Modelling of Building Energy Use and Carbon Emissions

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Introduction

- **Energy** is important to every society
  - Economic, environmental & social impacts
  - It is also a key issue for *sustainable development*

- Use energy …
  - Consume finite fossil fuels (oil, coal, natural gas)
  - Cause air pollution & environmental damage
  - Contribute to global warming
  - Cost money
World total final consumption from 1971 to 2009 by fuel (Mtoe)

World CO₂ emissions from 1971 to 2009 by fuel (Mt of CO₂)

***Other includes industrial waste and non-renewable municipal waste

Energy efficiency potential used by sector: a huge opportunity going unrealised

The building sector has the largest potential

Energy end-use in Hong Kong by sectors, 1984-2009

(Data source: EMSD)
Energy end-use by sector (2009)

Residential: 19%
Commercial: 40%
Transport: 32%
Industrial: 9%

(Data source: EMSD)
Greenhouse gas (GHG) emission trends of Hong Kong 1990-2008

(Source: www.epd.gov.hk)
Greenhouse gas (GHG) emission of Hong Kong 2008
## Timeline of building energy efficiency regulations in Hong Kong

<table>
<thead>
<tr>
<th>Period</th>
<th>Key Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>1991-1995</td>
<td>• 1991 Feasibility study on introduction of OTTV control in Hong Kong</td>
</tr>
<tr>
<td></td>
<td>• 1995 Building (Energy Efficiency) Regulations (Cap. 123 sub. Leg. M); HK OTTV Code of Practice</td>
</tr>
<tr>
<td></td>
<td>• 1999 Electrical Code</td>
</tr>
<tr>
<td></td>
<td>• 2000 Lift and Escalator Code; Revised OTTV limits</td>
</tr>
<tr>
<td></td>
<td>• 2005 Updated edition of the five codes</td>
</tr>
<tr>
<td>2006-2010</td>
<td>• 2007 Updated edition of the five codes; Updated Guidelines on Energy Audit</td>
</tr>
<tr>
<td></td>
<td>• 2010 Buildings Energy Efficiency Ordinance (Cap. 610) (mandatory)</td>
</tr>
<tr>
<td>2011-Now</td>
<td>• 2011 Revised OTTV limits</td>
</tr>
<tr>
<td></td>
<td>• 2012 Full operation of the Buildings Energy Efficiency Ordinance (including Building Energy Code and Energy Audit Code)</td>
</tr>
</tbody>
</table>
The Buildings Energy Efficiency Ordinance

Air-conditioning installation

Lift & escalator installation

Energy Audit Form

(Source: EMSD)

(See http://www.beeo.emsd.gov.hk for details)
Building Energy Simulation

- Energy performance of buildings is usually complicated and requires detailed analysis to determine the characteristics.
- Building energy simulation and modelling techniques are often used to study it so as to support decisions for building design, operation and management.
Ways to study a system

- Experiment with the actual system
  - Physical model
  - Analytical solution

- Experiment with a model of the system
  - Mathematical model
  - Simulation
Building Energy Simulation

• **Simulation**: (模擬)
  - From Latin “*simulare*” – to pretend
  - Using a mathematical model of a system to predict its output for a given input
    - Asking “*what if*?” within an imaginary framework
  - To simulate => to imitate the operations of real-world facilities or process

• Examples:
  - Computer simulation games like “SimCity”
  - A child who role plays with toys
SimCity of Hong Kong’s buildings
Building Energy Simulation

• **Simulation**
  - The process of developing a representative model of a system and using it to analyze and predict system behaviour and performance

• **Modelling**
  - Deals primarily with the relationship between actual dynamic processes and models
  - Usually involves iterations
* Simulation enables the performance of the building to be established before critical design decisions are taken, enabling optimum building performance to be obtained.
Key factors influencing energy consumption

(Source: Energy Efficiency in Buildings: CIBSE Guide F)
Energy flow and concept in buildings
Components of building cooling load

External loads:
- Solar radiation
- Conductive heat gains
- Infiltration of hot air

Internal loads:
- Electric lighting
- Computer and equipment
- Occupant

+ Ventilation load & system heat gains
Building energy simulation process

- Energy input by appliance
- Energy input by HVAC air/water systems
- Energy storage

**HVAC air systems**

**HVAC water systems**

**Plant (water-side & refrig.)**

Sources of Cooling Load

- solar radiation
- conductive heat gains
- infiltration
- hot air
- electric lighting
- computer & equipment
- occupant

Thermal Zone

Energy input by HVAC plant
Building Energy Simulation

- Building energy simulation can be used to:
  - Assess building design (design evaluation tool)
  - Calculate energy saving or performance (building energy analysis tool)
  - Evaluate energy cost (economic analysis tool)
  - Design & optimise building systems (system design/optimization tool)
  - Satisfy energy code (code compliance tool)
  - Support green building assessment (green design tool)
Building Energy Simulation

• Model existing buildings
  • Useful for “energy performance contracts”
  • Help improve the bldg’s operation/control
• Evaluate energy conservation measures (ECM)
  • Estimate energy savings
  • Study the costs and benefits
  • Provide info to design, retrofit & operation
• Comply with building energy code
  • Such as performance-based building energy code
Building Energy Simulation

- For green building assessment (e.g. LEED)
- Using ASHRAE 90.1 Building Energy Standard to check compliance and determine credits
- Energy cost budget (ECB) method
  - To determine minimum compliance
  - Design Energy Cost $\leq$ Energy Cost Budget
- Appendix G: building performance rating method
  - To rate the energy efficiency of building designs that exceed the requirements of the standard 90.1
  - $\%$ improvement = $\frac{\text{Baseline} - \text{Proposed}}{\text{Baseline}} \times 100\%$
Building Energy Simulation

• What can building simulation do?
  • Compare different design options
    • Based on energy performance, peak demand, and cost-benefit implications
  • Predict the dynamic response and performance of buildings
  • Evaluate complex, innovative and ‘green’ technologies
    • Such as natural ventilation, advanced controls operation and passive design
Building Energy Simulation

• Further reading:
Simulation Tools

- **Types of building simulation tools**
  - *Simplified software* for overall energy consumption assessment, peak temperature prediction, cooling/heating load calculations
  - *Sophisticated software* for hourly simulation of heat, light & air movement
  - *Complex specialist software*, for lighting, computational fluid dynamics (CFD), 2- and 3-dimensional conduction calculations
  - *Integrated design and analysis systems* which combine a number of the above categories
Building Energy Simulation Software

- Solar-5
- DOE-2
- ESP-r
- TRNSYS
- Hot2000
- EE4
- E-20-II & HAP
- TRACE 700
- IES-VE
- Carrier
- Tas
- Adeline
Simulation Tools

• Many software tools in the market
  • From simplified to complicated one
  • Select according to the task
• For beginners, we recommend
  • Energy-10, HAP, TRACE 700, eQUEST
• For sophisticated study, may consider
  • DOE-2, EnergyPlus, ESP-r, TRNSYS, IES-VE
• Further information:
  • Building Energy Software Tools Directory (by US-DOE)
    • http://www.eere.energy.gov/buildings/tools_directory/
Simulation Tools

• Examples of building energy simulation tools
  • **Energy-10**
    • [http://www.sbicouncil.org/energy-10-software](http://www.sbicouncil.org/energy-10-software)
  • **VisualDOE** (based on DOE-2.1e)
    • [http://gundog.lbl.gov/dirsoft/d2whatis.html](http://gundog.lbl.gov/dirsoft/d2whatis.html)
  • **MIT Design Advisor** (do online simulation)
    • [http://designadvisor.mit.edu/design/](http://designadvisor.mit.edu/design/)
Example: Energy-10

*ENERGY-10* focuses on the first phases (conceptual design)

<table>
<thead>
<tr>
<th>Phase</th>
<th>Activity</th>
<th>Tool</th>
</tr>
</thead>
<tbody>
<tr>
<td>Develop Brief</td>
<td>Develop reference case</td>
<td>ENERGY-10</td>
</tr>
<tr>
<td></td>
<td>Develop low-energy case</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rank order strategies</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Initial strategy selection</td>
<td></td>
</tr>
<tr>
<td>Pre-design</td>
<td><strong>Set performance goals</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Review goals</td>
<td>Preliminary team meetings</td>
</tr>
<tr>
<td></td>
<td>Review strategies</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Set criteria, priorities</td>
<td></td>
</tr>
<tr>
<td>Schematic Design</td>
<td>Develop schemes</td>
<td>EnergyPlus or other HVAC simulation and tools</td>
</tr>
<tr>
<td></td>
<td>Evaluate schemes</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Select scheme</td>
<td></td>
</tr>
<tr>
<td>Design Development</td>
<td>Confirm that component performances are as assumed</td>
<td></td>
</tr>
<tr>
<td>Construction Documents</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Example: Energy-10
Example: Energy-10

- Creates two building descriptions based on five inputs and user-defined defaults.

**Location**
- Building Use
- Floor area
- Number of stories
- HVAC system

**For example:**

<table>
<thead>
<tr>
<th>Reference Case</th>
<th>Low Energy Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-8.9 walls (4&quot; steel stud)</td>
<td>R-19.6 Walls (6&quot; steel stud with 2&quot; foam)</td>
</tr>
<tr>
<td>R-19 roof</td>
<td>R-38 roof</td>
</tr>
<tr>
<td>No perimeter insulation</td>
<td>R-10 perimeter insulation</td>
</tr>
<tr>
<td>Conventional double windows</td>
<td>Best low-e double windows</td>
</tr>
<tr>
<td>Conventional lighting</td>
<td>Efficient lights with daylight dimming</td>
</tr>
<tr>
<td>Conventional HVAC</td>
<td>High efficiency HVAC</td>
</tr>
<tr>
<td>Conventional air-tightness</td>
<td>Leakage reduced 75%</td>
</tr>
<tr>
<td>Uniform window orientation</td>
<td>Passive solar orientation</td>
</tr>
<tr>
<td>Conventional HVAC controls</td>
<td>Improved HVAC controls</td>
</tr>
<tr>
<td>Conventional duct placement</td>
<td>Ducts located inside, tightened</td>
</tr>
</tbody>
</table>

*Get you started quickly.*
Example: Energy-10

2,000 m² office building

ANNUAL ENERGY USE

<table>
<thead>
<tr>
<th>Component</th>
<th>Reference Case</th>
<th>Low-Energy Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating</td>
<td>47.3</td>
<td>1.5</td>
</tr>
<tr>
<td>Cooling</td>
<td>6.7</td>
<td>4.1</td>
</tr>
<tr>
<td>Lights</td>
<td>15.1</td>
<td>6.9</td>
</tr>
<tr>
<td>Other</td>
<td>27.4</td>
<td>22.7</td>
</tr>
<tr>
<td>Total</td>
<td>96.5</td>
<td>35.1</td>
</tr>
</tbody>
</table>
Example: Energy-10

RANKING OF ENERGY-EFFICIENT STRATEGIES

Duct Leakage
Glazing
Insulation
Energy Efficient Lights
HVAC Controls
Air Leakage Control
Shading
Daylighting
High Efficiency HVAC
Economizer Cycle
Thermal Mass
Passive Solar Heating

Net Present Value, 1000 $

-100 -50 0 50 100 150

115.04
72.49
57.33
56.56
48.43
45.92
45.24
38.84
37.82
-57.14
-4.02
-6.23
-57.14
Example: Energy-10

Average Hourly HVAC Energy Use by Month

- Heating
- Cooling
- Inside T
- Outside T
Example: Energy-10

Components of Life-Cycle Cost

![Chart showing the components of life-cycle cost for Building 1 and Building 2, including capital, property taxes, utilities, maintenance, mortgage, HVAC replacement, tax deductions, and life cycle cost, with a present value axis ranging from -600,000 to 1,200,000 dollars.]
Example: VisualDOE

- VisualDOE Interface
  - Project File
  - VisualDOE Library File
  - DOE-2 Input File
    - Weather File
    - DOE-2 Library
  - DOE-2 Output File
  - Text Processor
  - Reports
Example: VisualDOE

DOE-2
Example: VisualDOE
Example: VisualDOE
Example: VisualDOE

### VisualDOE 4.0 - Results

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Total Electric</th>
<th>Total Fuel</th>
<th>Total Utility</th>
<th>Incremental First Cost</th>
<th>PV Life Cycle Cost^1</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASHRAE 90.1 Budget Design Case</td>
<td>$214,115</td>
<td>$50,449</td>
<td>$264,564</td>
<td>$0</td>
<td>$2,252,383</td>
</tr>
<tr>
<td>Proposed Design</td>
<td>$203,404</td>
<td>$76,084</td>
<td>$251,466</td>
<td>$0</td>
<td>$2,396,466</td>
</tr>
</tbody>
</table>

**Incremental Energy Savings ($/y)** (compared with previous alternative, negative savings represent those savings)

| Proposed Design | $10,711 | $-27,635 | $-16,924 | $0 | $-144,084 |

^1 20 year life cycle w/ 10% discount rate.
Example: VisualDOE

Electric End Uses

- Lights
- Equipment
- Cool
- Tower
- Pumps
- Fans
- Exterior Equipment

kWh/y

693424
25507
45294
36679
673682
Example: VisualDOE

Monthly Electricity

- Existing Building
- ASHRAE 90.1 Budget Design Case
- Proposed Design

kWh

Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec

0 | 50000 | 100000 | 150000 | 200000

Graphs:
- Monthly Electricity
- Monthly Electric Demand
- Monthly Fuel
- Monthly Electricity and Fuel
- Energy Cost
- Average Temperatures
- Degree Days

Design Alternatives:
- Existing Building
- ASHRAE 90.1 Budget Design Case
- Proposed Design

Update Graph
Copy Graph
Edit Graph
Exit
UPDATE - Changes have been made to the MIT Design Advisor!

Building energy simulation in minutes.

Overview
Architects and Building Designers can use computer modeling to improve indoor comfort and energy performance of conceptual building designs. But most simulation tools are too complicated for this purpose.

Quick, visual comparisons are needed for early-stage design. The MIT Design Advisor is a tool which allows you to describe and simulate a building in less than five minutes. No technical experience or training is needed. An annual energy simulation can be run in less than a minute, and graphical results are immediately available for review. Give it a try.

Getting Started
1. Begin by clicking the SETUP tab to the left and follow the directions to create a building design.
2. To save and simulate your building scenario, click Save on one of the colored scenario boxes at the bottom panel.
3. View the simulation results by clicking on any of the tabs to the left (Comfort, Energy, etc.)

Look for the information buttons for extra help:

About Us
MIT Building Technology Program
NE Solar Incubator

MIT Design Advisor, http://designadvisor.mit.edu/design/
Practical Techniques for Building Simulation
Modelling Process

• How to perform building simulation?
  • Select and master how to use a program
  • Represent the building and HVAC systems
    • Construct the simulation model
  • Prepare the input data
  • Run and control the program
  • Interpret the results, analysis and reporting
    • e.g. determine energy and cost savings
Building description
- physical data
- design parameters

Simulation tool (computer program)

Simulation outputs
- energy consumption (MWh)
- energy demands (kW)
- environmental conditions
# Building energy simulation: Inputs and Outputs

<table>
<thead>
<tr>
<th><strong>INPUTS:</strong></th>
<th><strong>OUTPUTS:</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>- Weather data</td>
<td>- Space temperatures</td>
</tr>
<tr>
<td>- Building geometry</td>
<td>- Surface temperatures</td>
</tr>
<tr>
<td>- Construction type</td>
<td>- Humidity levels</td>
</tr>
<tr>
<td>- HVAC type / usage</td>
<td>- HVAC parameters</td>
</tr>
<tr>
<td>- Occupancy info</td>
<td>- Energy consumption</td>
</tr>
<tr>
<td>- Quantity of users</td>
<td>- Component</td>
</tr>
<tr>
<td>- Lights</td>
<td>- System</td>
</tr>
<tr>
<td>- Equipment</td>
<td>- Whole-building</td>
</tr>
<tr>
<td>- Usage</td>
<td></td>
</tr>
</tbody>
</table>
Garbage In, Garbage Out (GIGO)
Modelling Process

• Building energy simulation is based upon
  • Load calculation – thermal or HVAC
    • Determine peak HVAC design loads
  • Energy calculation – energy to meet the loads
    • Estimate annual energy requirements

• Time intervals
  • Full hour-by-hour (8,760 hours = 365 x 24)
  • Simplified hourly: e.g. one day per month
  • Bin method or degree days
Major elements of building energy simulation

- Climatic influence
- Building design parameters
- Building model
- HVAC system model
- HVAC plant model
- Control system model
- Indoor environmental conditions
- Energy performance
Information flow in building simulation

- Input:
  - Climatic data
  - Bldg. Info.
  - AC system info.
  - Plant info.
  - Econ. Info.

- Simulation process:
  - LOAD
  - SYSTEMS
  - PLANT
  - ECONOMICS

- Output:
  - Bldg. load
  - AC system energy
  - AC plant energy
  - Econ. results
Make things as simple as possible, and no simpler. (Albert Einstein)
Combine several rooms into one zone
Assess Carbon Emissions

• **Carbon** is frequently used as shorthand for either carbon dioxide (CO$_2$) or carbon dioxide equivalents (CO$_2$-e) of greenhouse gases
  • Used as an indicator for environmental impact or sustainability level

• **Carbon footprint**
  • Measure the exclusive direct (on-site, internal), and indirect (off-site, external, embodied, upstream, and downstream) CO$_2$ emissions of an activity, or over the life cycle of a product, measured in kg
Urban cities and their ecological footprints

Human needs and development

Supporting ecosystems and resource base

Supply  Waste

Waste Supply
Carbon footprint of a building and its components

- Building construction
- Building operation
- Building renovation
- De-construction

- Materials manufacturing
- Materials transport
- Demolition wastes transport
- Demolition wastes treatment
- Electricity consumption
- On-site fuel consumption
- On-site waste water treatment
- On-site solid wastes treatment
- Industrial processes housed in the building
Assess Carbon Emissions

- International standards for carbon footprint calculation and analysis
  - ISO 14040: Life Cycle Assessment - Principles and Framework
  - BSI: PAS 2050 - Specification for the Assessment of Life-Cycle GHG Emissions of Goods/Services
  - WRI/WBCSD: Greenhouse Gas Protocol
  - IPCC: 2006 Guidelines for National Greenhouse Gas Inventories
Cradle-to-grave is the full Life Cycle Assessment from resource extraction ('cradle') to use phase and disposal phase ('grave').
Life Cycle Assessment

- Transportation
- Water use
- Energy use
- Resource extraction effects
- Emission to air
- Solid wastes
- Emission to water

LCA: a methodology for assessing the life cycle environmental performance of products and processes
Life cycle assessment framework

Goal, scope and definition

Inventory analysis

Impact assessment

Interpretation

(Source: US-EPA)
Assess Carbon Emissions

• HK’s carbon audit guidelines for buildings to report on greenhouse gas emissions focus on:
  • Physical boundaries (site boundaries of building)
  • Operational boundaries (to identify and classify the activities to determine the scope)
    • Scope 1 – direct emissions and removals
    • Scope 2 – energy indirect emissions
    • Scope 3 – other indirect emissions
  • Reporting period (usually one year)
  • Collecting data and information to quantify the greenhouse gas performance
Scope of greenhouse gas (GHG) emissions

(Source: UNEP Sustainable Buildings and Climate Initiative, www.unepsbci.org)
The 5 sectors of ecological footprint (for Hong Kong)

- Energy Use
- Water Use
- Food Consumption
- Material Use
- Urban Use

(Source: Friends of the Earth (Hong Kong), www.foe.org.hk)
Energy efficiency standards focus on just 24% of the total CO₂. Operational Carbon: 65%
Balancing carbon emissions for zero carbon buildings (ZCB)

Balancing Carbon

Operating energy of building
Embodied carbon in building materials
People, "use" and transportation

- On-site renewable and generation
- Off-site renewable, generation and supply
- Other purchased carbon offsets

Zero "0"
Allowable emission reduction options for zero carbon buildings

1. Energy Efficiency

2. On-site renewable / low carbon energy
   - 2a: In building footprint
   - 2b: On land title
   - 2c: Private wire
   - 2d: On-site generation from off-site resources

3. Off-site renewable / low carbon energy
   - 3a: Off-site generation
   - 3b: Off-site supply e.g. Green Power
Assess Carbon Emissions

- Current limitations
  - Unclear definition of ‘zero carbon’
  - Lack of scientific assessment methods for carbon footprint of building projects
  - Limited data availability and uncertainty of data
  - Complicated process for whole life cycle analysis
  - Still weak market demand and awareness

- Future research
  - Zero carbon building: definition
  - Assessment tool for footprint analyses
THANK YOU 謝謝

Questions?