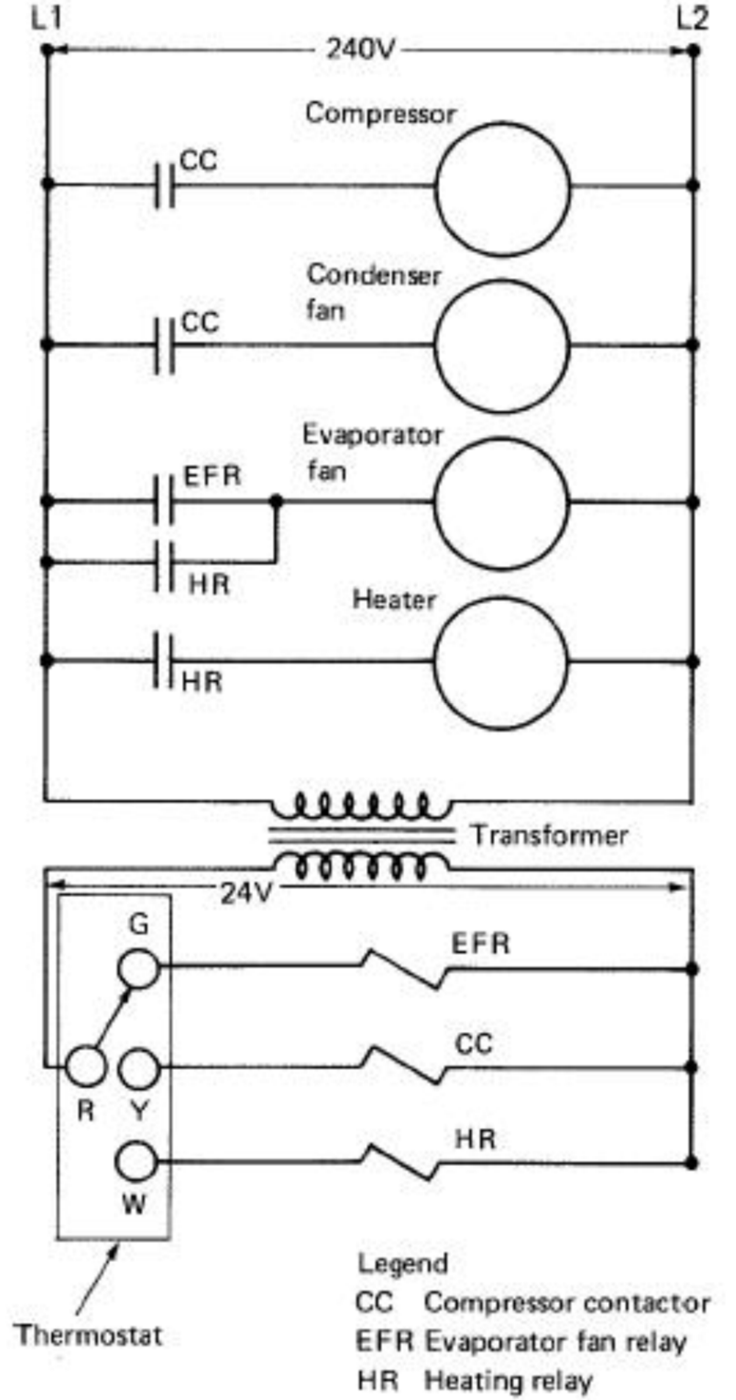


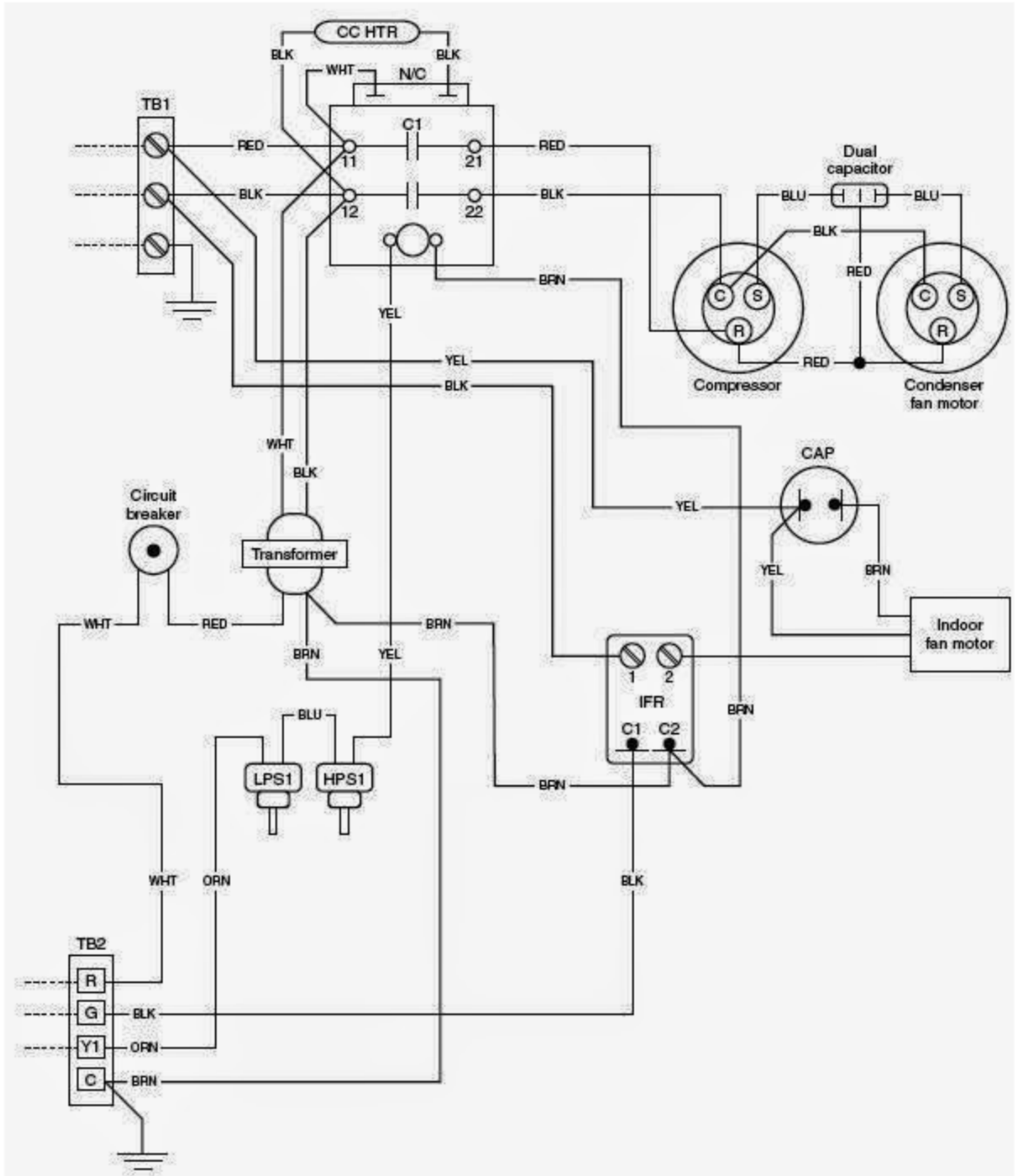
(b) Polling LAN diagram



(Source: http://www.ddc-online.org)

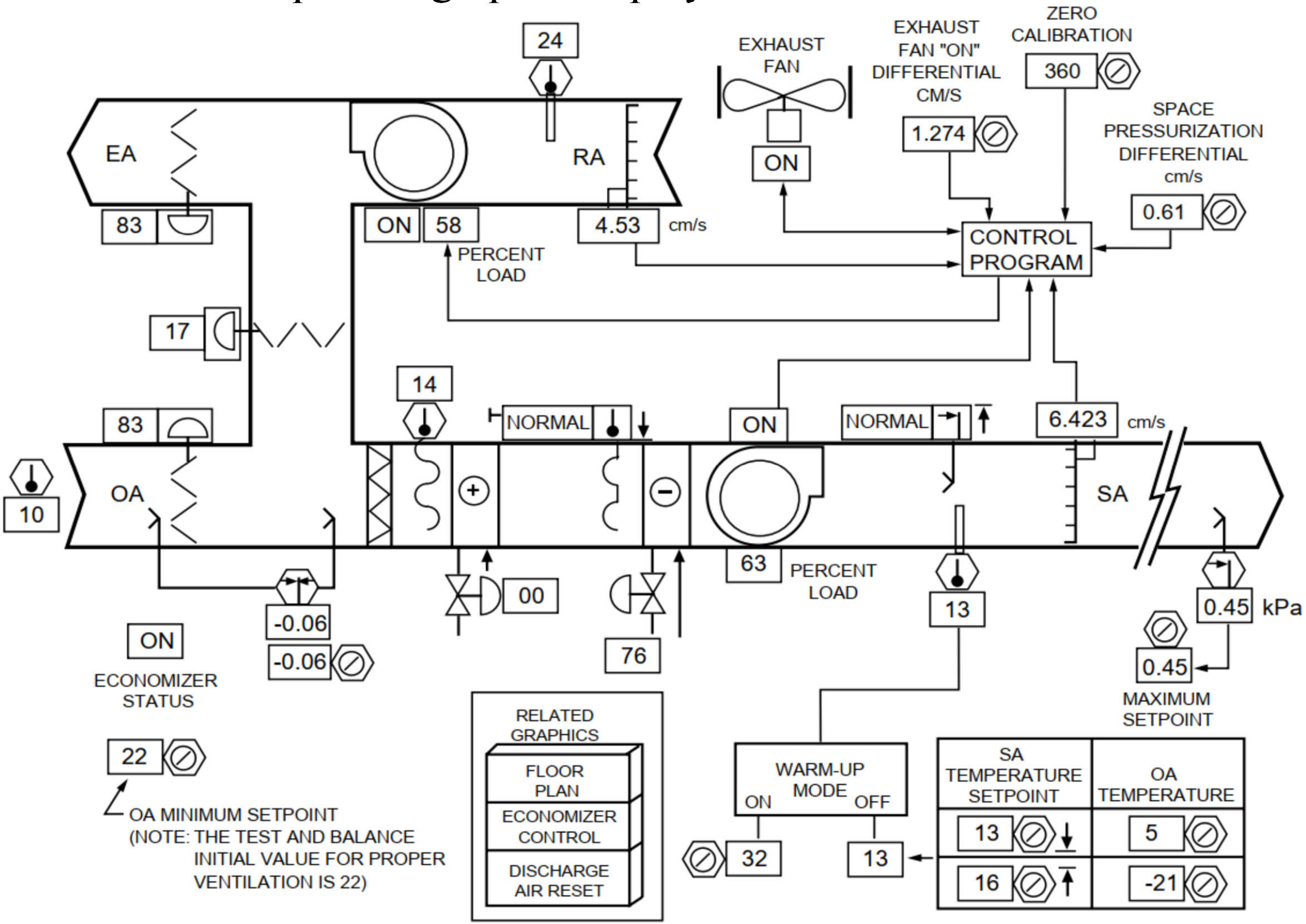
Examples of ladder & line diagrams for HVAC systems





[Source: http://www.electrical-knowhow.com/2014/05/How-to-read-Electrical-Wiring-Diagrams.html]

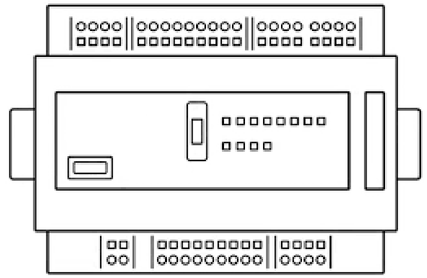
Operator graphic display for HVAC control

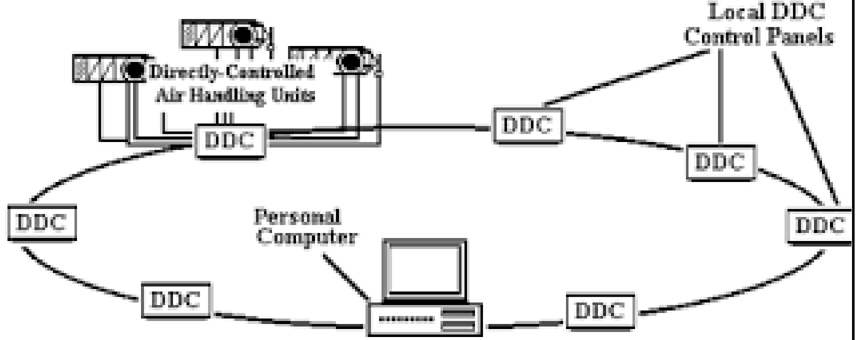


[Source: Honeywell, 1997. *Engineering Manual of Automatic Control for Commercial Buildings*]

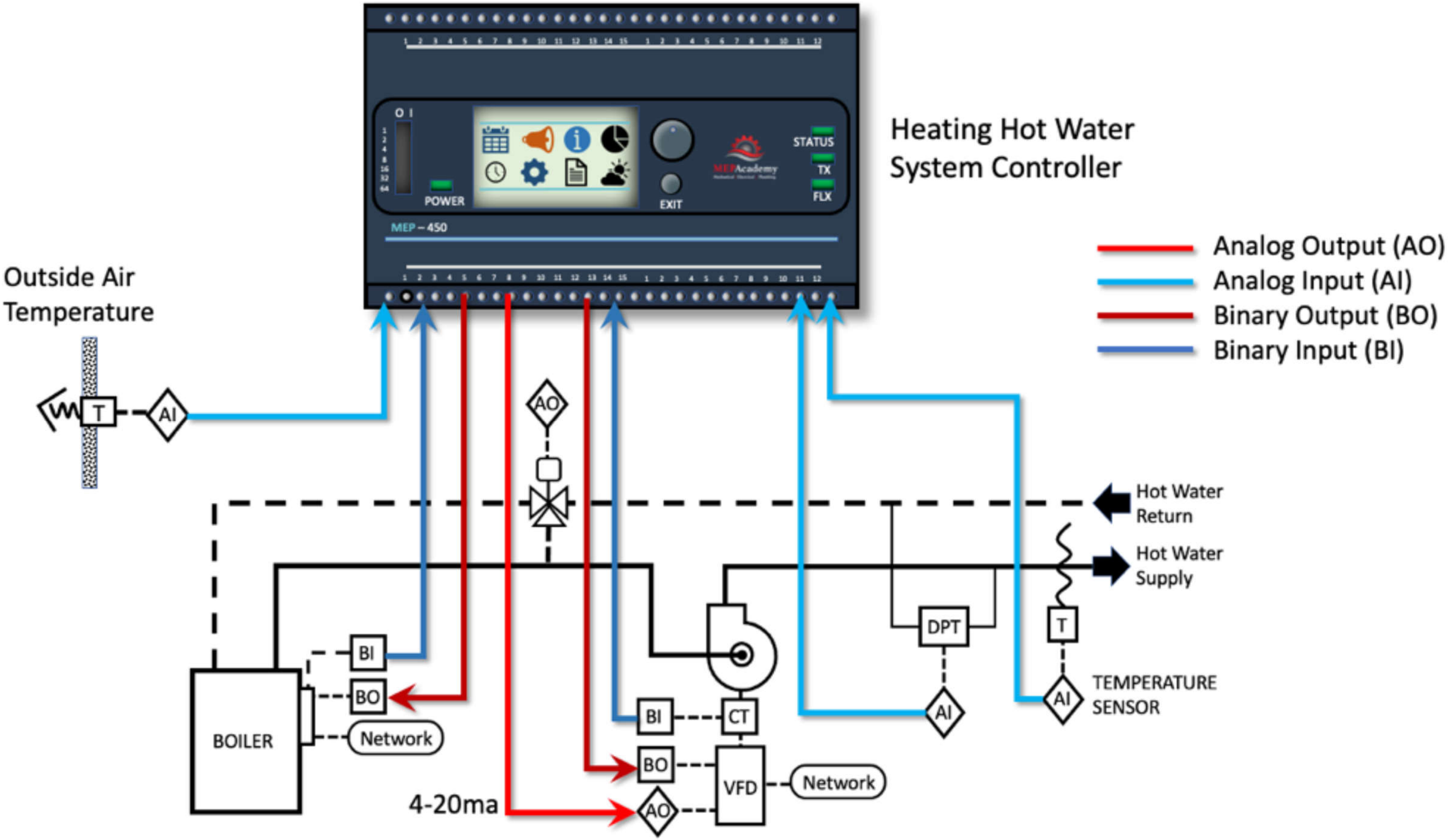
DDC controllers

- DDC controller or control panel
  - The "brain" of the system
  - Main components:
    - Power supply
    - Central processing unit (CPU)
    - Terminal board or module
    - Communication board or module
    - Battery back-up
    - Gateways, bridges, routers & repeaters





HVAC DDC controller for a heating hot water boiler system

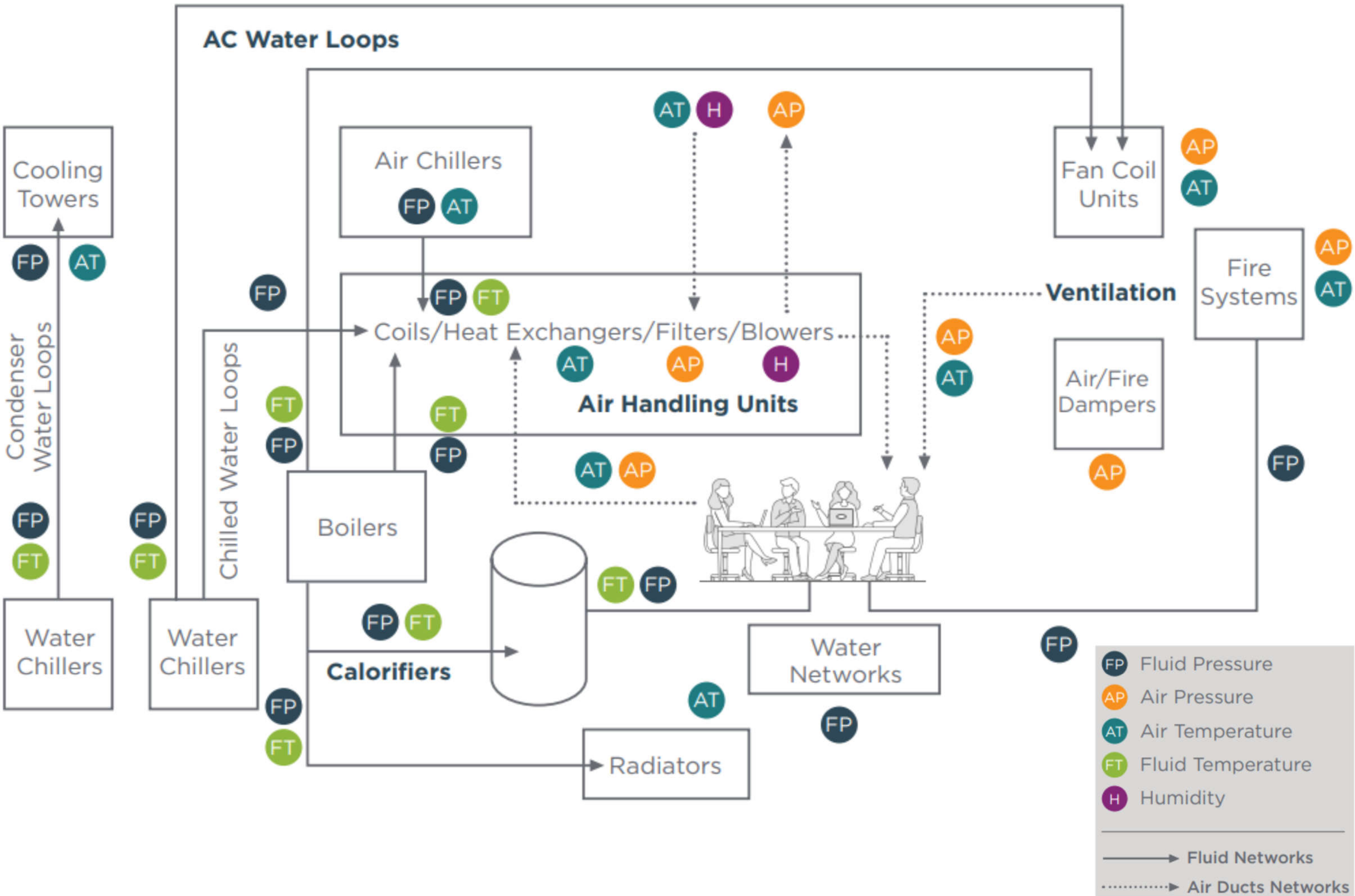


(Source: https://mepacademy.com/6-steps-for-designing-hvac-ddc-controls/)

DDC controllers

- External components
  - Uninterruptable power supply (UPS)
  - Operator/human machine interface (OMI/HMI)
    - Human-machine or person-machine interface
    - A monitor & a keyboard or a personal computer
  - Smart sensors & actuators
    - Temperature, humidity & pressure sensors
    - Contain intelligence & some form of control capability
    - May transmit/receive signal directly to/from the network

Sensors for building automation system (BAS)



(Source: TE Connectivity)

DDC controllers

- Classification of DDC controllers
  - Unit level: unitary, zone level, application specific
    - Small size, limited points & non-expandable, less costly
  - Equipment level: equipment, system level
    - Larger size, adequate points for a range of applications
  - Plant level: more than one equipment
    - Much larger size & more point count, programming
  - Building level (network)
    - A system level router, handle high-speed network traffic

[Source: https://www.automatedbuildings.com/news/apr08/columns/080325113602calabrese.htm]

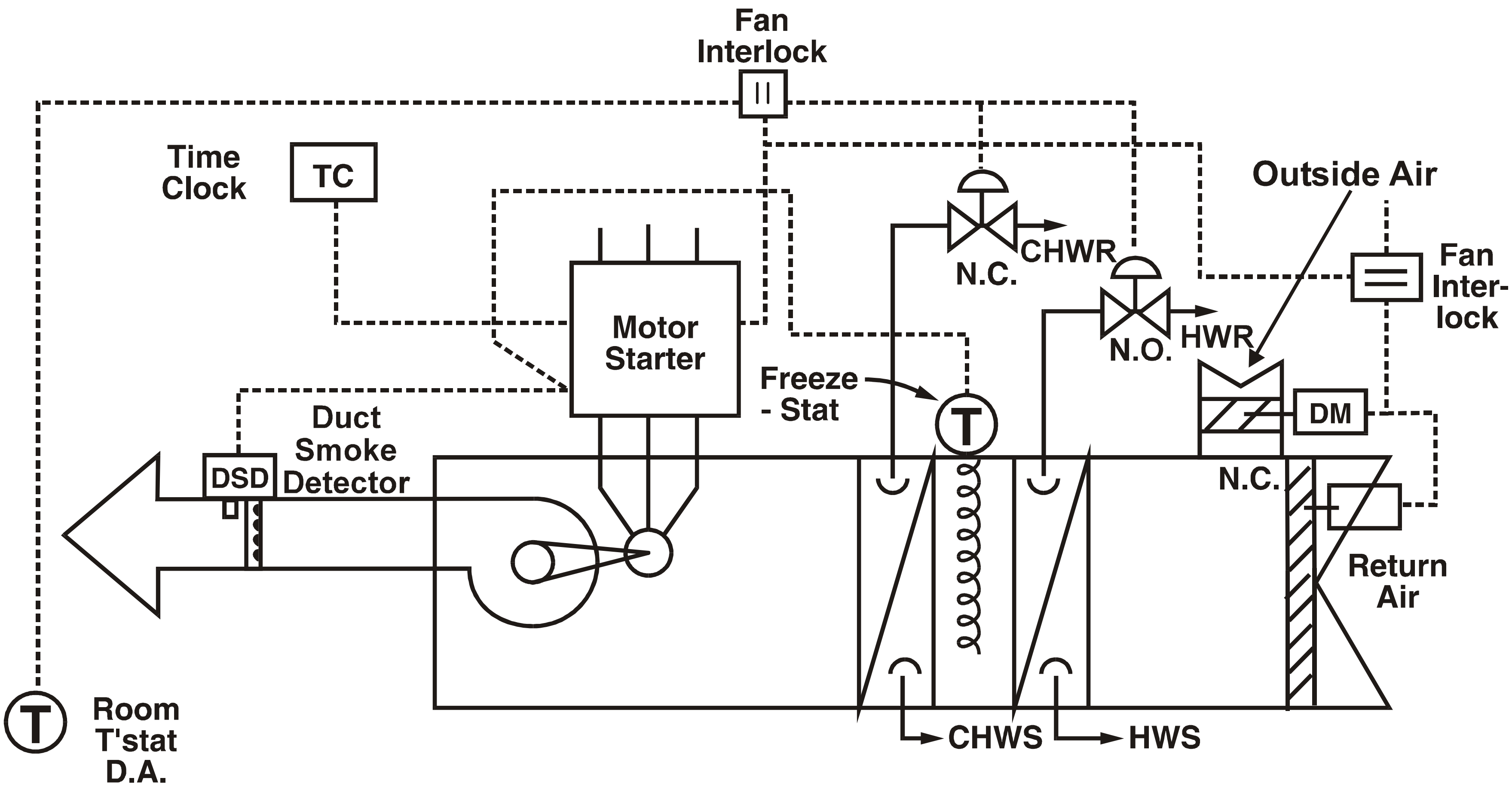
DDC controllers

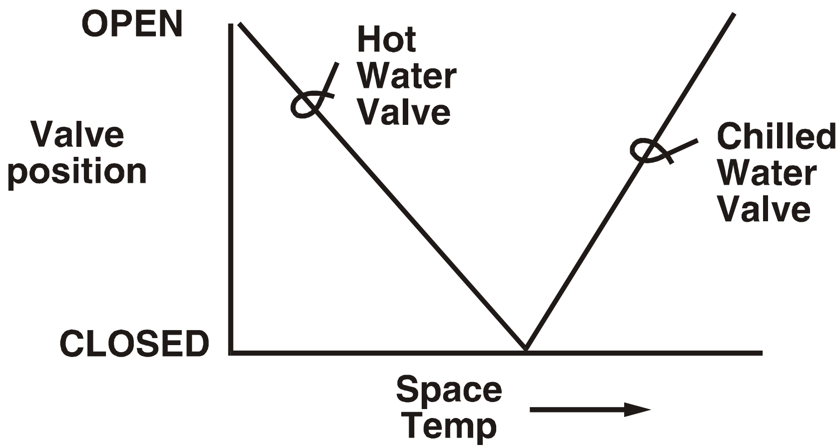
- DDC controller software
  - The software determines the functionality
  - Two categories of controller software:
    - 1. <u>Operating software</u>: controls the basic operation of the controller; normally stored in non-volatile memory e.g. ROM (read-only memory), as firmware
    - 2. <u>Application software</u>: addresses the unique control requirements of specific applications e.g. energy management, lighting control, event initiated programs plus other alarm & monitoring functions; using different programming languages
  - May also integrate Supervisory Control and Data Acquisition (SCADA) package for real-time monitoring

HVAC control examples

- Examples of HVAC control applications:
  - Typical single-zone air handler
    - Single-zone unit with dual setpoint thermostat
  - Typical variable air volume (VAV) system
    - Chilled water, economizer & hot water sequencing
    - VAV box control
  - Typical constant air volume (CAV) system
  - Chillers, pumps & boilers – monitoring & control
  - Direct expansion (DX) systems & heat pumps

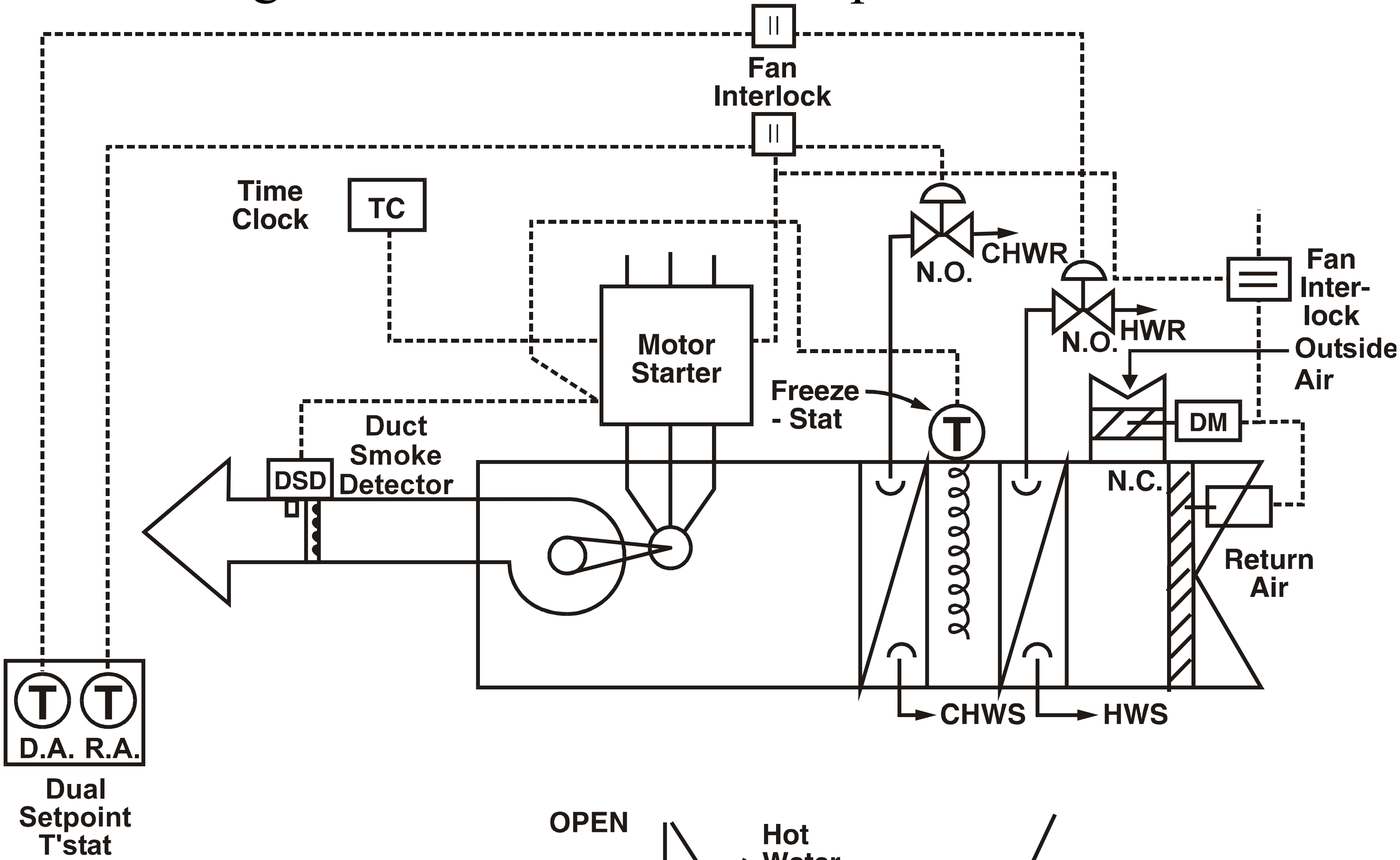
Typical single-zone air handler



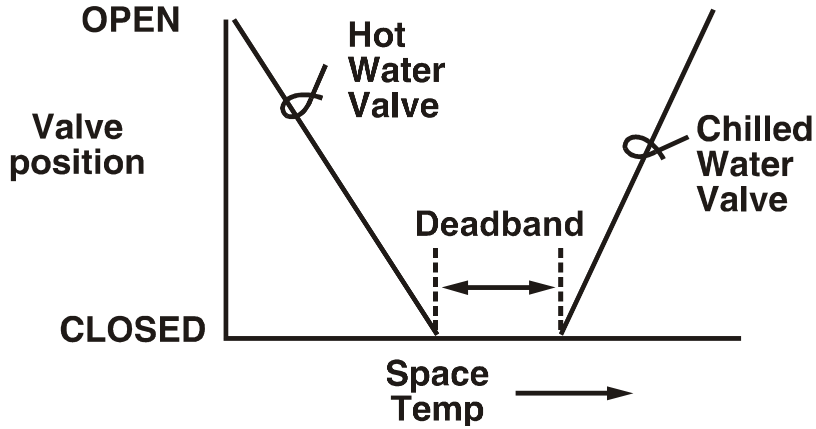


[Source: Montgomery, R. and McDowall, R., 2008. *Fundamentals of HVAC Control Systems*]

Single-zone unit with dual setpoint thermostat

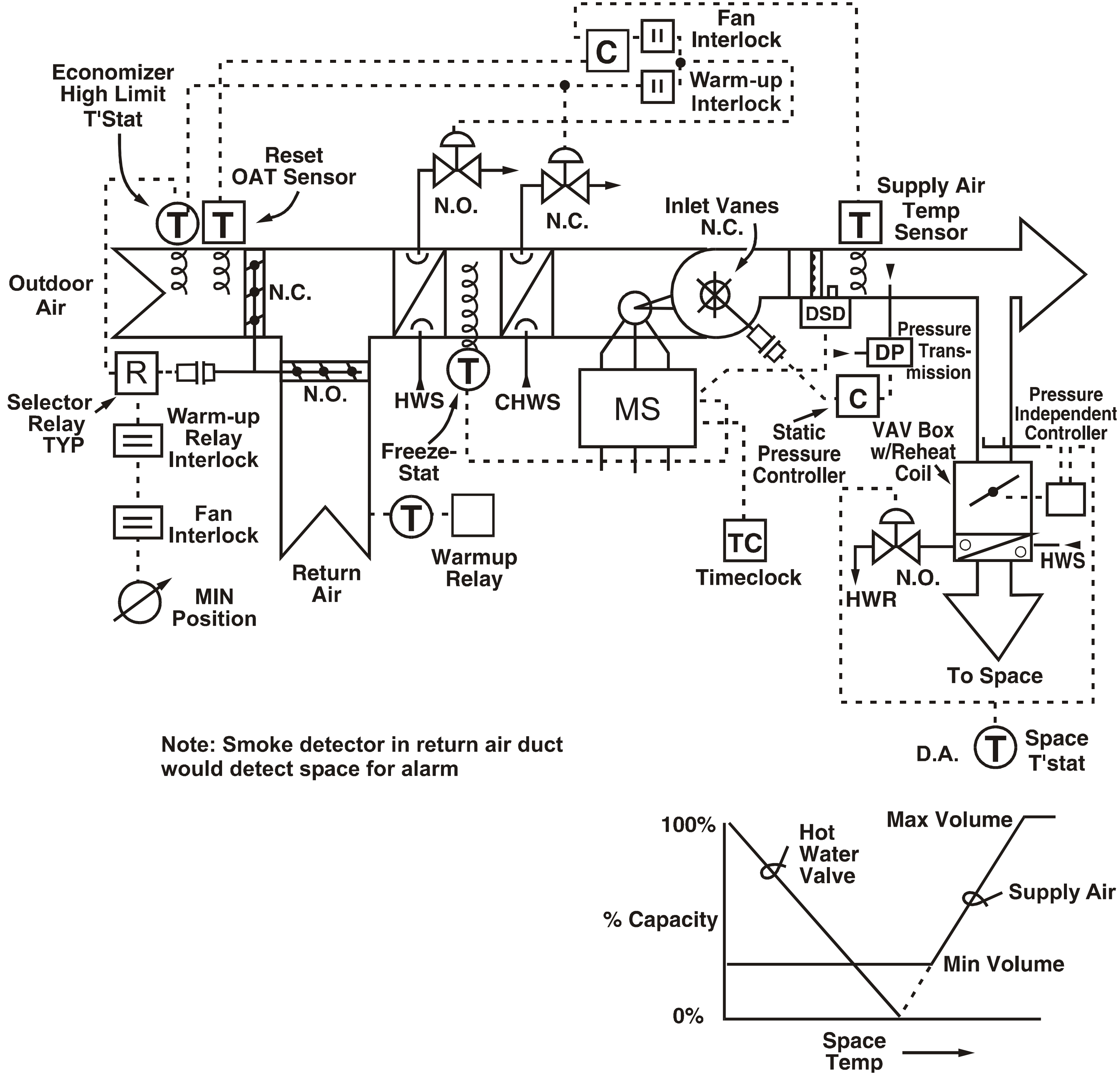


Note: Duct smoke detector in return air duct would detect space for alarm



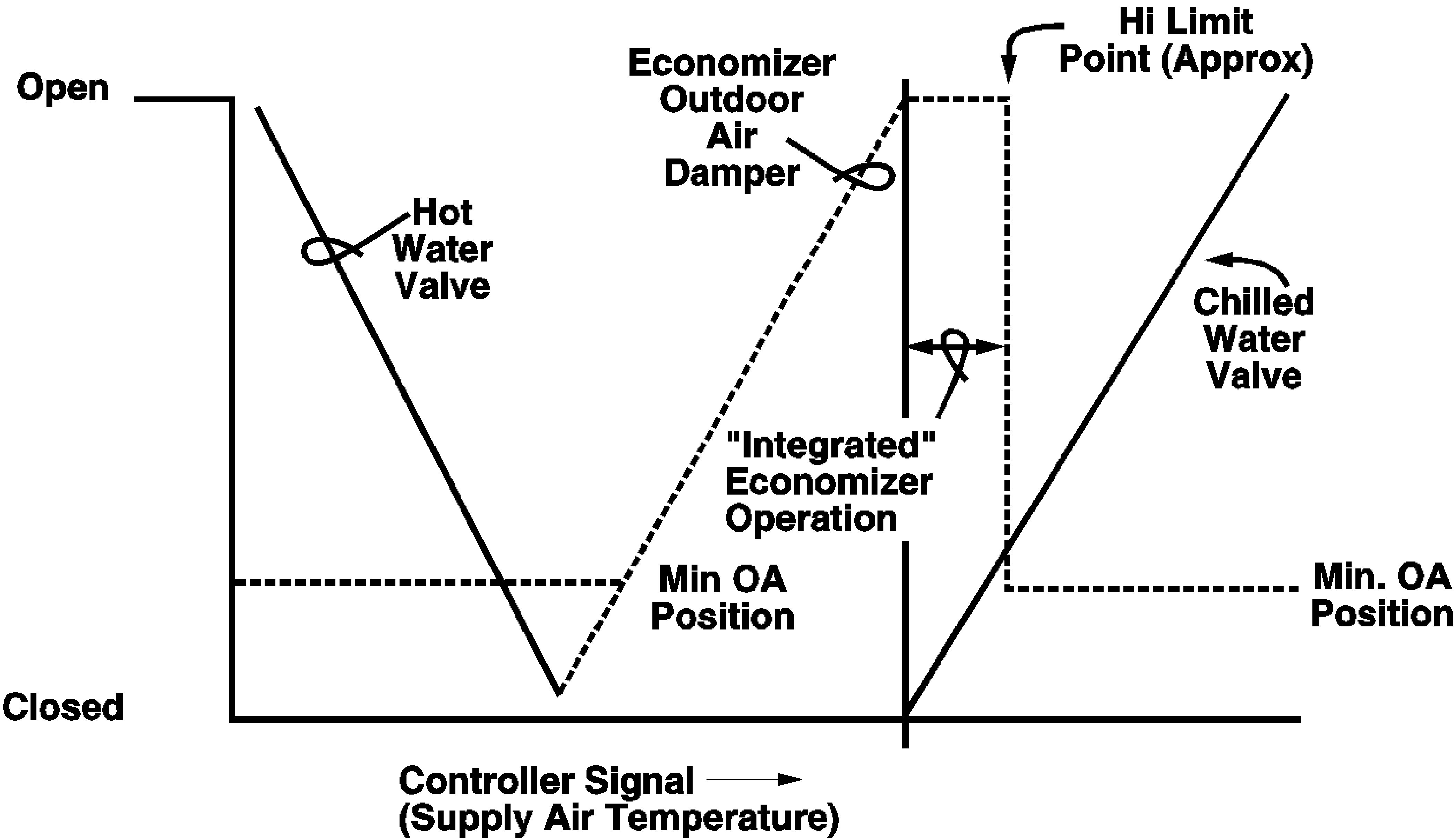
[Source: Montgomery, R. and McDowall, R., 2008. *Fundamentals of HVAC Control Systems*]

Typical variable air volume (VAV) system



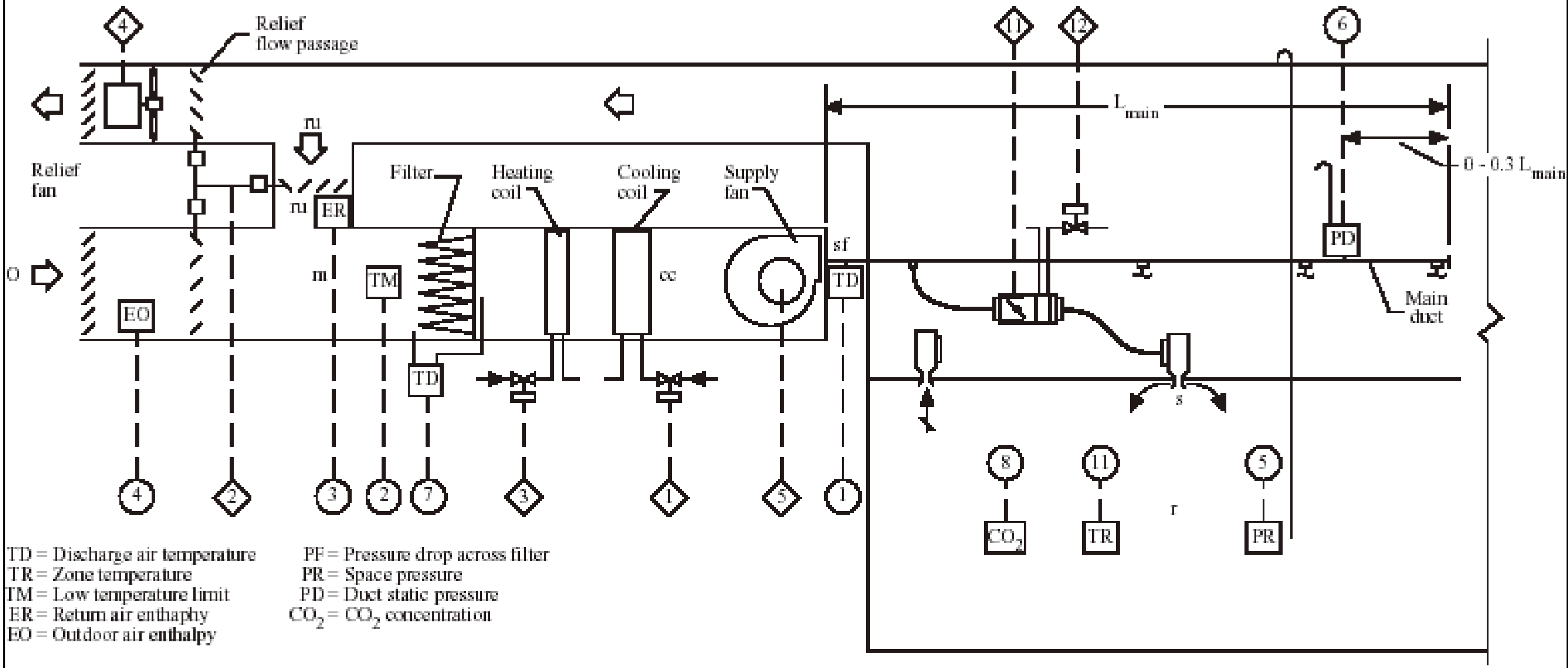
[Source: Montgomery, R. and McDowall, R., 2008. *Fundamentals of HVAC Control Systems*]

Chilled water, economizer & hot water sequencing



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

Control diagram of a variable air volume (VAV) reheat system for year-round operation

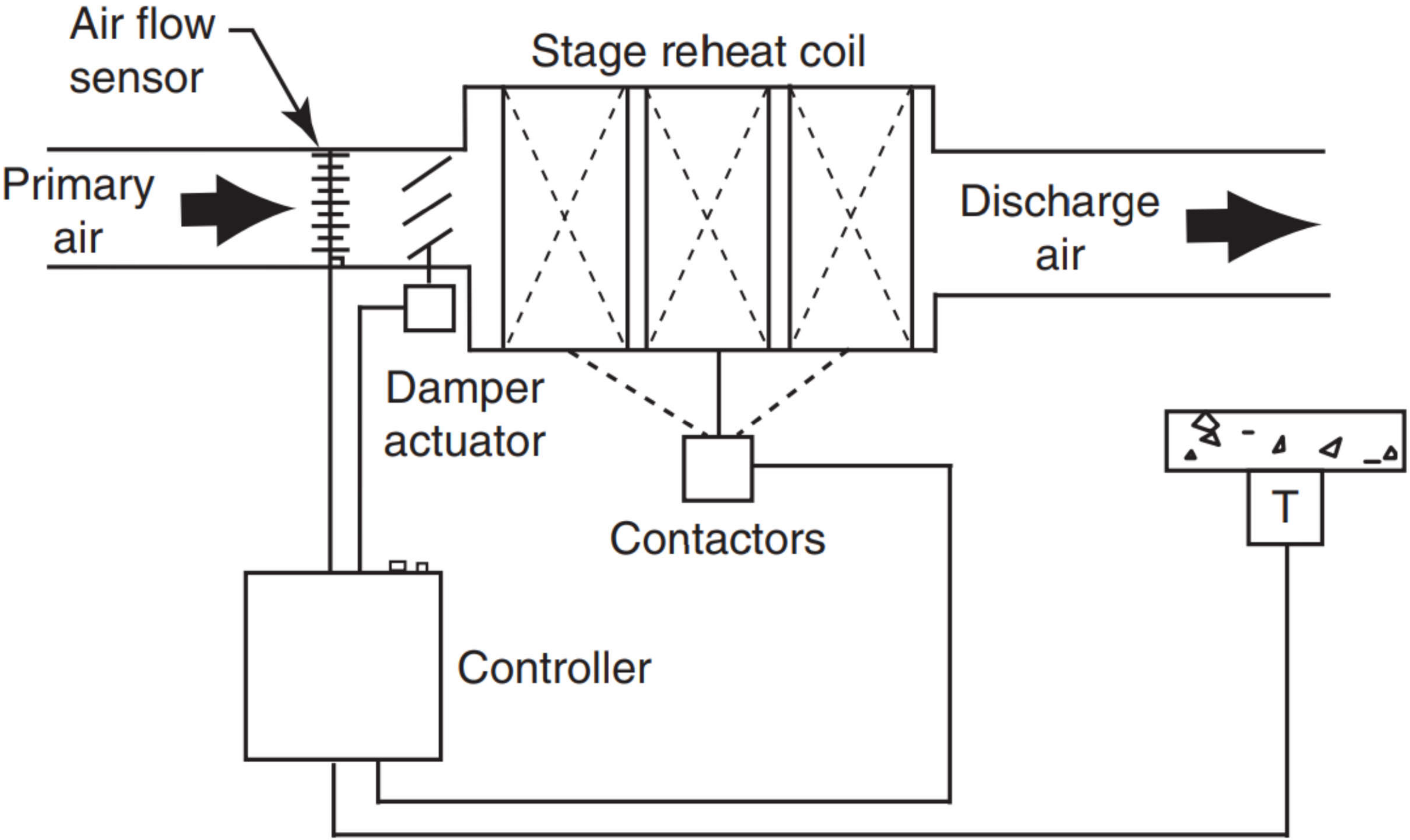


TD = Discharge air temperature
TR = Zone temperature
TM = Low temperature limit
ER = Return air enthaphy
EO = Outdoor air enthalpy
PF = Pressure drop across filter
PR = Space pressure
PD = Duct static pressure
CO_2 = CO_2 concentration

Can you understand all the symbols & abbreviations?

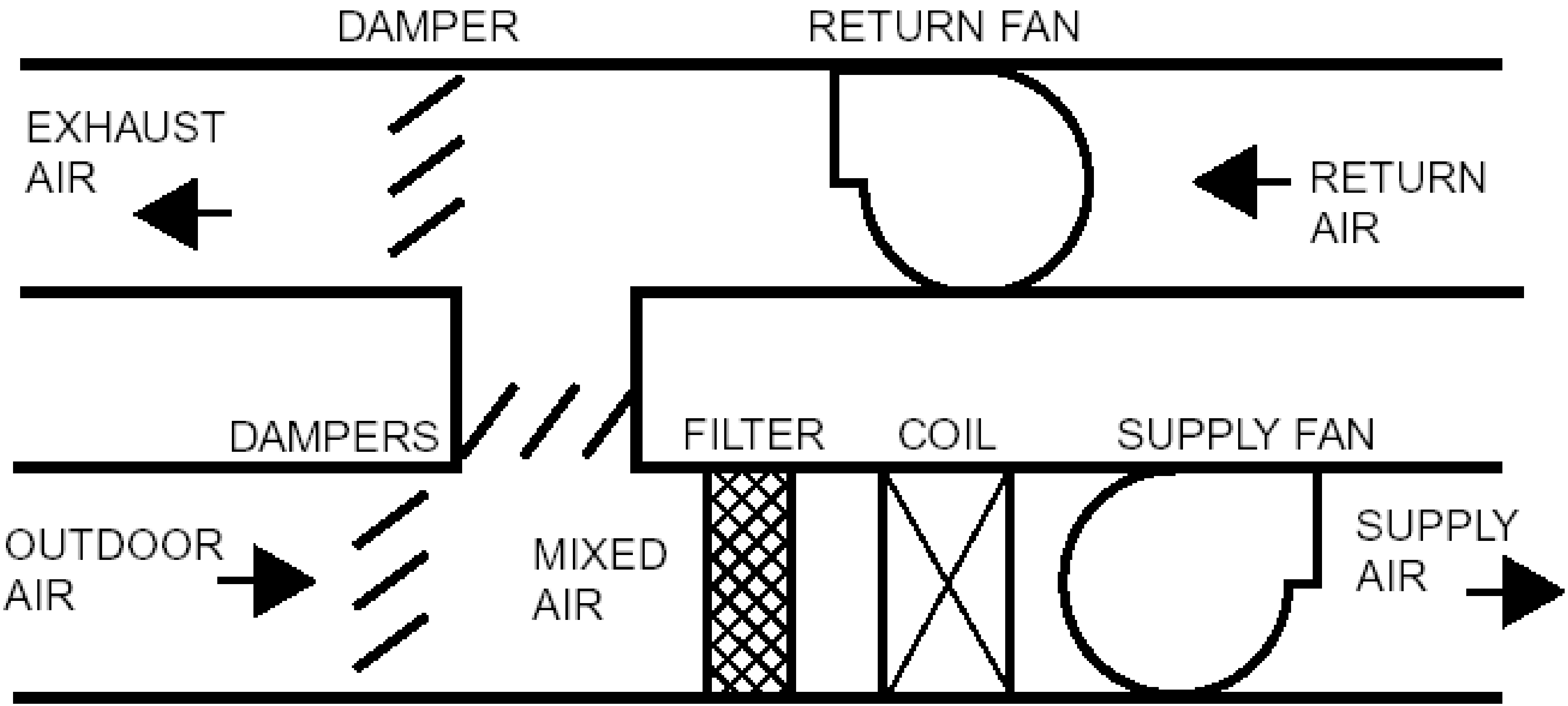
[Source: Wang, S. K., 2001. *Handbook of Air Conditioning and Refrigeration*]

VAV box control diagram



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

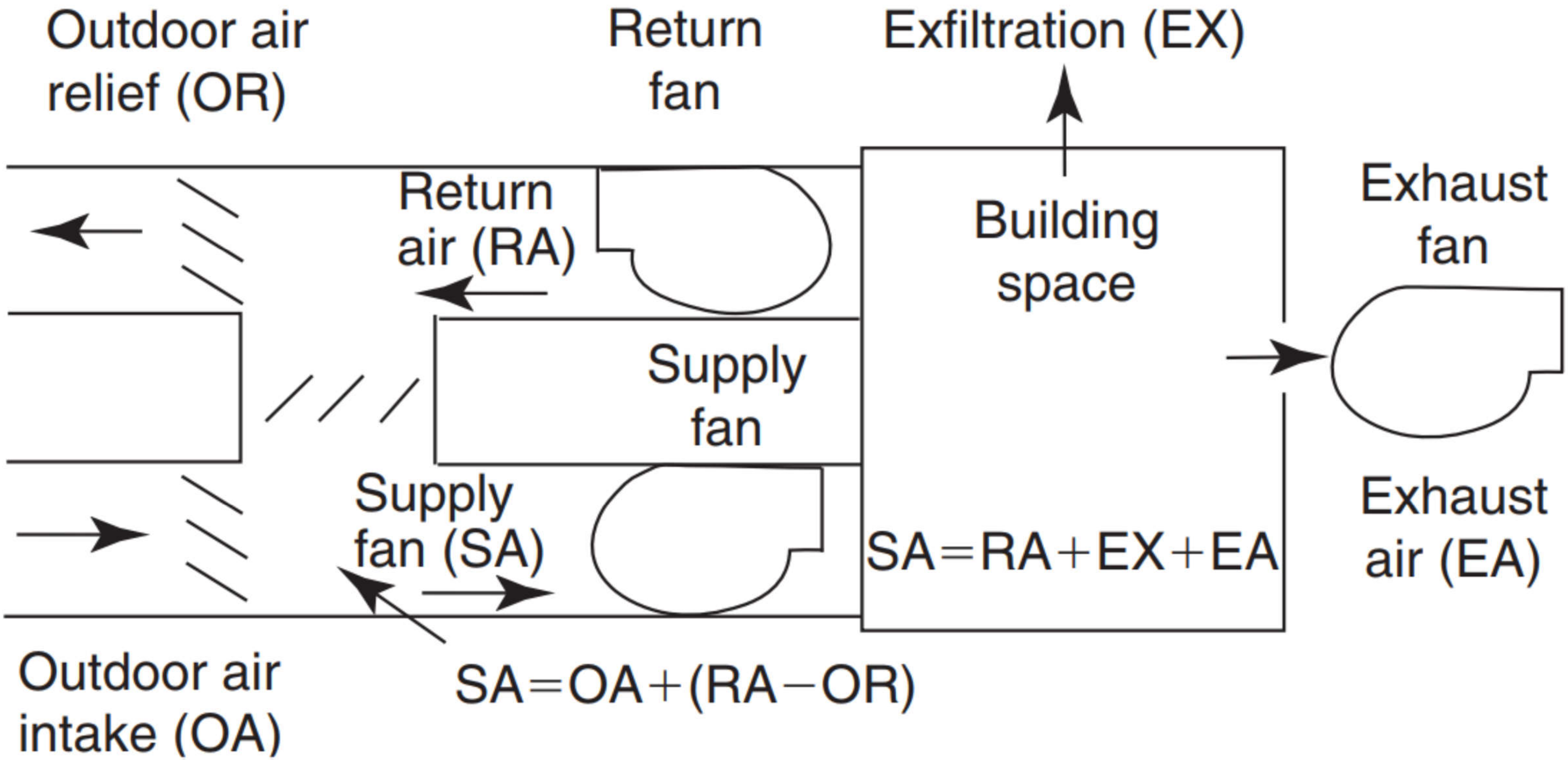
Schematic diagram of a typical constant air volume (CAV) system



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

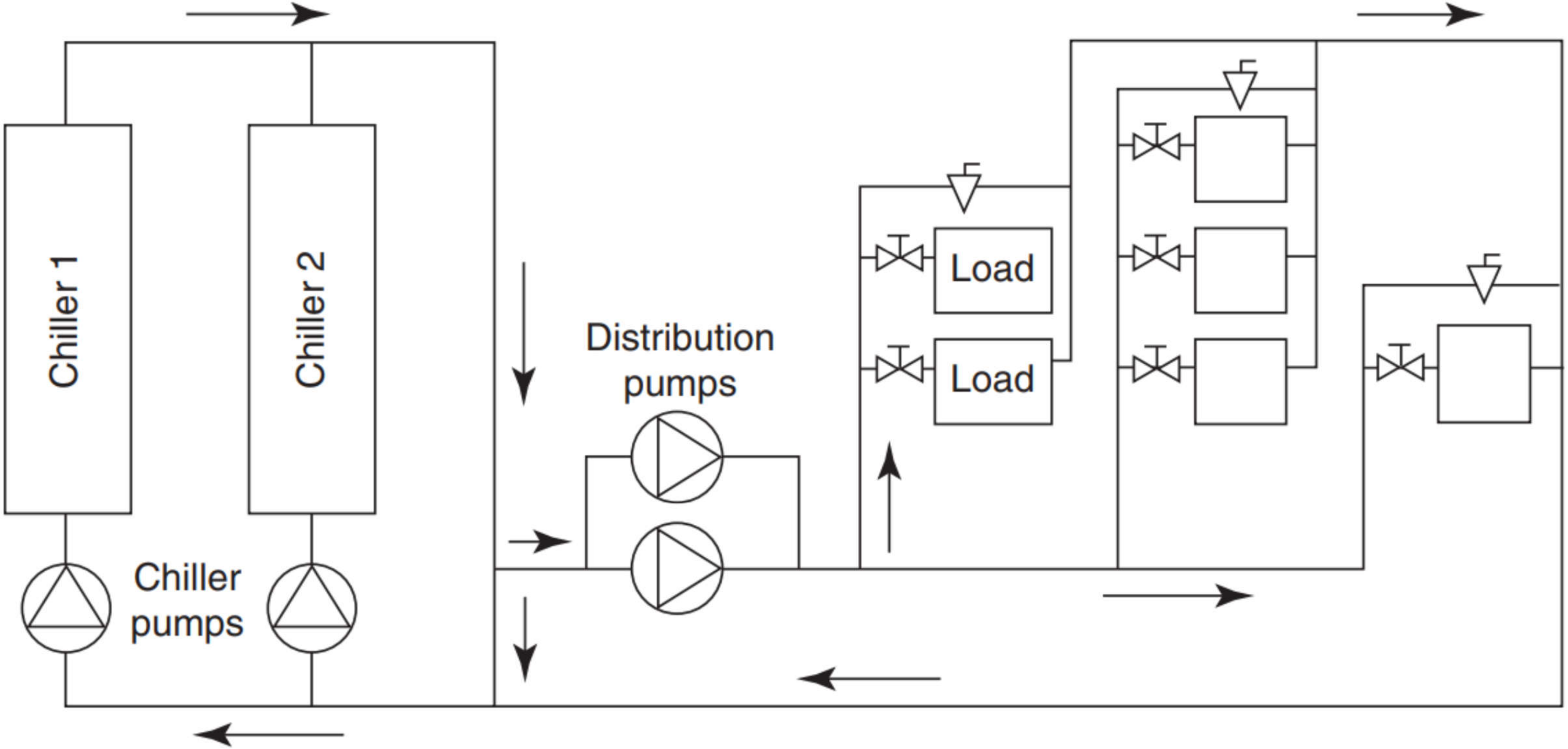
[Source: Honeywell, 1997. *Engineering Manual of Automatic Control for Commercial Buildings*]

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



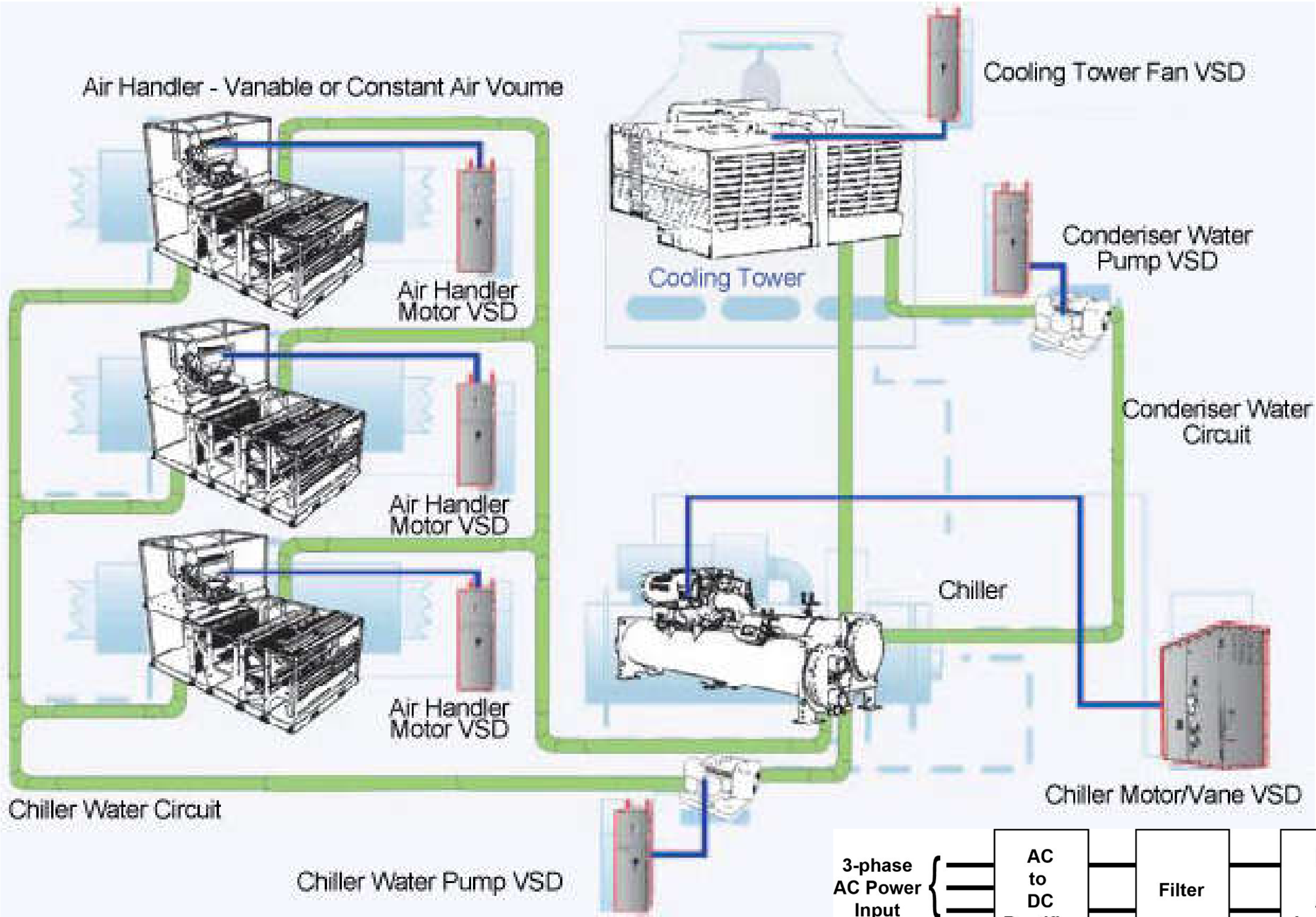
[Source: Montgomery, R. and McDowall, R., 2008. *Fundamentals of HVAC Control Systems*]

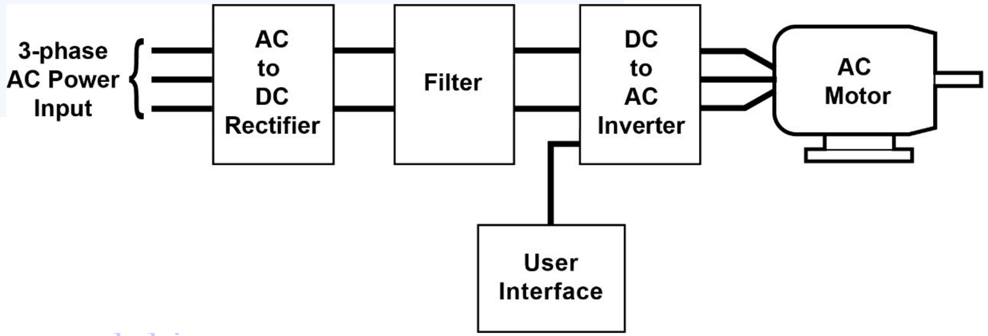
Chiller plant & primary secondary chilled water pumping system



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

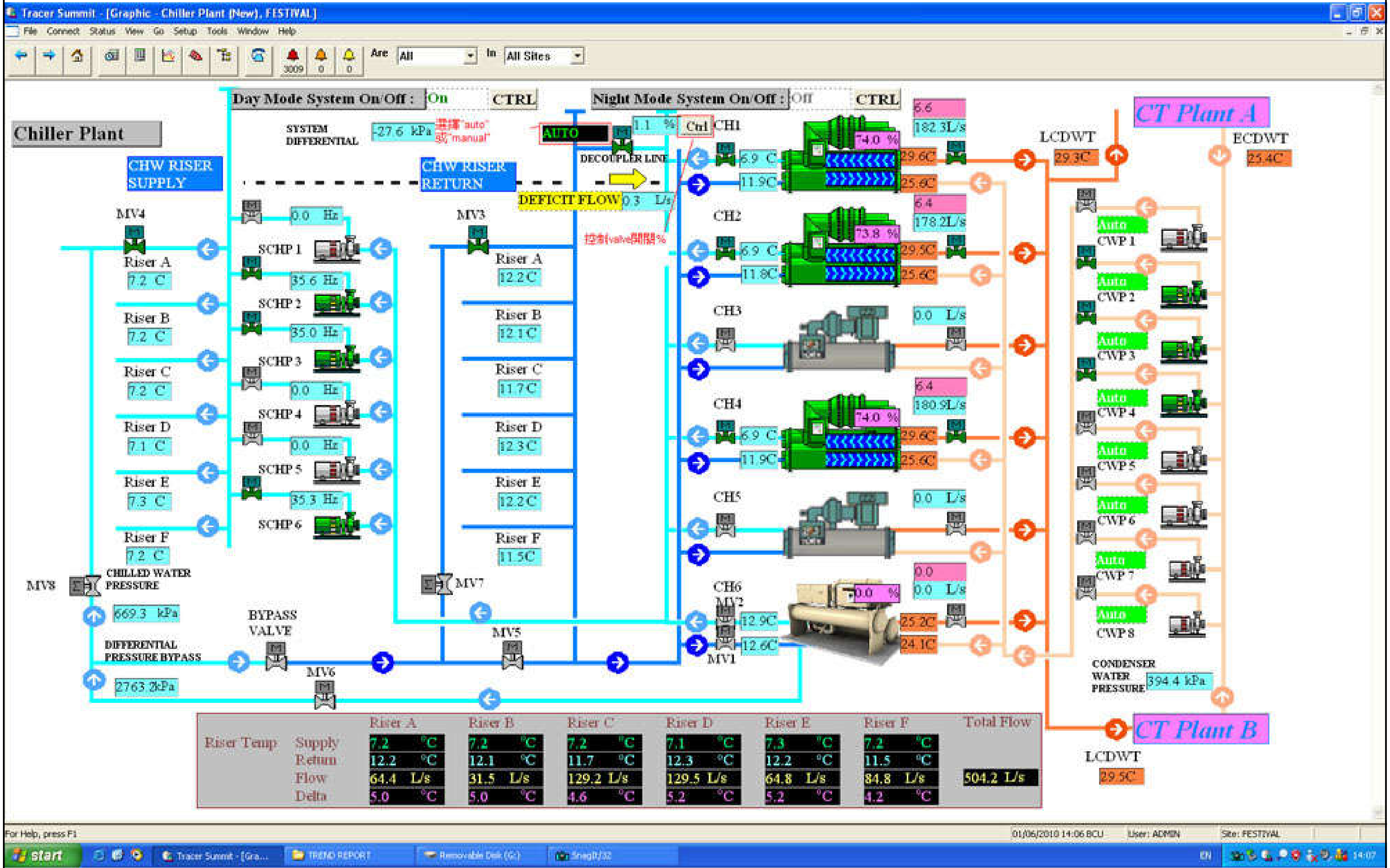
Variable speed drives (VSDs) in air-conditioning systems





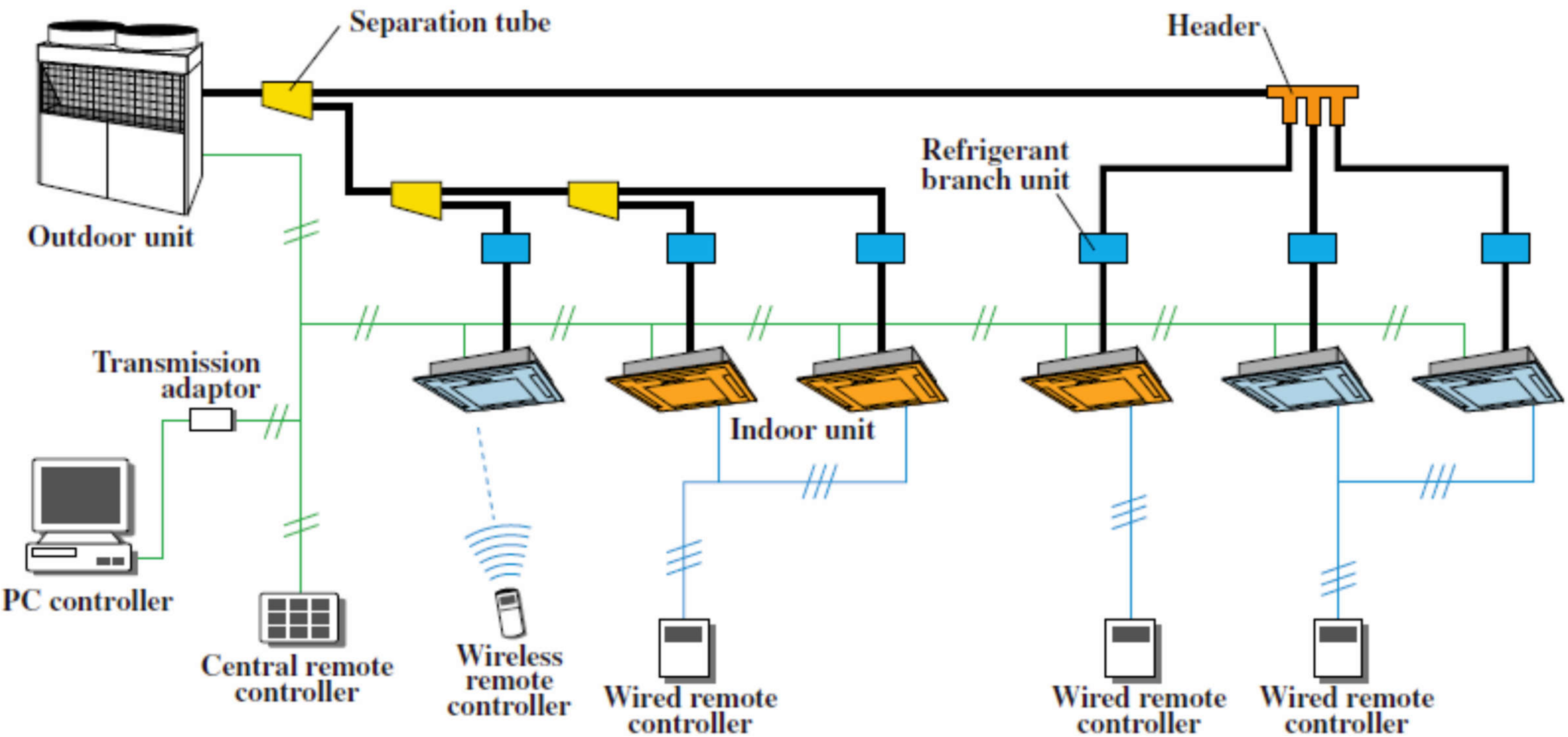
[Source: https://www.pnnl.gov/projects/om-best-practices/variable-speed-drives; https://www.emsd.gov.hk/energyland/en/appAndEquip/equipment/air_conditioning/vsd.html]

Example of chiller plant control interface



(Source: Trane)

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

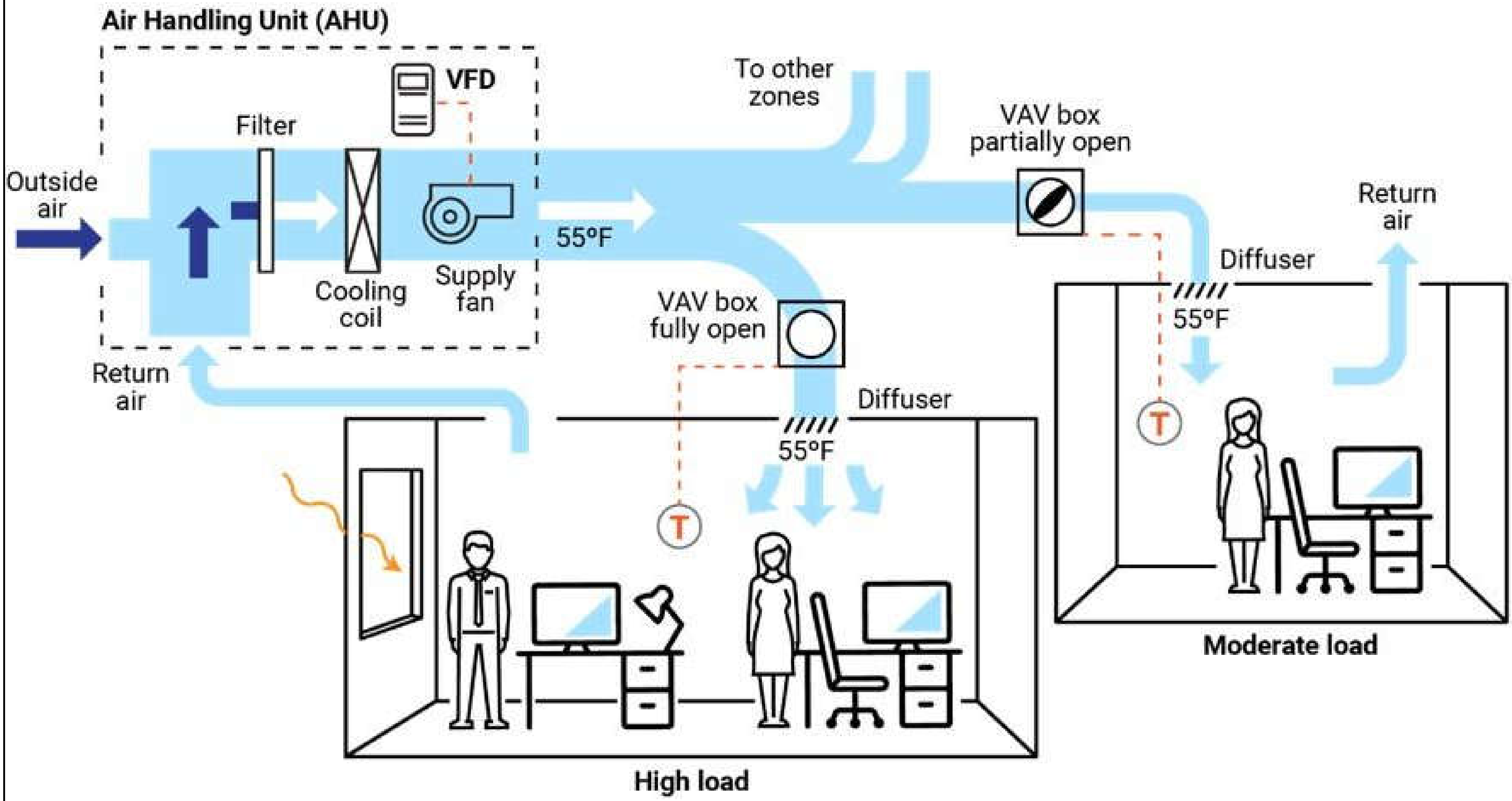


(Source: Fujitsu)

HVAC control examples

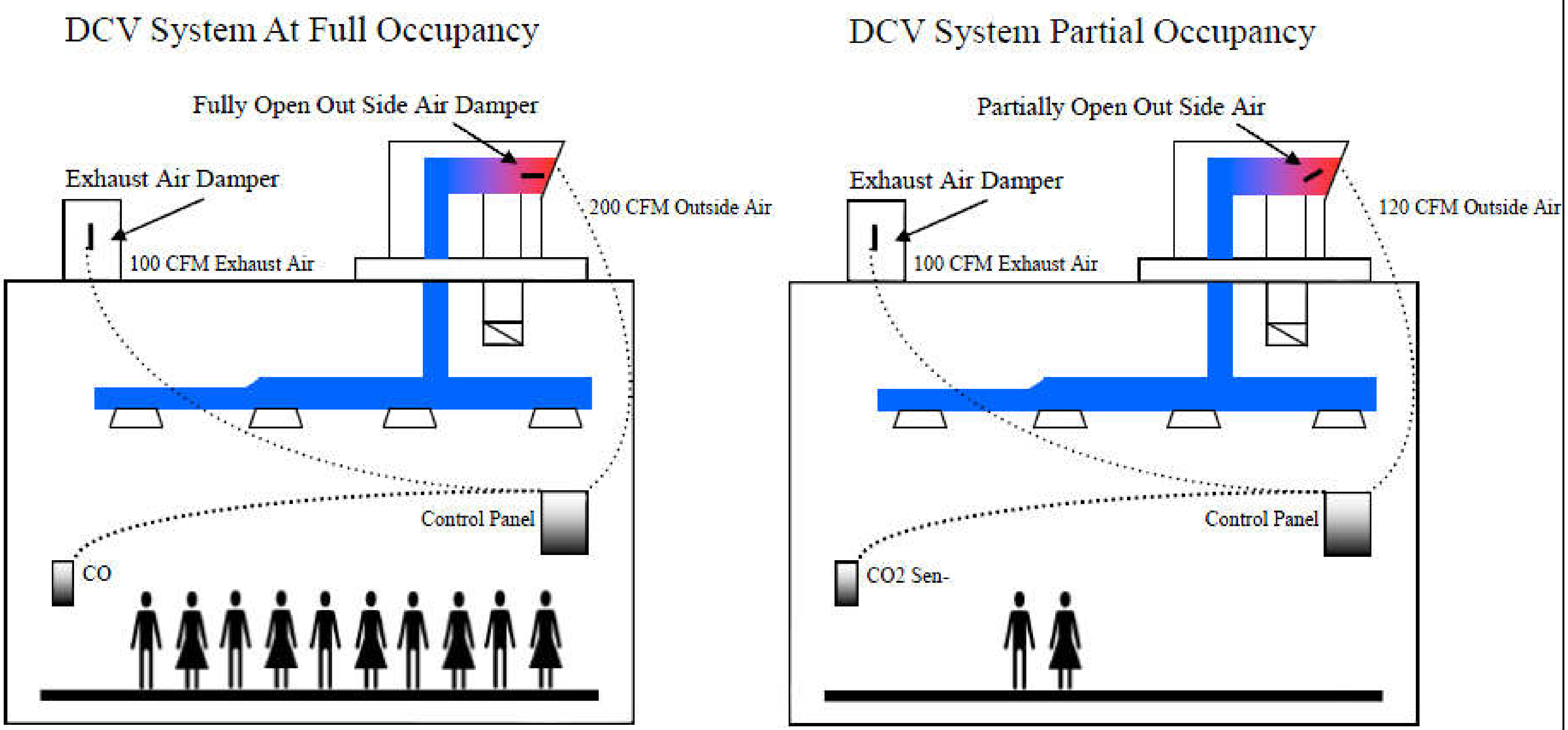
- HVAC indoor control applications:
  - Temperature & humidity monitoring & control
  - Carbon dioxide control (ventilation rate)
  - Exhaust fan control (thermostats or interlock)
  - Fume hood control (in laboratories)
  - Condensate management & control (on microbial)
  - Ventilation/outside air monitoring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

Operation of variable air volume (VAV) systems



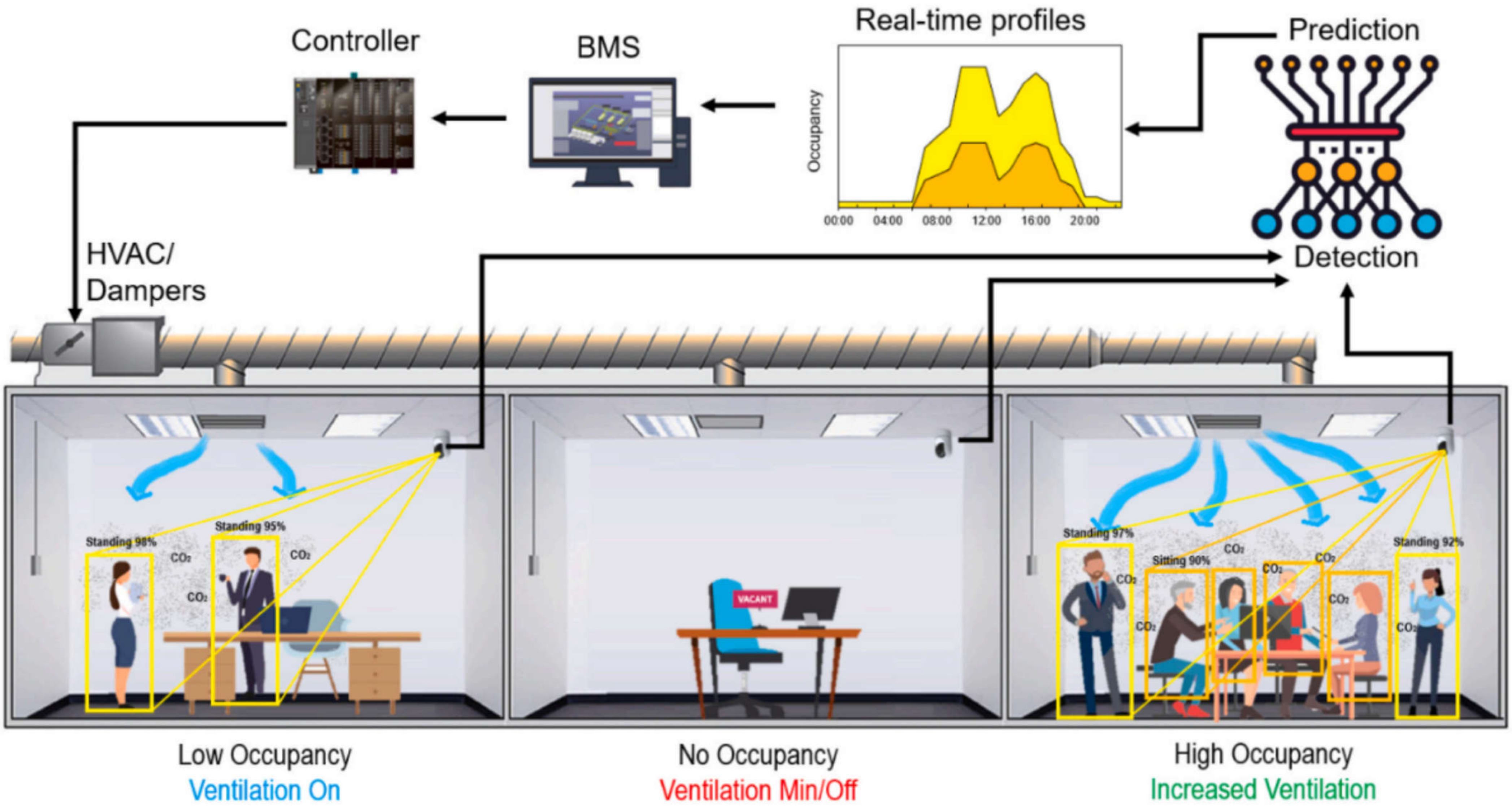
(Source: https://www.pnnl.gov/projects/om-best-practices/variable-air-volume-systems)

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



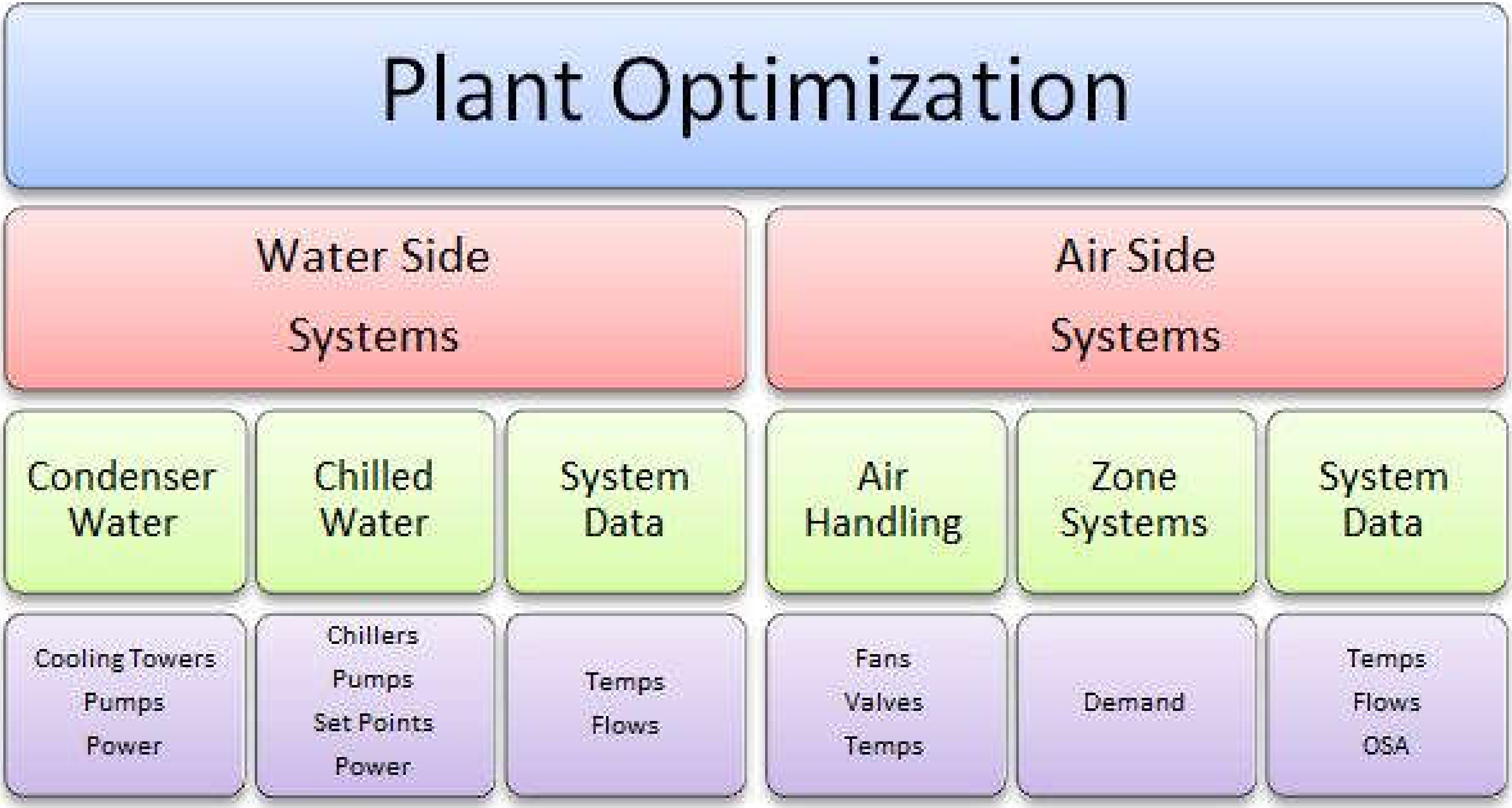
(Source: https://www.advancedcontrolsolutions.com/Demand-Control-Ventalation-and-Energy-Savings)

Vision-based approach framework for demand-based ventilation control



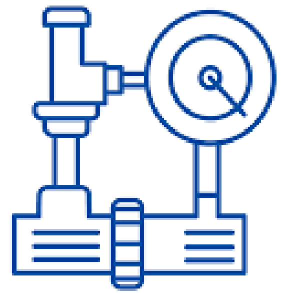
(Source: Wei S., Tien P. W., Chow T. W., Wu Y. & Calautit J. K., 2022. Deep learning and computer vision based occupancy CO2 level prediction for demand-controlled ventilation (DCV), *Journal of Building Engineering*, 56: 104715. https://doi.org/10.1016/j.jobe.2022.104715)

Major components of HVAC plant & system optimization



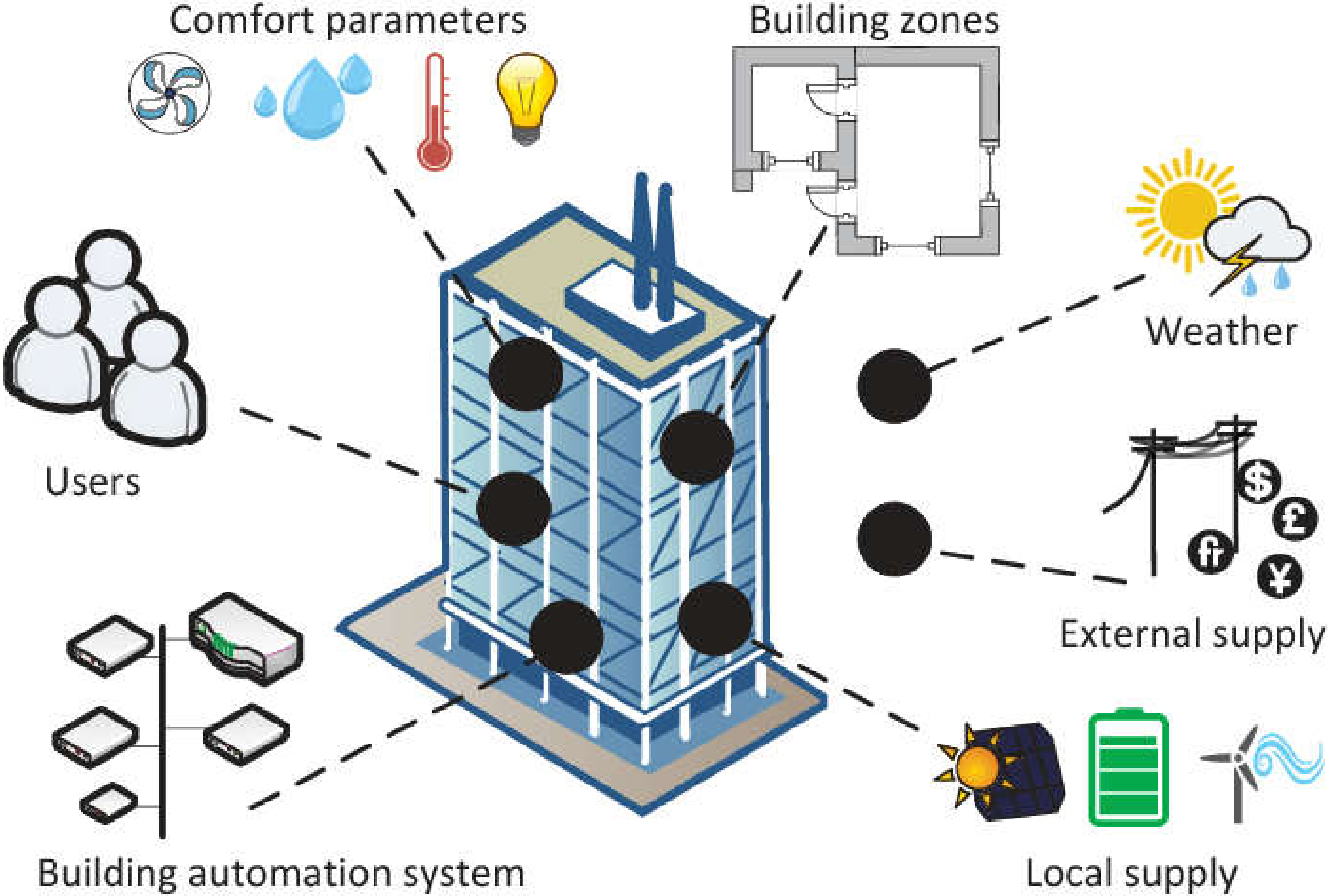
(Source: https://www.automatedbuildings.com/news/aug12/articles/climatec/120724035404climatec.html)

Central plant optimization



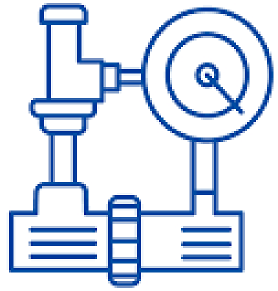
- In large buildings, a HVAC central plant is usually the primary source of cooling or heating, delivering thermal energy as chilled or hot water to HVAC systems
- Improving the efficiency of the generation & distribution of thermal energy reduces energy wastage at the source
- A small percentage improvement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

Relevant influencing factors for optimization in building energy management system



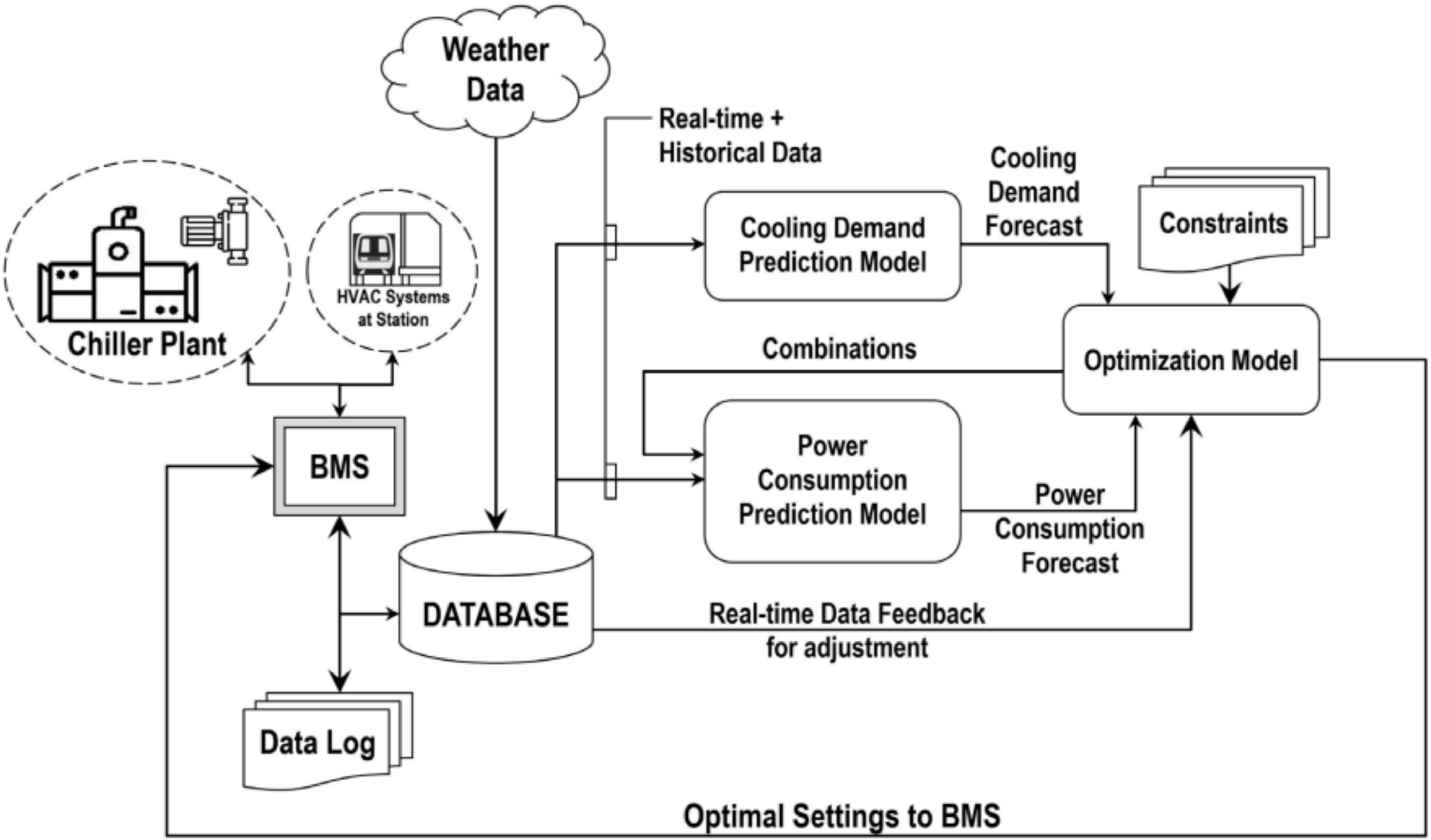
(Source: Schachinger D. & Kastner W., 2018. Context-aware optimization strategies for universal application in smart building energy management, In *2018 IEEE 16th International Conference on Industrial Informatics (INDIN)*, Porto, Portugal, 2018, pp. 478-483. http://doi.org/10.1109/INDIN.2018.8472000)

Central plant optimization



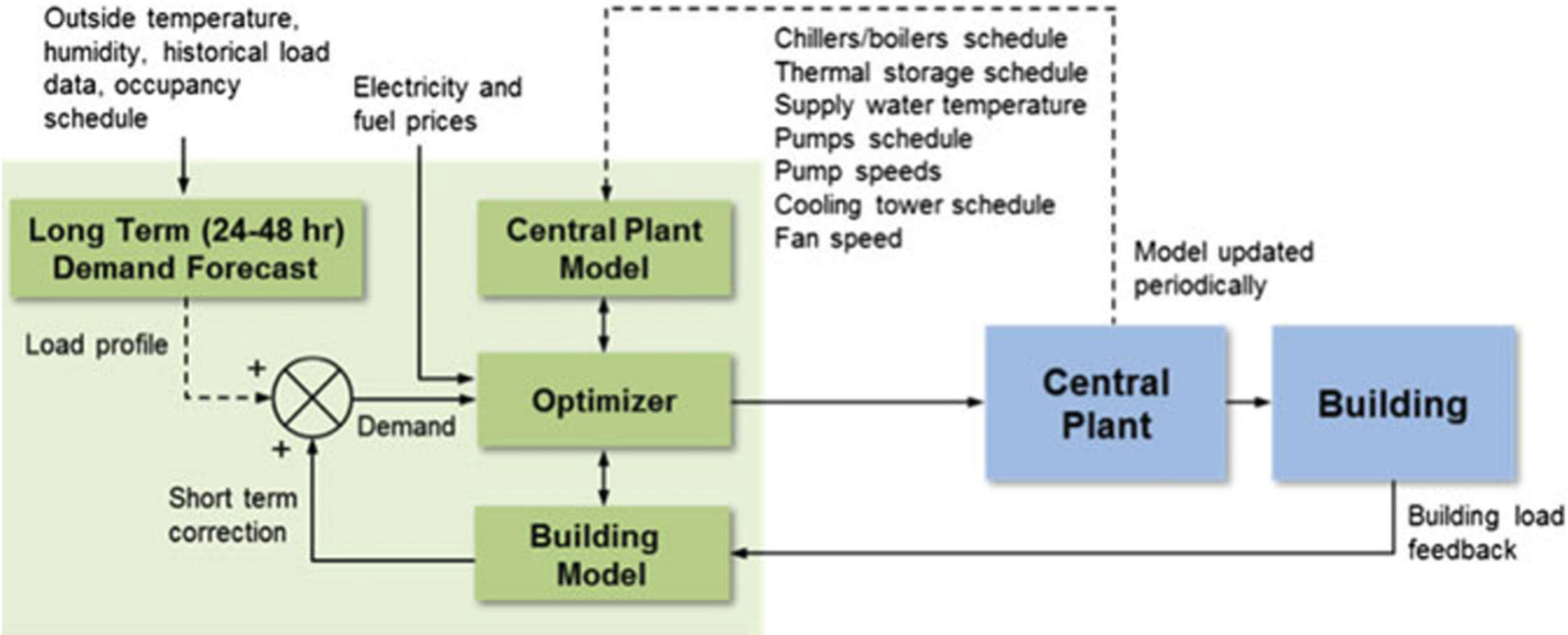
- Plant equipment efficiencies vary with load & external conditions
- Central plants have multiple chillers, boilers, & power generators, which may differ from each other in capacities & performance
  - The ability to select equipment & operate it at optimized points to minimize the total energy
- Modelling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



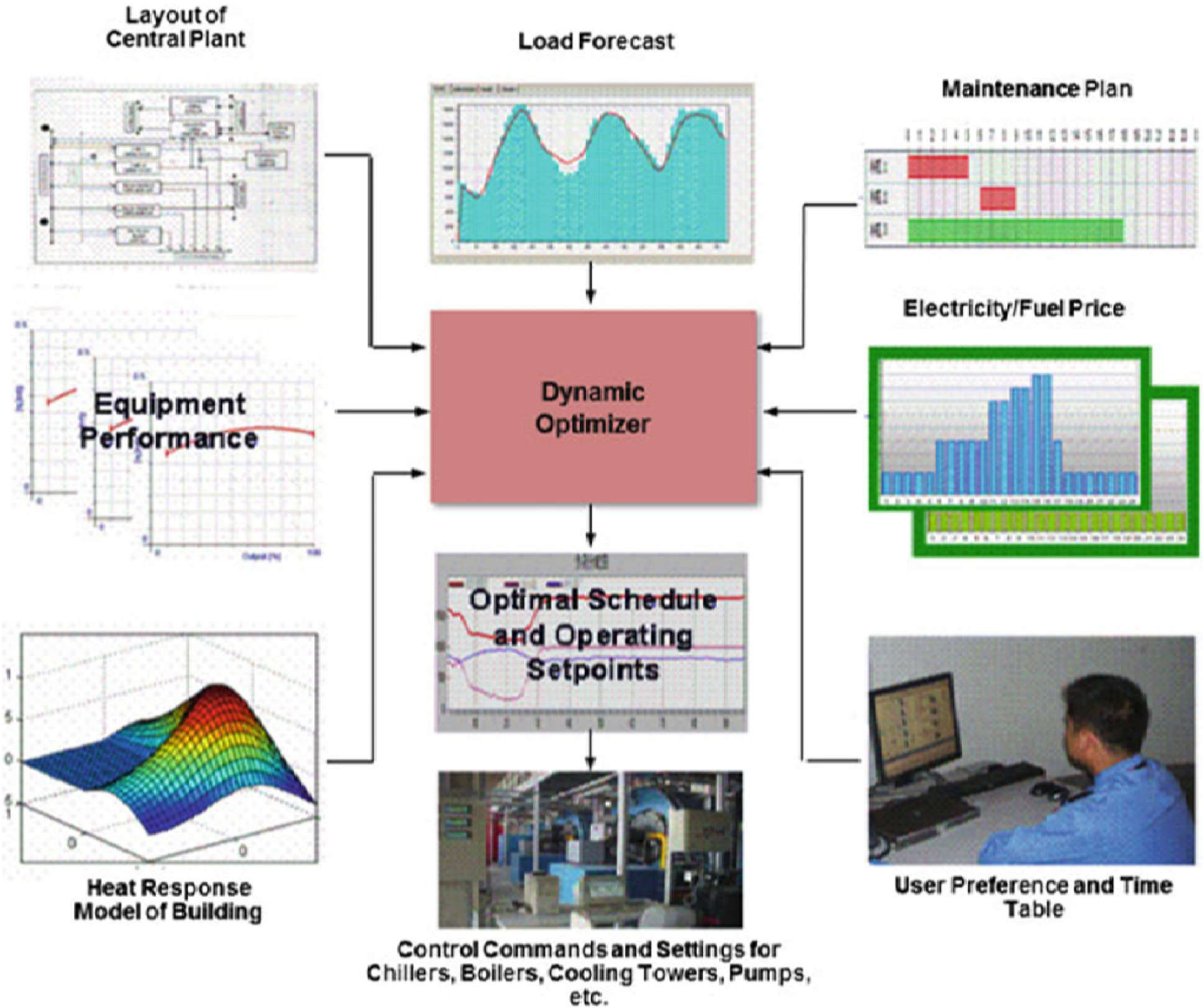
A demand forecaster predicts loads for the next 24 hours period based on the current weather, load history, & occupancy criteria.

A dynamic load model represents the building response to changes in energy supplied.

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

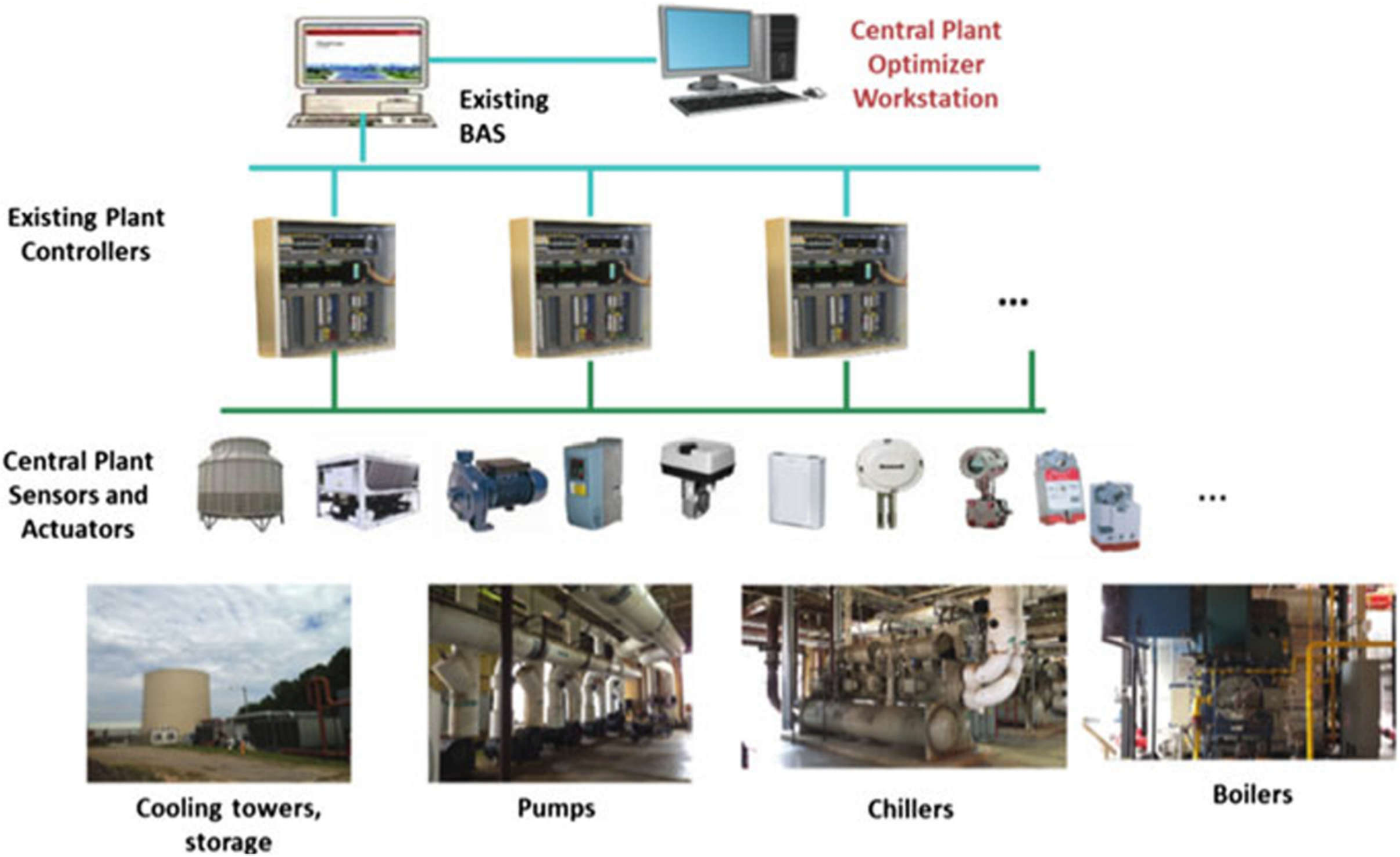
(Source: Wen J. T. & Mishra S., 2018. *Intelligent Building Control Systems A Survey of Modern Building Control and Sensing Strategies*)

Basic concept of a dynamic real-time supervisory optimizer



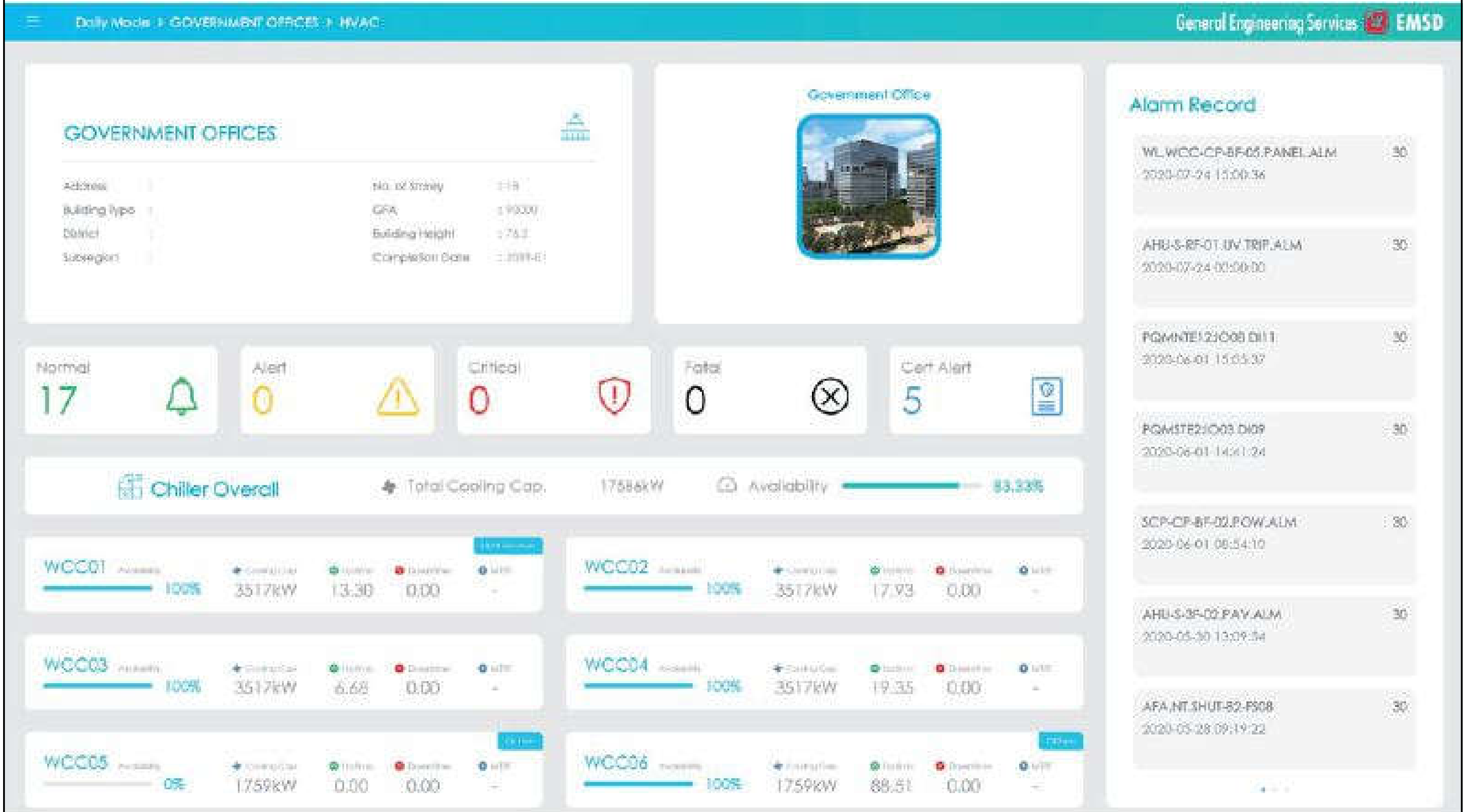
(Source: Wen J. T. & Mishra S., 2018. *Intelligent Building Control Systems A Survey of Modern Building Control and Sensing Strategies*)

HVAC control implementation of a real-time supervisory optimizer



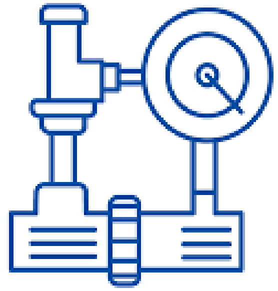
(Source: Wen J. T. & Mishra S., 2018. *Intelligent Building Control Systems A Survey of Modern Building Control and Sensing Strategies*)

Dashboard showing the real-time monitoring of chiller plants



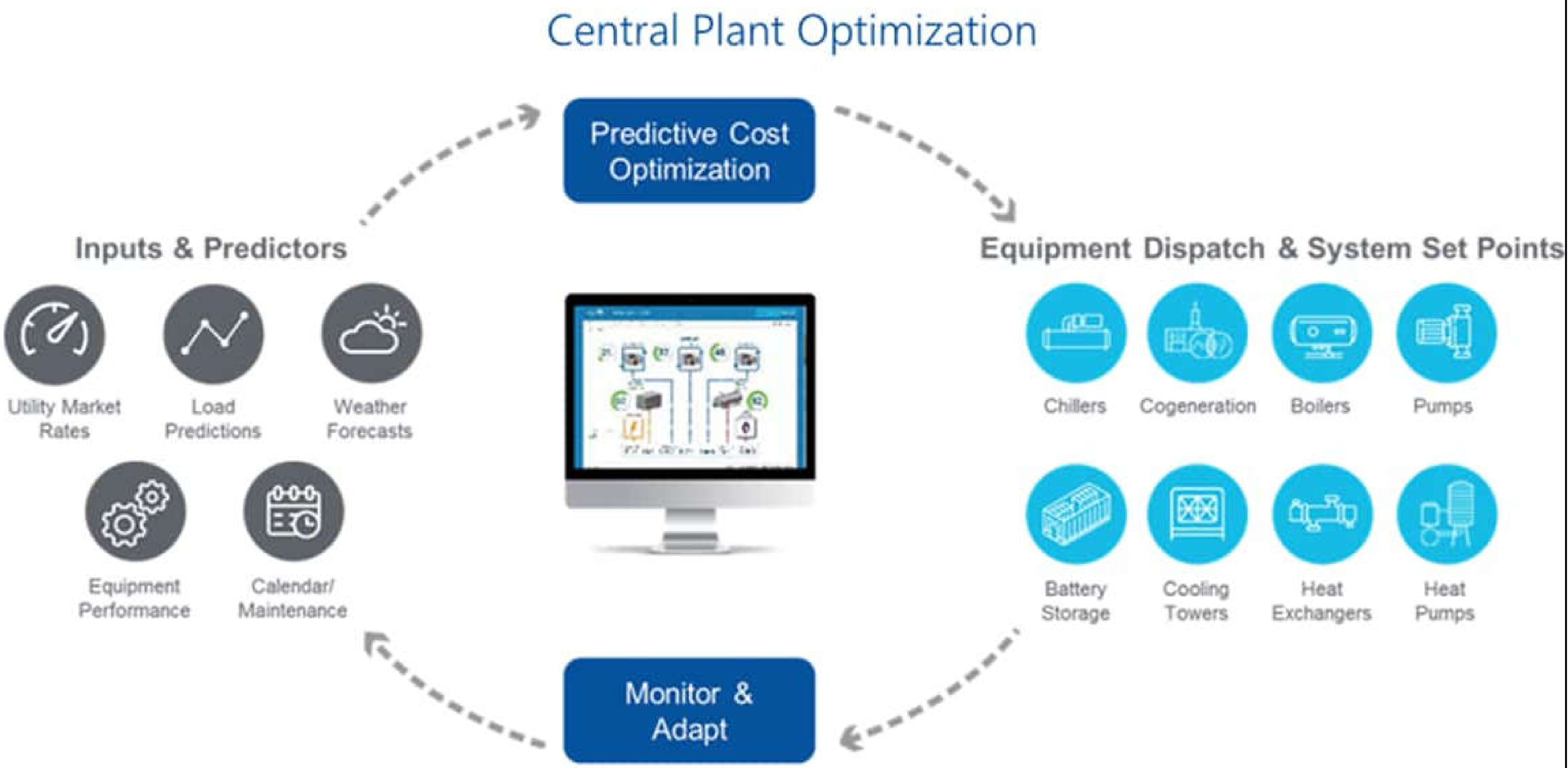
(Source: https://www.hkengineer.org.hk/issue/vol50-oct2022/feature_story/?id=17083)

Central plant optimization



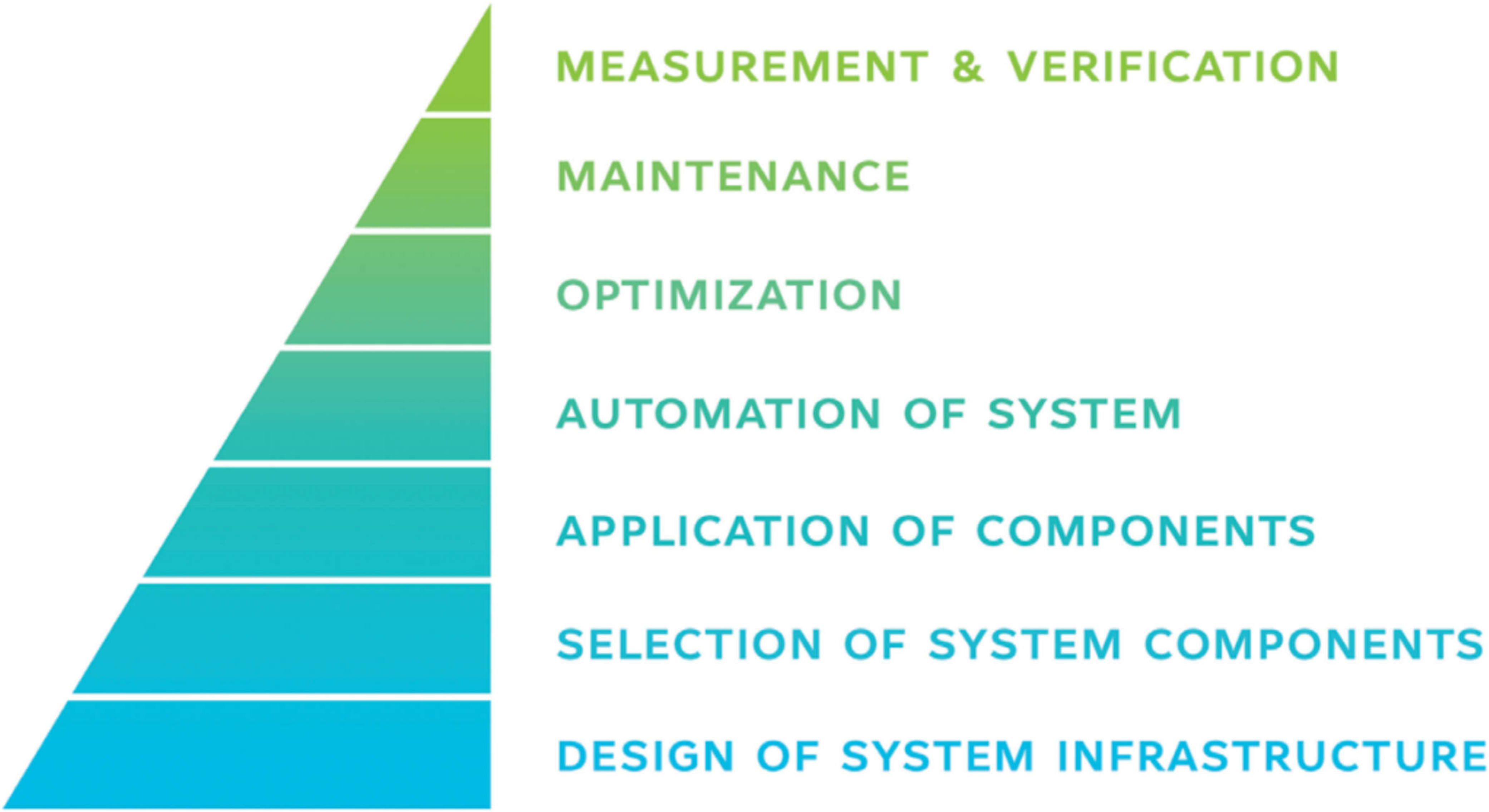
- Analysis of inputs for plant optimization
  - Equipment performance models (predictors)
  - Weather forecasts (for ambient conditions)
  - Load predictions (for hourly loads)
  - Utility pricing (demand chargers & tariffs)
  - Calendars & maintenance schedules (events)
- Help operators on both plant 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



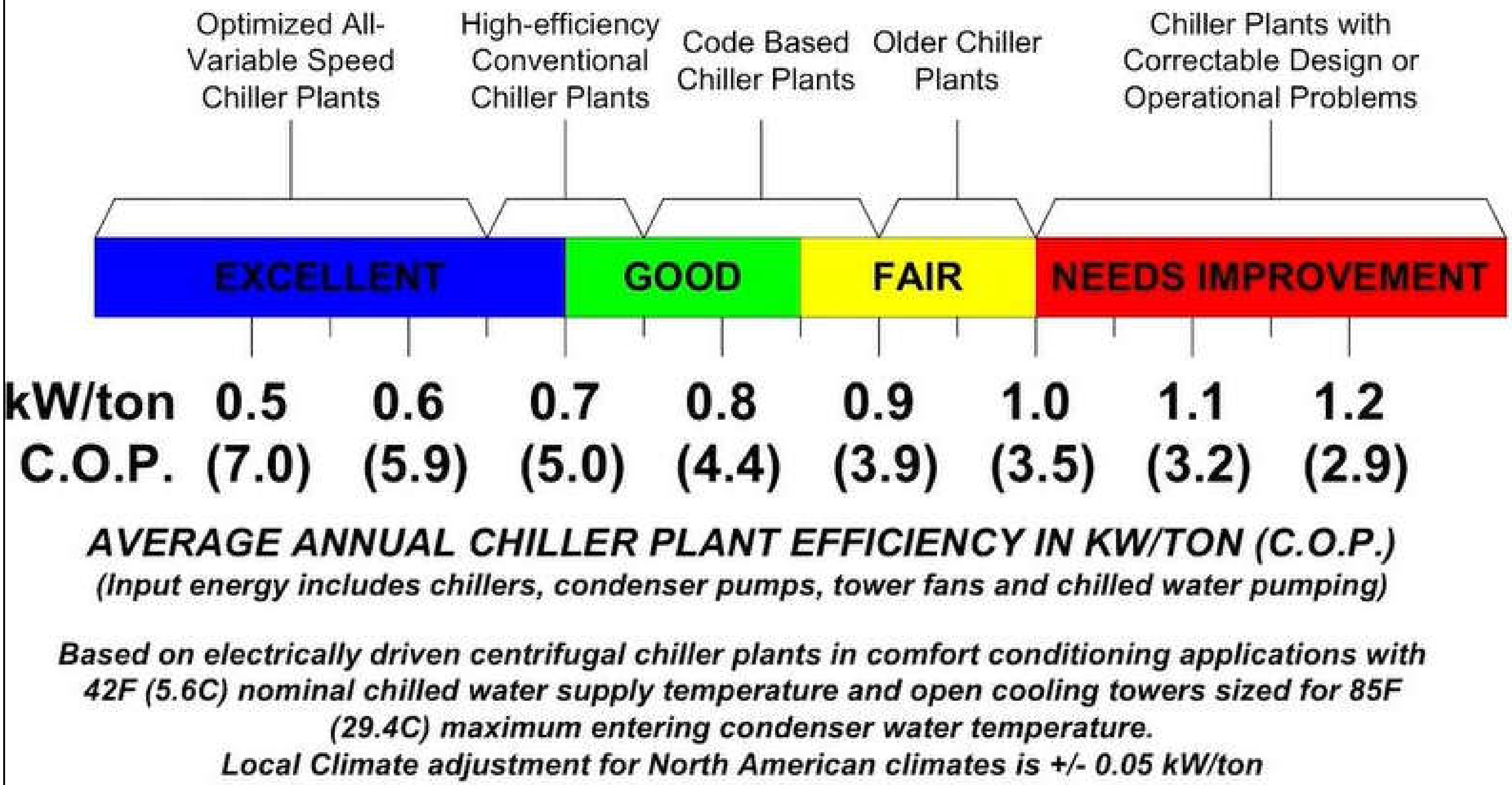
(Source: https://www.johnsoncontrols.com/en_au/digital-solutions/central-plant-optimization)

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)

Further reading

- Basic HVAC Controls
  https://mepacademy.com/basic-hvac-controls/
- 6 Steps for Designing HVAC DDC Controls
  https://mepacademy.com/6-steps-for-designing-hvac-ddc-controls/
- How to optimize an HVAC system
  https://optimumenergyco.com/how-to-optimize-an-hvac-system/