Integrative design for radical efficiency at lower cost

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Hibiya Tōkyō Midtown, 5 October 2018
Edwin H. Land (1909–91)

“People who seem to have had a new idea have often just stopped having an old idea.”

Bú wàng chū xīn
Hoshin wasuru bekarazu
Don’t forget original mind

—Avataṃsaka Sūtra, 華嚴經, 대방광불화엄경
The Nine Dots Problem

Art by Chris Lotspeich...
The Nine Dots Problem
The Nine Dots Problem
origami solution
geographer’s solution
mechanical engineer’s solution
statistician’s solution
“wide line” solution
## Component-optimization vs. integrative design

Typical analysis for a 1,208-m² Denver office

<table>
<thead>
<tr>
<th>Energy Measure</th>
<th>Incremental Cost</th>
<th>Annual Savings</th>
<th>Payback Period (yrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daylighting</td>
<td>$4,900</td>
<td>$1,560</td>
<td>3.14</td>
</tr>
<tr>
<td>Glazing</td>
<td>$5,520</td>
<td>$1,321</td>
<td>4.18</td>
</tr>
<tr>
<td>Energy Efficient Lighting</td>
<td>$1,400</td>
<td>$860</td>
<td>1.63</td>
</tr>
<tr>
<td>Energy Efficient HVAC</td>
<td>$3,880</td>
<td>$739</td>
<td>5.25</td>
</tr>
<tr>
<td>HVAC Controls</td>
<td>$2,900</td>
<td>$506</td>
<td>5.73</td>
</tr>
<tr>
<td>Shading</td>
<td>$4,800</td>
<td>$325</td>
<td>14.77</td>
</tr>
<tr>
<td>Economizer Cycle</td>
<td>$1,200</td>
<td>$165</td>
<td>7.27</td>
</tr>
<tr>
<td>Insulation</td>
<td>$1,600</td>
<td>$101</td>
<td>15.84</td>
</tr>
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Each improvement by itself is too expensive for a cash-short developer.
Component-optimization vs. integrative design
Analysis for a typical 1,208-m² Denver office

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<tr>
<td>Fewer E &amp; W Windows</td>
<td>-$4,160</td>
</tr>
<tr>
<td>Small &amp; Different HVAC</td>
<td>-$17,700</td>
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</table>

net investment: $4,350

saving ~$4,500/y in energy—a 1-y payback
Multiple benefits from single expenditures

Save energy and capital costs throughout the design

- 10 benefits from superwindows
- 18 from efficient motors and dimming ballasts
- A front-end part in a Lotus *Elise* car has 7 functions but one cost
- My home’s central arch has 12 functions but one cost

**Grand Forks (North Dakota) office—subarctic**

**Incremental costs**

<table>
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<tr>
<th>Item</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Windows</td>
<td>$67,500</td>
</tr>
<tr>
<td>Daylighting</td>
<td>$18,000</td>
</tr>
<tr>
<td>Insulation</td>
<td>$17,200</td>
</tr>
<tr>
<td>Lighting</td>
<td>$21,000</td>
</tr>
<tr>
<td>HVAC</td>
<td>−$160,000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>−$36,300</td>
</tr>
</tbody>
</table>

**Energy savings: $75,000/year**

Greg Franta FAIA, deceased Team Leader, RMI/ENSAR Built Environment
Lovins House, Old Snowmass, Colorado (1983)
US office buildings: $3-4\times$ energy efficiency worth $4\times$ its cost (site energy intensities in kWh/m$^2\cdot$y; US office median ~293)

Yet all the technologies in the 2015 example existed well before 2005!
5x-more-efficient new Indian commercial buildings

Infosys’s 1.5 million m$^2$ of 22k-m$^2$ office blocks (2009–14) in six Indian cities:

Site energy use (EPI) fell 80%, to 66 kWh/m$^2$-y
with construction cost 10–20% lower than usual, and comfort better

Courtesy of Peter Rumsey PE FASHRAE (Senior Advisor, RMI) and Rohan Parikh (then at Infosys in Bengaluru, now at McBERL)
Cooling midrise apartment buildings in India

These convective double-wall building envelopes need little or no air conditioning, cost 2% more; 0.2 million m² were successfully built 1998–2000 in Powai and Thane near Mumbai.
“Factor-Ten Modernizations” (retrofits) in Hannover (from proKlima 2010):
L 15 kWh/m²y, R 21 kWh/m²y

Before and after passive-house treatment
Installing *interior* superinsulation

“Energiesprong” unsubsidized mass retrofit of public housing

Before: 5 Dutch units, each with annual energy bills ~€1.5–2k

After: net-zero-energy, expected to be financed just from energy savings by industrializing the €460k (soon €40k)/unit retrofit
"Tunneling through the cost barrier" in peer-reviewed studies of ambitious European building retrofits.

European retrofitted building savings reported 2006–13 (IPCC AR5 WG3 p 703), 3%/y real discount rate over 30 y.

Note that the better cases show virtually no rise in cost up to >90% savings. Some cases cost more, but they needn't. Some examples do show higher costs, but they needn't: they should just emulate best practice.

IPCC AR5 WG3 pp 702–704 (2014) reports that high-ambition European new (left) and retrofit (right) buildings show no significant increase in the cost of saved energy up to ≥90% savings. Some examples do show higher costs, but they needn't: they should just emulate best practice.
Germany’s 2017 analysis of national building-sector improvement potential: save the climate while saving money and making good durable jobs

81–86% (mainly 84–86%) CO$_2$ reductions from buildings’ primary energy (L) via diverse trajectories with similar costs (R)—all far cheaper than business-as-usual

Umweltbundesamt (Berlin), Klimaneutraler Gebäudebestand 2050, Nov 2017
Integrative Design in Retrofitting the Empire State Building
Integrative Design in Retrofitting the Empire State Building

- Windows: $4M
- Radiative Barrier: $2.7M
- DDC Controls: $5.6M
- VAV AHUs: $2.4M
- Lighting & Plugs: $8.7M
- Avoided Chiller Plant Retrofit: $8.7M
- Annual Savings: $4.4M

Minus $17.4
Similar results in a Japanese office, without superwindows

Rohm HQ, Kyoto
44% energy saving by retrofit
2-years payback

Primary energy consumption (MJ)

Before retrofit
After retrofit

planned -30%
implemented -44%

Primary energy consumption - intensity (MJ/m²)

Before retrofit
After retrofit-Planned
After retrofit-actual

Courtesy of Yanase Masaake-san via Iida Tetsunaru-san
75% retrofit saving in an office like ~80% of Japan’s offices

Takenaka’s 1318-m² two-story Higashi Kantō office, Chiba-shi
Built 2003, renovated 2015
Latest primary EUI = 348 MJ/m²y,
~75% below original ~1400
Now a Positive-Energy Building

Sources: 竹中工務店東関東支店ZEB 化改修: 田中 宏治, 筑竹中工務店 設計部設備部門;
Packard Foundation Headquarters
Los Altos, CA, 2012
18,606-m² 1974 Chicago curtainwall office tower: a 1994 retrofit integrative design
<table>
<thead>
<tr>
<th>Calculated Energy Saving</th>
<th>Approx. Marginal Investment</th>
<th>Months' Payback (Typical)</th>
</tr>
</thead>
<tbody>
<tr>
<td>76%</td>
<td>$/m²</td>
<td>-5</td>
</tr>
</tbody>
</table>

18,606-m² 1974 Chicago curtainwall office tower: a 1994 retrofit integrative design
The right steps in the right order: lighting

1. Improve visual quality of task
2. Improve geometry of space, cavity reflectance
3. Improve lighting quality (cut veiling reflections and discomfort glare)
4. Optimize lighting quantity
5. Harvest/distribute natural light
6. Optimize luminaires
7. Controls, maintenance, training

Photos courtesy of Clanton & Associates, Boulder, CO
The right steps in the right order: space cooling

0. Cool the people, not the building
1. Expand comfort envelope
2. Minimize unwanted heat gains
3. Passive cooling
4. Active nonrefrigerative cooling
5. Superefficient refrigerative cooling
6. Coolth storage and controls

Result: ~90–100% less energy, more comfort, lower capex, higher uptime
Superefficient big refrigerative HVAC too

(10^5+ m^2 water-cooled centrifugal, Singapore, turbulent induction air delivery — but underfloor displacement could save even more energy)

<table>
<thead>
<tr>
<th>Element</th>
<th>Std kW/t (COP)</th>
<th>Best kW/t (COP)</th>
<th>How to do it</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply fan</td>
<td>0.60</td>
<td>0.061</td>
<td>Best vaneaxial, ~0.2–0.7 kPa TSH (less w/UFDV), VAV</td>
</tr>
<tr>
<td>ChWP</td>
<td>0.16</td>
<td>0.018</td>
<td>120–150 kPa head, efficient pump/motor, no pri/sec</td>
</tr>
<tr>
<td>Chiller</td>
<td>0.75</td>
<td>0.481</td>
<td>0.6–1 Cº approaches, optimal impeller speed</td>
</tr>
<tr>
<td>CWP</td>
<td>0.14</td>
<td>0.018</td>
<td>90 kPa head, efficient pump/motor</td>
</tr>
<tr>
<td>CT</td>
<td>0.10</td>
<td>0.010</td>
<td>Big fill area, big slow fan at variable speed</td>
</tr>
</tbody>
</table>

**TOTAL**

1.75 (COP 2.01) 0.588 COP 5.98, 3x better

**Better comfort, lower capital cost**

Best Singapore practice with dual ChW temp., e.g. 4.5°C condensing and 12°C sensible: **0.52 total kW/t** including 0.41 chiller, **COP 6.8**
Low-face-velocity, high-coolant-velocity coils

Correct a 1921 mistake about how coils work

Flow is laminar and condensation is dropwise, so turn the coil around sideways, run at <1 m/s (<200 fpm):
29% better dehumidification, ΔP –95%; smaller chiller, fan, and parasitic loads
Designing to save ~80–90% of pipe and duct friction—equivalent to about half the world’s coal-fired electricity

thin, long, crooked

fat, short, straight

Typical paybacks $\leq 1$ y retrofit, $\leq 0$ new-build
But not yet in any textbook, official study, or industry forecast
Retrofitted Low-Friction Piping Layout

Images courtesy of Peter Rumsey, PE, FASHRAE, Senior Advisor, Rocky Mountain Institute

Courtesy of Peter Rumsey, PE, FASHRAE, Senior Advisor, Rocky Mountain institute
Which of these layouts uses less capital and energy?

- Less space, weight, friction, energy
- Fewer parts, smaller pumps and motors, less installation labor
- Less O&M, higher uptime
100 Energy units

-70% Power Plant
-9% Power Grid
-12% Motor/Drivetrain
-55% Pump/Throttle
-20% Pipe

10% Delivered flow
Then cut utility losses by ~50%

...then cut support overhead by 90%

...then cut IT equipment’s internal losses by 75%

First debloat software and ensure that every computation cycle is needed

Start saving downstream for data centers
Principles of integrative building design

• Define the end-use (why cool a building if it can’t feel hot?)
• Optimize the building as a system: costly windows reduce total construction cost
  ➡ Efficiency shrinks or eliminates HVAC; saved capital cost buys the efficiency
• Start saving downstream, at the point of use, shrinking capital cost upstream
• Do the right steps, in the right order, at the right time

And by the way…get rewarded for excelling in these achievements!
Designing for efficiency

- Task elimination before task: why do it?
- Eliminate *muda*, *muri*, *mura*
- Demand before supply
- Downstream before upstream
- Application before equipment
- People before hardware
- Passive before active
- Quality before quantity
Benchmarking a big new office
(~10,000+ m², semitropical climate, no PVs, USA; ~2012 Japan; 2015 1,451-m² RMI Innovation Center; ~2012 India)

<table>
<thead>
<tr>
<th></th>
<th>Normal</th>
<th>Better</th>
<th>Best</th>
</tr>
</thead>
<tbody>
<tr>
<td>delivered MJ/m²-y</td>
<td>1,100/1,737</td>
<td>450–680/566</td>
<td>100–230/126/182/158–194</td>
</tr>
<tr>
<td>del. el. kWh/m²-y (EPI)</td>
<td>270/203/~200–400</td>
<td>160/195</td>
<td>20–40/35/51/&lt;75 (25 cooling)</td>
</tr>
<tr>
<td>lighting W/m² as-used</td>
<td>16–24/12</td>
<td>10</td>
<td>1–3/2/1/&lt;1.6</td>
</tr>
<tr>
<td>plug W/m² as-used</td>
<td>50–90/12</td>
<td>10–20</td>
<td>2</td>
</tr>
<tr>
<td>glazing W/m² K center-of-glass</td>
<td>2.9</td>
<td>1.4</td>
<td>0.3–0.5/0.43/1.1</td>
</tr>
<tr>
<td>glazing T&lt;sub&gt;vis&lt;/sub&gt;/SC</td>
<td>1.0</td>
<td>1.2</td>
<td>&gt;2.0</td>
</tr>
<tr>
<td>perimeter heating</td>
<td>extensive</td>
<td>medium</td>
<td>none/none</td>
</tr>
<tr>
<td>roof α, ε</td>
<td>0.8, 0.2</td>
<td>0.4, 0.4</td>
<td>0.08, 0.97/0.1,0.9</td>
</tr>
<tr>
<td>m²/kW&lt;sub&gt;th&lt;/sub&gt; cooling</td>
<td>7–9</td>
<td>13–16</td>
<td>26–32/+∞/20–26 (750–1000sf/TR)</td>
</tr>
<tr>
<td>cooling syst. COP</td>
<td>1.85</td>
<td>2.3/2.0–2.7</td>
<td>6.8–25+//&gt;6.4 (&lt;0.55 kW/TR)</td>
</tr>
<tr>
<td>relative cap. cost</td>
<td>1.0</td>
<td>1.03</td>
<td>0.95–0.97/1.11/0.85–0.90</td>
</tr>
<tr>
<td>relative space eff.</td>
<td>1.0</td>
<td>1.01</td>
<td>1.05–1.06/1.01</td>
</tr>
</tbody>
</table>

Japan Normal: median of 40 buildings, Energy Conservation Center of Japan; Better: average of six SHASEJ Junen Award-winning buildings; Best: the most efficient of those six buildings (Nissei Yokkaichi Building, 293 MJ), now Takenaka Higashi Kanto 2015 retrofit, ~126 MJ; data courtesy of Urabe-san, CRIEPI, via Asano-sensei, Todai, & Rob Knapp; 2 W/m² lighting is Shimizu Building 2012. India: empirical Infosys new-office performance data from Rohan Parikh; standard estimate from Indian designers—100 of the 200–400 (nom ~250) is cooling.
The secret of great design integration: 
**No compromise!**

“A pelican is not compromise between a seagull and a crow.” It is the best possible pelican (so far)—and after 90 million years, it’s a pretty good one.