BISCUIT: Building Intelligent System CUstomer Investment Tool

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Design of smart buildings

Optimal design

Optimal control and operation

...with focus on intelligent system investment

$101Billion market (2016), with ~10% growth rate

The Internet of Things in Smart Commercial Buildings 2018 to 2022

MARKET PROSPECTS, IMPACTS & OPPORTUNITIES

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Occupancy sensor selection problem

- Problem: which sensor to install to enable occupancy-based lighting?

	Sensor	Cost	Precision	Computation level	Lighting compatible
	environmental sensor: CO_2, temperature, etc.	Low	Low	High	Yes
	motion sensor: PIR	Medium	Medium	Low	Yes
	camera sensor	High	High	Medium	No

- What sensors are available? What are the costs?
- What are the precision? Do they require computational infrastructure?
- Are they compatible? Can they be shared by other systems (e.g. HVAC)?

Smart building design lesson #1:

In addition to costs,

we should also consider performance and functional constraints.

Heating ventilation and air conditioning (HVAC) system retrofit evaluation

- Problem: cost-benefit analysis of HVAC system retrofit plans

	Candidate	Control	Computation level
	Basic retrofit, no intelligent components	Basic control	Low
	smart variable air volume (VAV) box	Demand-based control	Medium
	smart HVAC system	Human-building interaction	High

- What is the annual cost of operation for the given building profile?
- Do they require additional computational infrastructure?

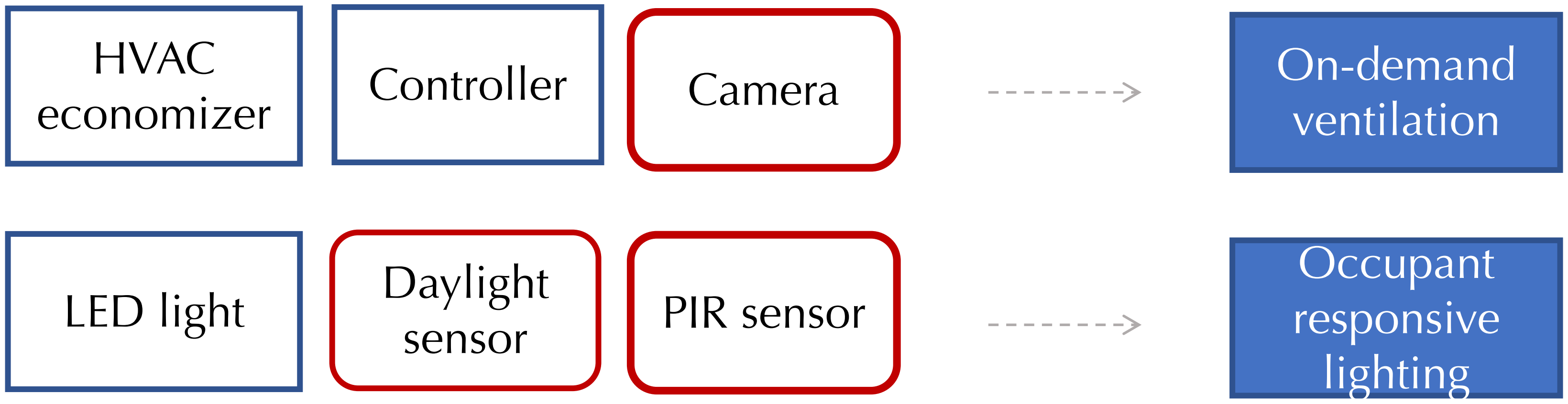
Smart building design lesson #2:

In addition to investment costs,

we should also consider available control strategies and operation cost.

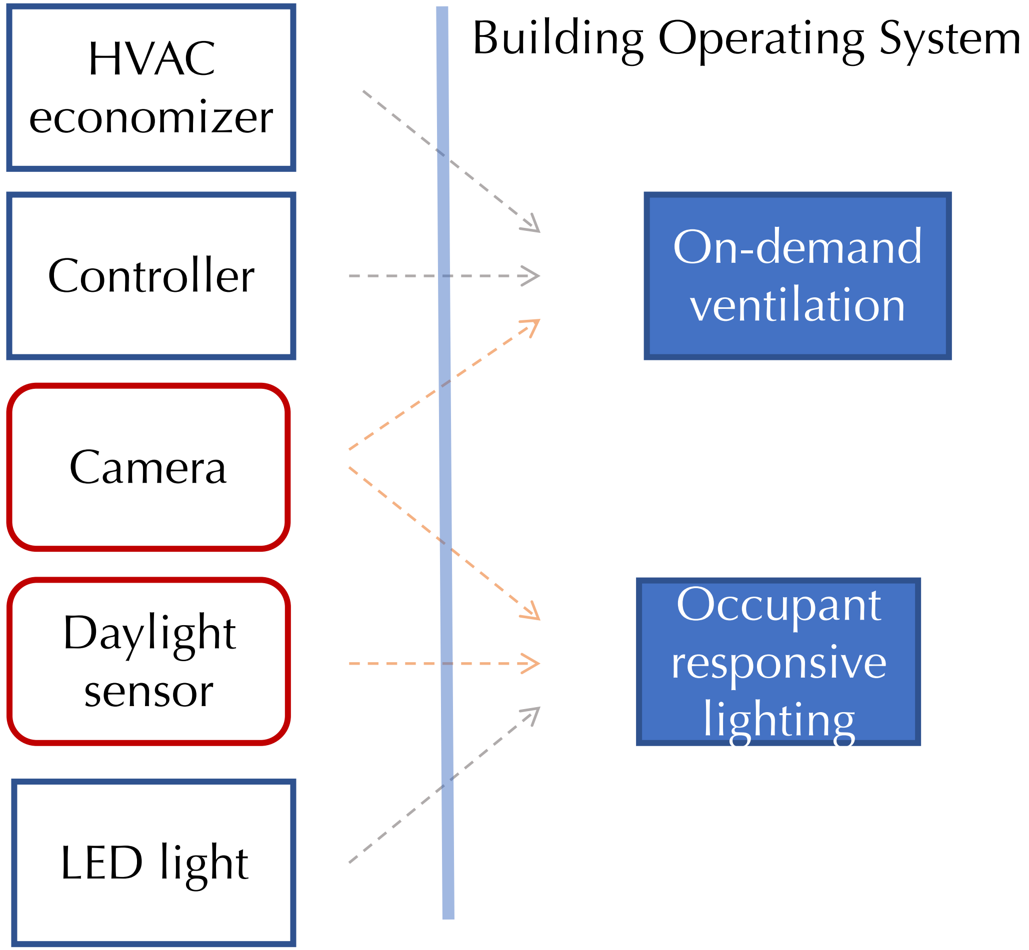
Traditional Design Paradigms

- One-function-one-box paradigm
  - Different systems are purchased from different suppliers
  - **+**: Support design optimization for a particular smart system offered by a supplier
  - **–**: Limit opportunities for component reuse



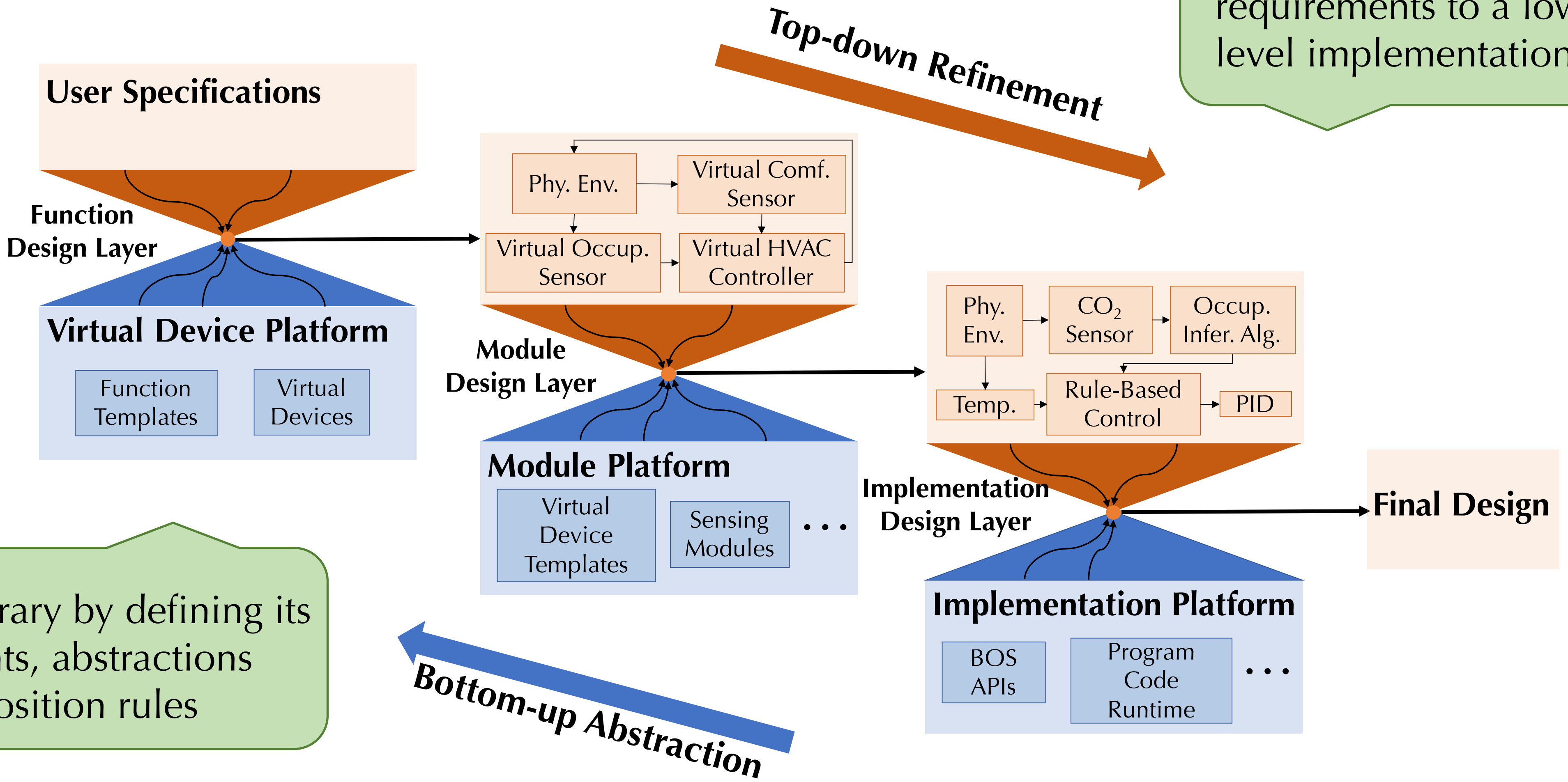
Traditional Design Paradigms

- Application Stack Paradigm
  - Different systems are allowed to share software, hardware, and data via building operating systems
  - +: Eliminate redundant resource deployment
  - –: Lack design space exploration



Platform-based design

Map high-level design requirements to a lower-level implementation

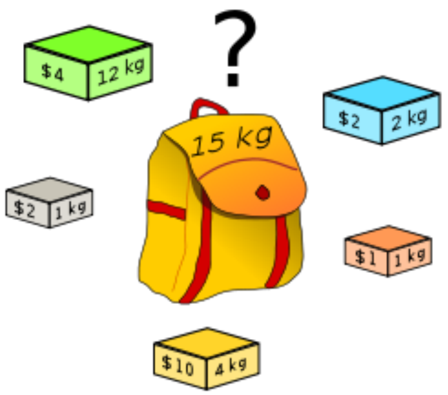


Build a library by defining its components, abstractions and composition rules

"Design Automation for Smart Building Systems." R. Jia, B. Jin, M. Jin, Y. Zhou, I. Konstantakopoulos, H. Zou, J. Kim, D. Li, W. Gu, R. Arghandeh, P. Nuzzo, S. Schiavon, A. L. Sangiovanni-Vincentelli, C. Spanos. *IEEE Proceedings, 2018*

“Knapsack problem” of smart buildings

- Original knapsack: which items should be chosen to maximize profits while not exceeding the weight limit?

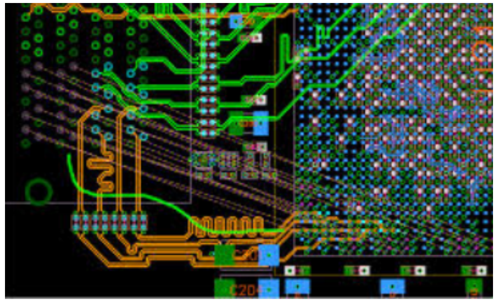


- Smart building version: which smart building technologies should be invested to maximize user satisfaction given limited budget?
  - Multiple constraints: budget, technology, privacy, security, etc.
  - Different timescales: one-time investment, lifetime operation
  - Multiple objectives: cost, comfort, energy efficiency…

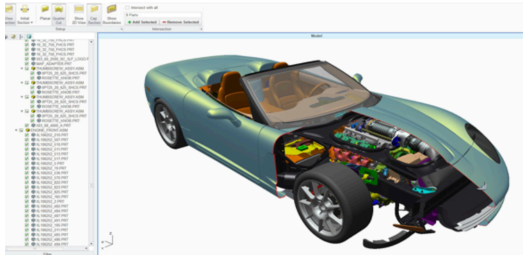
Challenges

- Large-scale: >100K variables
  - Annual operation, hourly precision (365*24=8640)
  - >50 technology selection candidates
- Nonconvexity (discrete optimization):
  - Integer decision variables: e.g., instalment of equipment
  - Logical relationship constraints: e.g., occupancy-based control can be enabled if there exists an occupancy sensor and an intelligent HVAC
- Human-centric designs (soft constraints):
  - Comfort, privacy, security, entertainment, etc.

Computer-aided design of smart building?



Integrated circuits

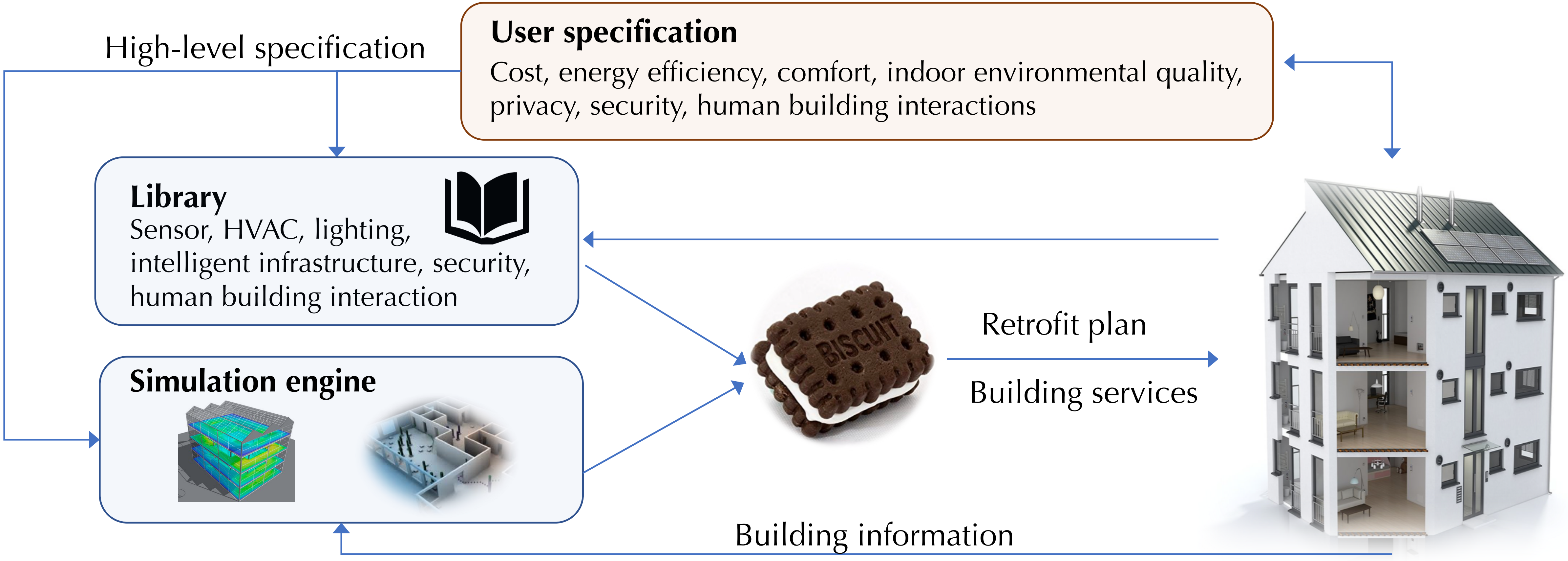


Automobiles

- Computer-aided design (CAD)
  - Efficient design space exploration
  - Automated constraint verification
  - Performance simulation
  - Optimal design
- Smart building design considerations:
  - Interaction among subsystems (HVAC, lighting, security, etc.)
  - Occupancy
  - User specifications (cost, energy efficiency, comfort, privacy, security, enteratinment etc.)

BISCUIT: **B**uilding **I**ntelligent **S**ystem **Cu**stomer **I**nvestment **T**ools

- Idea: Library + Optimization-based design space exploration



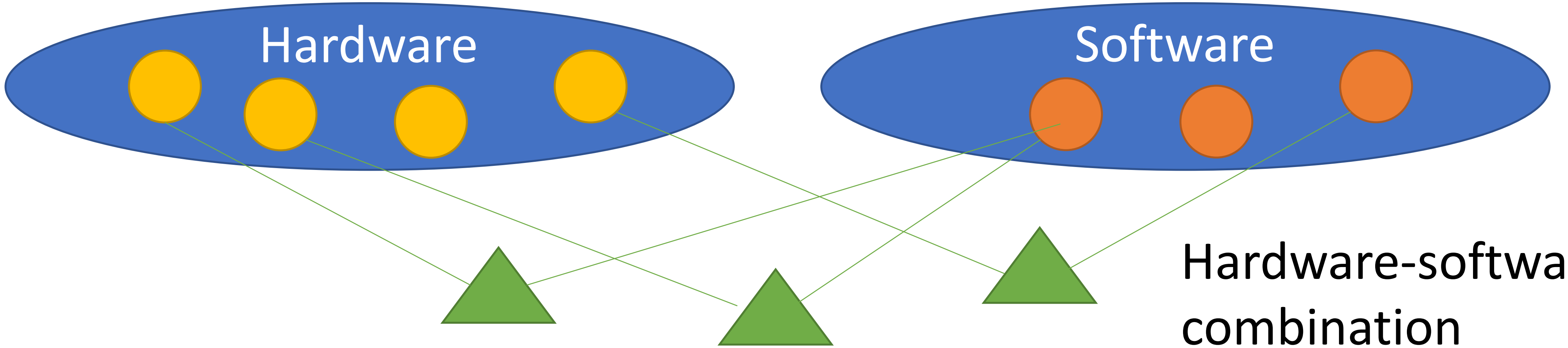
Key idea 1: functional-level abstraction

- Library: sensors, HVAC, lighting, intelligent infrastructure, etc.
- Component: properties and constraints

Library	Items	Properties	Constraints
Sensors	Available sensor models	Sensing modalities (environmental parameters, sound, visual), functions (presence/occupancy/indoor position/identity detection), cost	User specifications (privacy, IEQ, etc.); compatibility with intelligent HVAC/lighting/infrastructure
HVAC	Intelligent/ traditional systems	Vendor, investment cost, maintenance cost, rate power, efficiency, lifespan, supported control strategies	User specifications (intelligence upgrade, safety), requirement on the existence of compatible sensors and intelligent infrastructures
Lighting	Intelligent/ traditional systems	Vendor, investment cost, maintenance cost, rate power, efficiency, lifespan, supported control strategies	
Security	Available systems	Vendor, investment cost, subscription cost, lifespan	
HBI	Available systems	Maintenance cost, lifespan, control strategies, efficiency	
Infrastructure	Available packages	Vendor, cost, maintenance cost, lifespan	User specifications

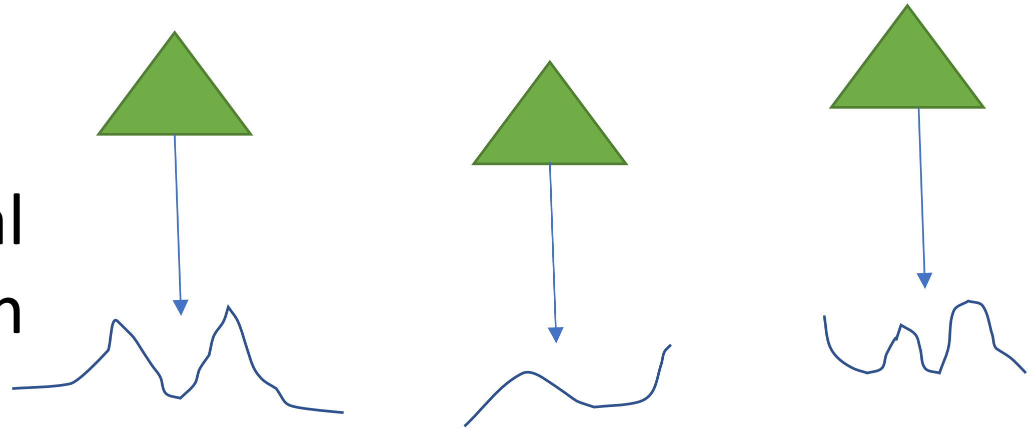
Key idea 2: software-hardware co-design

- Software design includes control algorithms and strategies:
  - Rule-based control, demand-based control, model-predictive control, reinforcement learning, etc.
- Each software candidate has hardware requirements, and can influence the efficiency of operations



Hardware-software combination

Key idea 3: simulation-based abstraction



- Obtain operational characteristics (energy consumption, maintenance costs) for the given occupancy profile
- Higher-level information to be incorporated in optimization

Formulation of intelligent building design

min **investment cost** + **annual operation cost**

s.t. **(1)** user specifications
(2) technology constraints
(3) operation constraints

- Mixed integer linear program
- Optimization over both integer and continuous variables:
    - Investment decision (binary)
    - System control strategy (binary)
    - Operational variables (continuous)

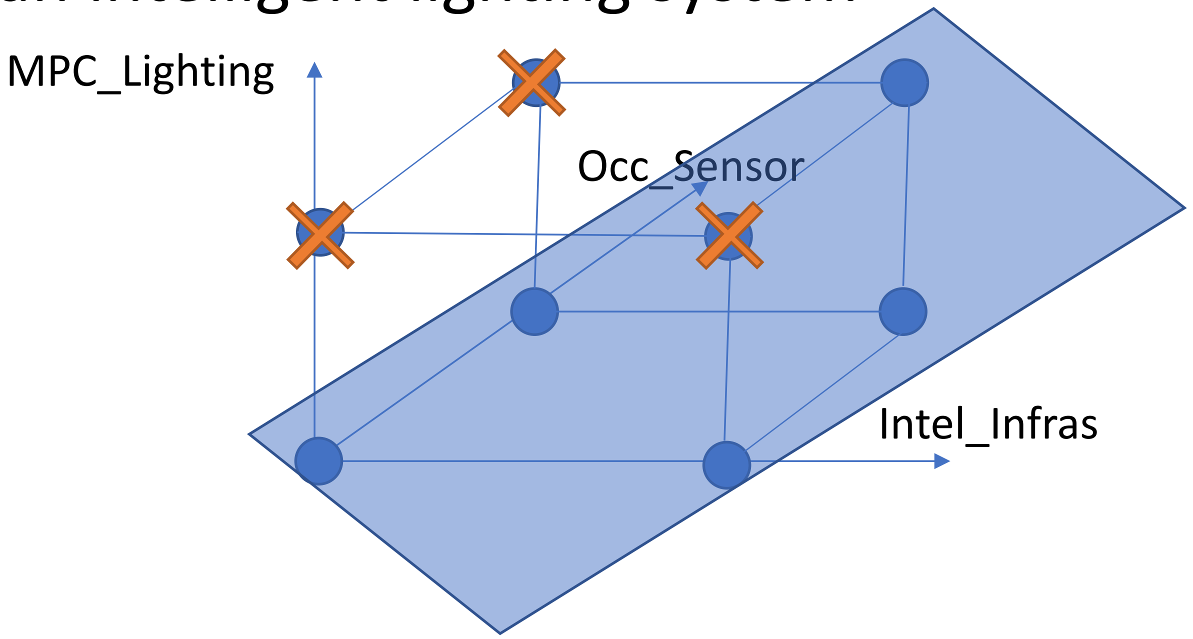
Encoding logical relations as linear constraints

- Example: model-predictive control of lighting is possible only if there exists an occupancy sensor and an intelligent lighting system

If MPC_Lighting=1
then Occ_Sensor=1 and Intel_Infras=1

⇕

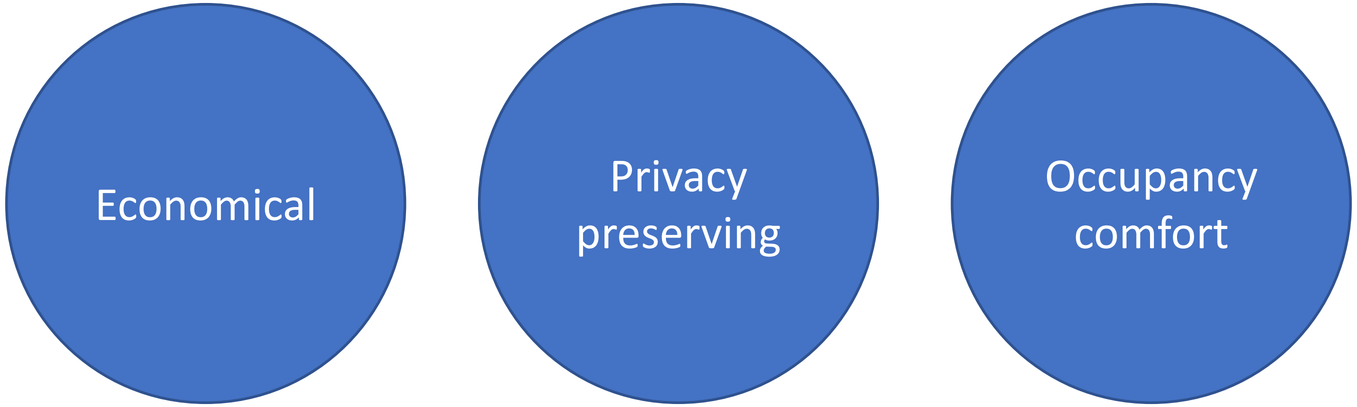
2*MPC_Lighting ≤ Occ_Sensor+Intel_Infras
MPC_Lighting, Occ_Sensor, Intel_Infras ∈ {0,1}

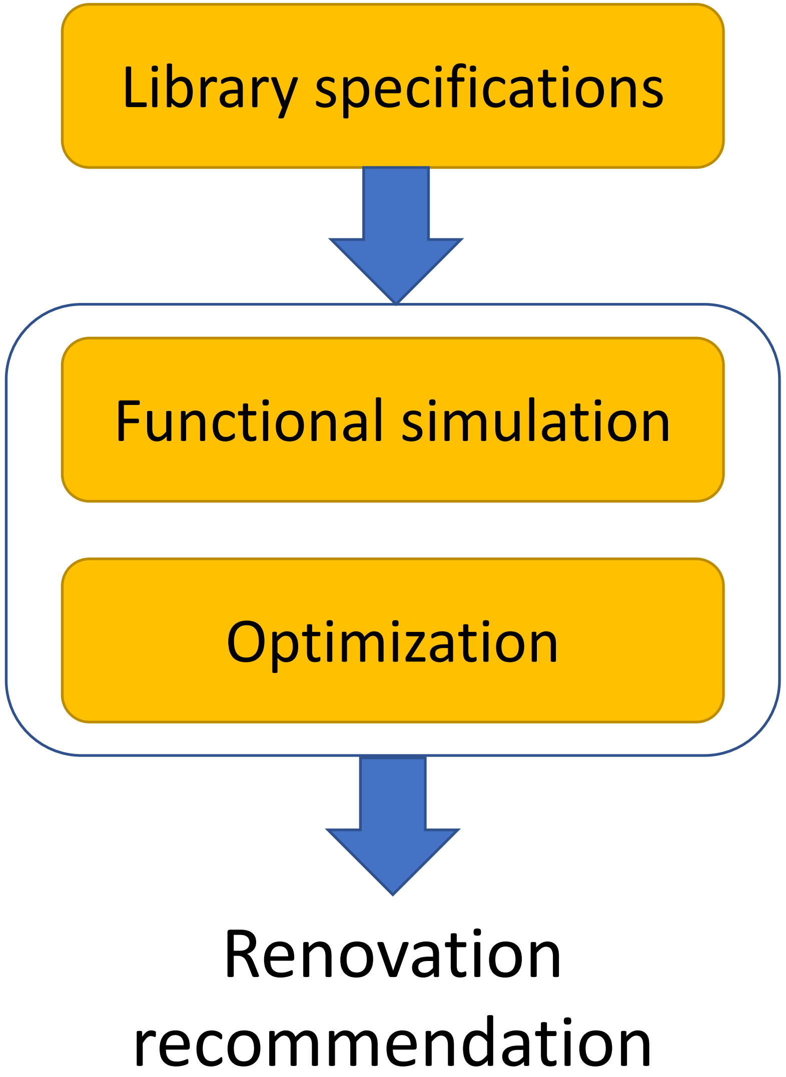


- This can be extended to logical relations of more than 3 variables
- The construction of constraints can be automated

Case study: medium-sized commercial building renovation

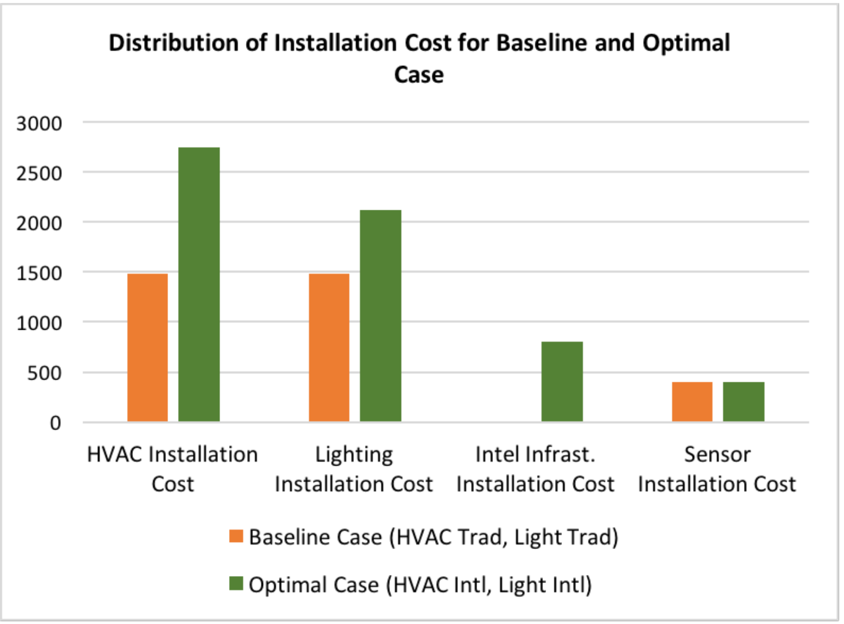
- Goal: finds the most economical plan to renovate a commercial building to be more comfortable and energy efficient

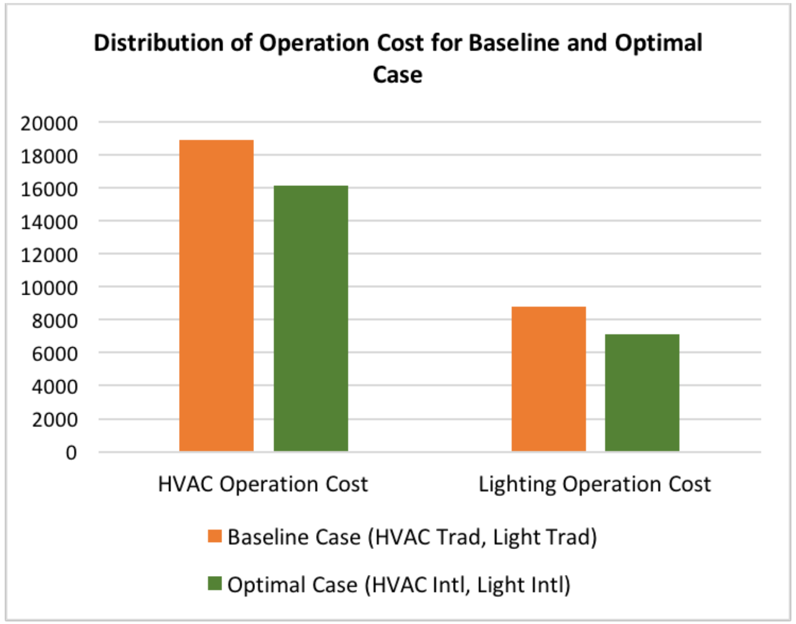


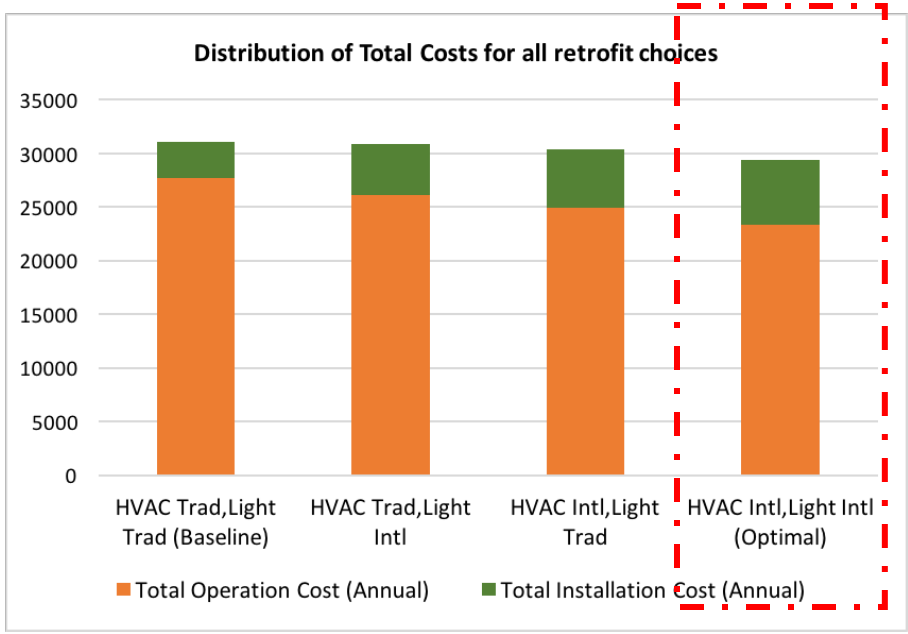


Case study: medium-sized commercial building renovation

- Setup: a medium-sized building (40 rooms, 100 occupants) in California, USA
- RSMeans cost manual and market prices







Conclusion and future work

- Formulation of the intelligent building design problem as a mixed integer programming
- Propose a platform-based design method: library + optimization
- Evaluated the tool for medium-sized commercial building renovation

Future work…

- Extend the tool to interface with more building simulators, code auto-generators, component libraries

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Acknowledgement

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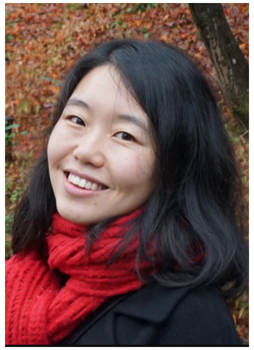
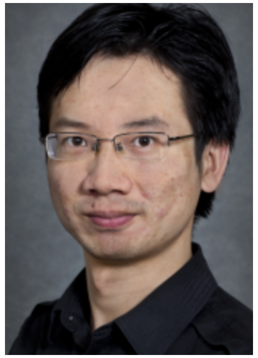
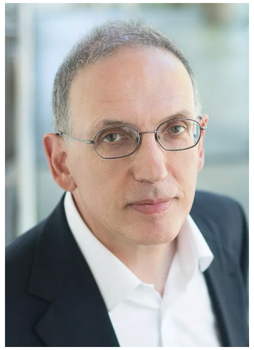

Ruoxi Jia


Hari Das


Wei Feng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