Resource-efficient building materials for a sustainable built environment

John E. Fernández
Ferrous metals

Cast irons
- Ductile iron
- Gray iron
- White iron

Carbon 1.8-4% (weight%)

Cast irons
- High carbon steels
- Medium carbon steels
- Low carbon steels

Steels
- Carbon 0.04 - 1.7% (weight%)
  - High alloy
  - Low alloy

- High carbon
- Medium carbon
- Low carbon
- High strength low alloy

Common nonferrous metals

- Pure copper
- Brass Cu + Zn
- Bronze Cu + Sn (10-30%)a
- Cupronickel Cu + Ni (30%)
- Stainless steel Fe + chromium (13-26%)
- Tool steel Fe + tungsten, cobalt
- Tool
- Plain
- Heat treatable
- Plain
- Chromium Cr
- Titanium Ti
- Lead Pb
- Manganese Mn
- Magnesium Mg
- Aluminum Al
- Aluminum series 1000-7000
  - 1000 Series
  - 2000 Series
  - 3000 Series
  - 4000 Series
  - 5000 Series
  - 6000 Series
  - 7000 Series

- Al + 6Zn + Mg, Cu, Mn
- Al + 3Li
- Al + Si
- Al + 1Mn
- Al + 3Mg, 0.5Mn
- Al + 0.5Mg, 0.5Si
- Al + 4Cu + Mg, Si, Mn
- Al > 99% Al
- Al + 4Cu + Mg, Si, Mn
- Al + Li

a All alloying proportions given in terms of percentage weight.
b Aluminum series 1000-7000

Figure by MIT OCW.
metal foams
Data from thermometer (red) and from tree rings, corals, ice cores and historical records (green).

Northern Hemisphere

(b) the past 1,000 years

Figure by MIT OCW.
Global $\text{CO}_2$ emissions from cement manufacturing production

source:

Adapted from:
van Oss, Hendrik G. and Padovani, Amy C.
Composition of Total Material Requirement (TMR; in Tonnes/Capita) in the European Union, Selected Member States and Other Countries.

Note: Hidden flows are included in fossil fuels, metals and minerals or are represented by excavation and erosion.

Figure by MIT OCW.

TMR (Total Material Requirement) = DMI + Domestic Hidden Flows + Foreign Hidden Flows
DMI (Direct Material Input) = Domestic Extraction + Imports
NAS (Net Additions to Stock) = DMI - DPO - Exports
TDO (Total Domestic Output) = DPO + Domestic Hidden Flows
DPO (Domestic Processed Output) = DMI - Net Additions to Stock - Exports

Figure by MIT OCW.

<table>
<thead>
<tr>
<th>MATERIAL INPUT</th>
<th>ECONOMY</th>
<th>MATERIAL OUTPUT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imports 475</td>
<td>Net additions to stock 938</td>
<td>Exports 228</td>
</tr>
<tr>
<td>Abiotic raw material 3443</td>
<td></td>
<td>Waste disposal (excl. incineration) 2329</td>
</tr>
<tr>
<td>Used: 1) minerals 898 2) energy carriers 253</td>
<td></td>
<td>1) controlled waste disposal 119</td>
</tr>
<tr>
<td>Unused: 1) non saleable extraction 1996 2) excavation 296</td>
<td>2) landfill and mine dumping 2210</td>
<td></td>
</tr>
<tr>
<td>Air 1080</td>
<td>Emission to air 1005</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1) CO₂ 990</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2) NO₂, SO₂, CO and others 15</td>
<td></td>
</tr>
<tr>
<td>TOTAL INPUT 5348</td>
<td>Emission to water from material 639</td>
<td>Emission to water 37</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dissipative use of products and dissipative losses 47</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Biotic raw materials (fresh weight) 225</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Erosion 126</td>
</tr>
</tbody>
</table>


Figure by MIT OCW.
Demand vs. Biocapacity

Figure by MIT OCW.

Material Resources

U.S. Flow of Raw Materials by Weight, 1900-2000
(non-fuel and non-food resources)

- Agriculture and Fishery
- Wood
- Nonrenewable Organics
- Metals
- Industrial Minerals
- Stone, Sand and Gravel

Figure by MIT OCW.
Renewable: 85%  
Nonrenewable: 15%
U.S. Copper Ore Grade Percent, 1880-2000

- **1907**: beginning of open pit mining
- **1920+**: flotation process for concentrating sulfide ores

Figure by MIT OCW.
Figure by MIT OCW.
Japan Copper cycle: One Year Stocks and Flows, 1990s

Figure by MIT OCW.

© STAF Project, Yale University
Zambia’s Copper Cycle: One Year Stocks and Flows, 1994

UNITS: Gg/yr
System Boundary: Zambia (ZM)

© STAF Project, Yale University

Figure by MIT OCW.
China’s Copper Cycle: One Year Stocks and Flows, 1994

**Diagram Description:**

- **Production Mill, Smelting, Refinery**
  - Ore: 510
  - Concentrate: 220
  - Tailings: 46
  - Reworked Tailings: 6
  - Stock: 48

- **Fabrication & Manufacturing**
  - Cathode: 1060
  - Blister: 75
  - Cathode: 62
  - New Scrap: 200
  - New Scrap: 110

- **Use**
  - Products: 1150
  - Stock: 1000
  - Discards: 150

- **Waste Management**
  - Old Scrap: 490
  - Landfilled Waste, Dissipated: 87
  - New Scrap: 1060
  - Old Scrap: 74
  - New Scrap: 270

- **Repositories**
  - Lith.: -510
  - REPOSITORIES

- **System Boundary:** China (CN)

**Units:** Gg Cu/yr

© STAF Project, Yale University
2002 Estimated In–Use Copper Stocks in Beijing—3D View

IPAT

I = P \times A \times T
MIPS

\[ MI = \frac{\text{resource}}{\text{unit service}} \]
Type I

Unlimited Resources \( M_i \) → Ecosystem

Ecosystem Component 1 → Ecosystem Component 2

Ecosystem Component 3 → Ecosystem Component n → Unlimited Sinks \( M_o E_o \)

\( M_i = \) Material resources
\( M_o E_o = \) Wastes

Source: Fernandez
$M_iE_i = \text{Material and energy resources}$

$M_oE_o = \text{Wastes}$
Type III

$E_i = \text{Energy input (solar radiation)}$

Source: Fernandez
Consumption attributes of contemporary buildings

**Temporal**
- Actual service lifetimes are uncertain (shorter or longer than intended)
- Buildings often outlast the firms that build them
- Buildings are one of the very few human artifacts that can span generations

**Spatial**
- Buildings are immobile over lifetime
- Materials and processes (energy) converge to site
- Materials (wastes or “residues”) are dissipated from site

**Physical**
- Buildings (cities and infrastructure) constitute the largest single stock type
- Each building is a “prototype”
- Buildings are meta-systems composed of complex semi-autonomous systems (with distinct lifecycles)
Comparative analysis of resource requirements

1. Brick and concrete masonry block wall

2. Glass and aluminum curtainwall

3. Precast concrete panel and structural steel stud wall

4. Structural straw bale, wood stud and exterior finish plaster construction

Data sources:
US EPA Lifecycle Methods (1993)
SETAC (1993)
BEES (2000)
ISO 1401 (1998)
Keoleian, G. (2001)
CES Materials Selector 4.5 (Beta version)
Figure by MIT OCW.
Total primary* system energy (GJ)

- **System 1**
  - Brick and CMU wall
  - (155GJ)

- **System 2**
  - Glass and Aluminum
  - (291GJ)

- **System 3**
  - Precast concrete
  - (112GJ)

- **System 4**
  - Straw bale wood frame
  - (147GJ)

*Primary energy includes pre-use phase extraction, manufacturing, fabrication, assembly, and transportation.
(a) Worker Transportation/Construction Energy

(b) Worker Transportation/Construction Greenhouse Gas Emissions

Figure by MIT OCW.
Wood Construction energy (MJ/m²)
Construction greenhouse gases (kg/m²)

- Wood
- Steel
- Concrete

(a) Average Construction Energy for Wood, Steel and Concrete Assemblies

(b) Average Construction Greenhouse Gas Emissions for Wood, Steel and Concrete Assemblies

Conclusion

Transportation - of workers and equipment - to and from the site represents the largest proportion of construction energy use for every material system and a substantial proportion of emissions.

Figure by MIT OCW.
Source: adapted from Bras, B. and Graedel and Allenby
Low energy buildings and resource content
(whole building)

Increased energy efficiency continually recalibrates proportion of pre-use to use phase energy investment.

For example:
Single family detached house (USA)

Typical systems
9% pre-use, 91% use phase

Low energy systems
26% pre-use, 74% use phase

Strategies

Pre-Use

• Integrated delivery (construction) including premanufactured assemblies for dematerialized built environment (renewable and non-renewable).

  Issues: employment, quality, material flow control, waste control and reuse, transportation energy in construction, firm MFA analysis, product LCA.

Use

• Extended Producer Responsibility (EPR) or better yet Extended Industry Responsibility (EIR): product LCA

• Material reclamation, recycle, downcycle.

• Comfort/Carbon Tax

Post-Use

• “Cities are the mines of the future.”, Jane Jacobs

Are we any closer to a Type III ecology?
Material flow analysis (MFA)

Life cycle assessment
Metabolism: the consumption of resources for the purpose of providing a unit of service.
Industrial ecology as steward of tools of analysis for *resource consumption*

\[
[M_i,E_i] = [M_o,E_o] + [A.S.]
\]
Building Types

<table>
<thead>
<tr>
<th>Material Content/Area</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Residential</td>
<td>80</td>
</tr>
<tr>
<td>2 Commercial</td>
<td>40</td>
</tr>
<tr>
<td>3 Industrial</td>
<td>20</td>
</tr>
</tbody>
</table>

KEY

1 = Residential
2 = Commercial
3 = Industrial

Figure by MIT OCW.

Rapid Urbanization  Stabilizing Urbanization  Incremental Densification

Material Consumption  Energy Consumption

Figure by MIT OCW.

Per Capita Annual Electricity Consumption KWh/Person, (Thousands)

A = Shanghai
B = Nanjing
C = Hangzhou
D = National average

Year
1990 1995 2000

Figure by MIT OCW.
Santa Monica Sustainable City Initiative

Source of recycled materials

Greater Los Angeles Basin (source of post-industrial and post-consumer materials)

Local Resource System Boundary: Urban Center and Local Ecology

Maximize material resource transfer

Minimize waste stream

Local site materials
**Ordnance Plant**  
Arden Hills, Minnesota  

Built: 1930s  
Dismantled: 2002  
Materials recovered:  
20,000 maple tongue and groove flooring,  
500,000 board feet of structural timber  
Cost of disassembly:  
$183,000  
Cost of demo/landfilling:  
$600,000

**Sears Catalog Warehouse Center**  
Chicago, Illinois  

Built: 1906  
Demolished: 1992-1994  
(Size: 9 story, 3 million sq. ft.)  
Materials recovered:  
7.5 million board feet timber,  
23 million bricks  
Site recovered for housing

The photographs on this and the following pages were removed for copyright reasons.
Murray Grove Apartments
London, England
Cartwright Pickard Architects

(Yorkon Building Modules)
Built: completed 2001
Size: 30 apartments, 5 stories
On-site construction: 2 weeks
Overall cost reduction: 10% (affordable housing contract)
Premanufactured building modules

Yorkon
Foreman's
Premanufactured components for buildings
Container City
India Wharf, London, UK

source: photo J. Fernandez
A) 'Linear metabolism' cities (consume and pollute at a high rate)

- **Inputs**
  - Organic Waste
  - Inorganic Waste

- **Outputs**
  - Emissions (CO₂, NOₓ, SO₂)
  - Organic Wastes (Landfill, sea dumping)
  - Inorganic Wastes (Landfill)

B) 'Circular metabolism' cities (minimise new inputs and maximise recycling)

- **Inputs**
  - Food
  - Recycled
  - Energy

- **Outputs**
  - Reduced Pollution and Wastes
  - Organic Waste
  - Inorganic Waste

- **Recycles**
  - Organic Waste
  - Inorganic Waste

---

**The 'Metabolism' of Cities: Towards Sustainability**

Figure by MIT OCW.
Domain of the built environment

Extraction of natural resources

Processing into materials

Manufacture into components

Assembly into buildings

Building use

Disassembly

Waste for dumping

Recycling of materials

Reprocessing of materials

Reuse of components

Relocation of entire building

Materials cycles in construction

Construction

De-construction
Scope

The analysis of the metabolism of the city of New Orleans may provide a unique understanding of the relationship between anthropogenic structures of industry and the built environment and the natural ecology of the lower Mississippi Delta.

1. System boundary
   i. Municipal (political)
   ii. Regional (geographic, ecological, etc.)

2. Physical accounting
   i. Listing of entities to ‘track’ (key resources)
   ii. Data sources