Sustainable Design: The Construction Industry

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Global Impact: the 'Standard Run'

Assumptions:

- 'continue historical path as long as possible - no major change'
- growth continues until environmental and resource constraints finally limit it

Results:

- irreversible environmental changes occur
- investment capital depreciates faster than it can be re-built
- as it falls, food and health services fall too
- death rates increase and life expectancy reduces

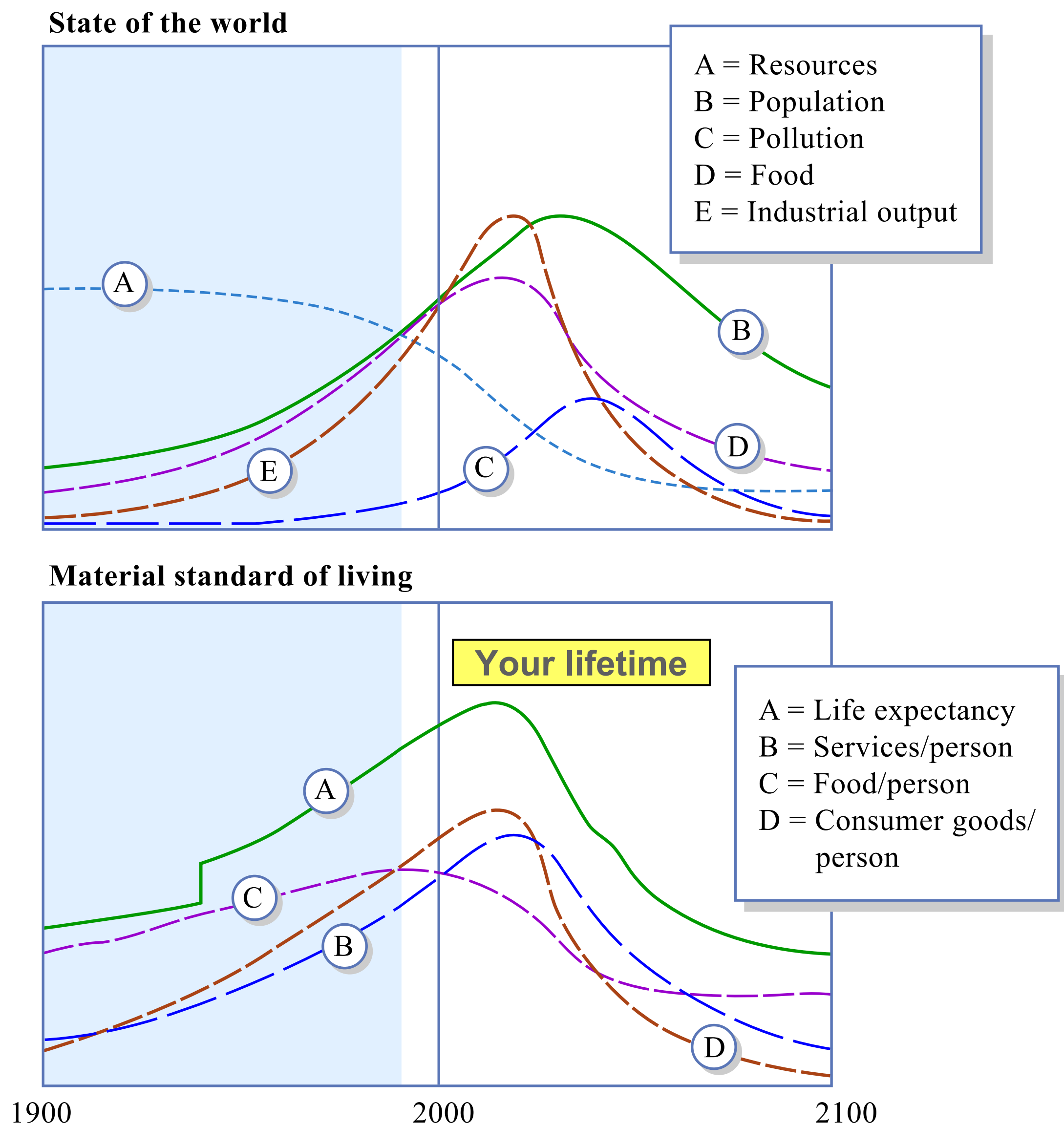
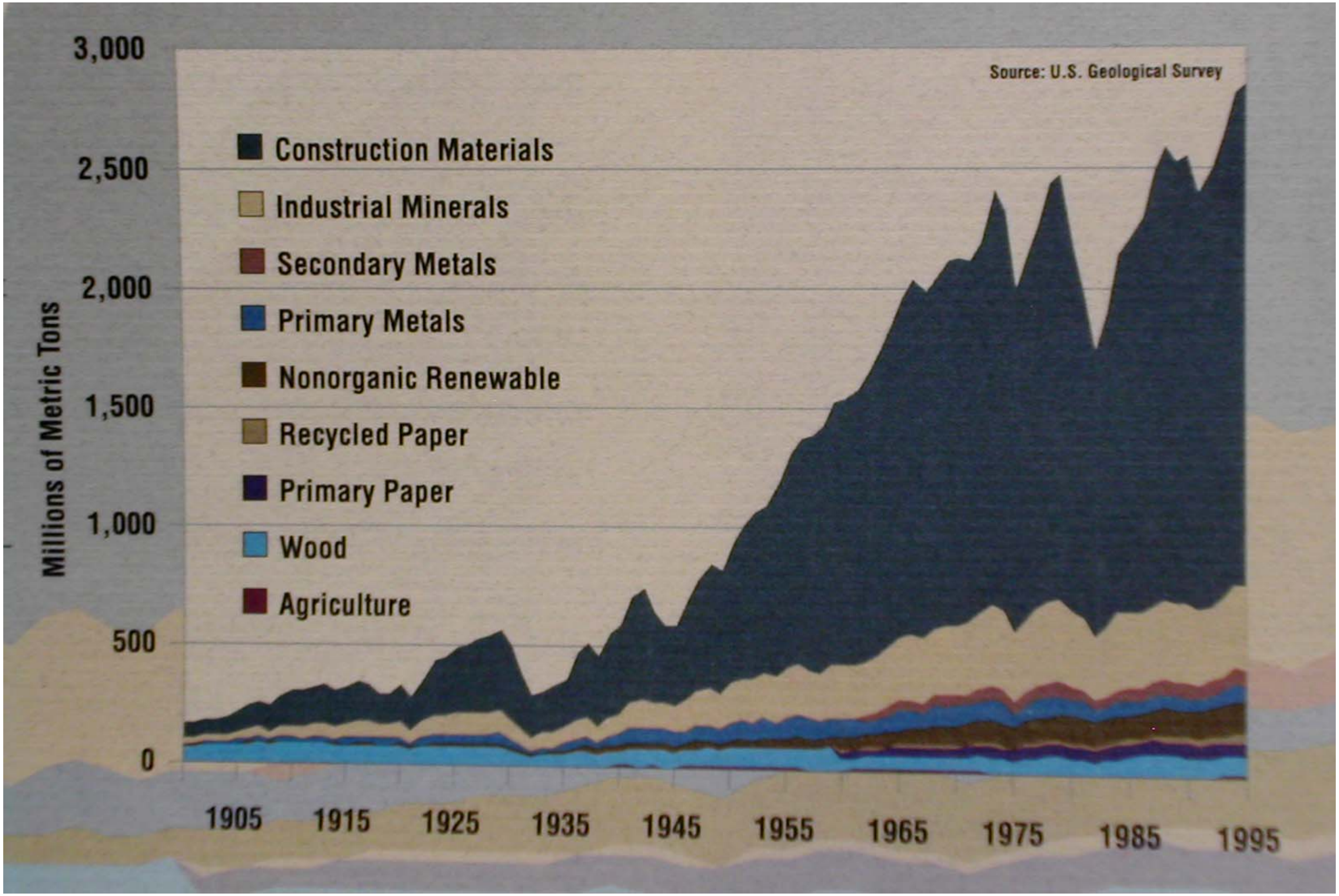


Figure by MIT OCW.

(From 'Beyond the Limits'', 1998)

Use of Raw Materials in the US



Average US House Sizes Tripled in 50 Years

Photographs of small and large houses.

Images removed for copyright reasons.

~800 square feet **~2400 square feet**

The earth is finite…
….natural resources have a limit

Whole Life Design

- **12 million computers are thrown away each year in US (~10% are recycled now)**
- **300-700 million computers will be obsolete in the US in the next few years**
- **The electronics and automobile industry are beginning to design for whole life of products**
  - **Source: National Safety Council**

Photograph of discarded computers.

Image removed for copyright reasons.

Problems with Electronics

- **Designers are not responsible for end of life design**
- **Product manufacturing does not consider the entire lifetime of the product**
- **Result is *waste***
  - **Economically inefficient**
  - **Environmentally harmful**
  - **Socially irresponsible**
- **→ UNSUSTAINABLE**

Photographs removed for copyright reasons.

Buildings are Not Permanent

- **Stone pinnacles of cathedrals are replaced ~200 years**

- **Buildings are *waste in transit***

Goals of Structural Design

- Efficiency
- Economy
- Elegance

The Tower and the Bridge: The New Art of Structural Engineering, by D.P. Billington

Goals of Structural Design

- Efficiency
- Economy
- Elegance
- But all must consider the environmental impact as well

19th Century Design Concern

EFFICIENCY IS IMPORTANT: New materials in construction, such as wrought iron and steel, lead to greater concern for efficiency

Photograph of steel bridge.

Image removed for copyright reasons.

20^{th} Century Design Concern

MAINTENANCE IS IMPORTANT: The initial design is important, though we must also design for maintenance throughout operating life

Photographs of bridges in need of repair.

Images removed for copyright reasons.

21st Century Design Concern

"END OF LIFE" IS IMPORTANT: Waste from the construction industry is a vast consumer of natural resources on a global scale

Photographs of bridges being demolished.

Images removed for copyright reasons.

Design Matters

- 19th Century: Efficient use of materials
- 20th Century: Maintenance matters
- 21st Century: End of life matters

Case Study: Williamsburg Bridge

- **Opened in 1903 as longest span in the world**
- **Designed with the elastic theory of suspension bridge design, which did not account for the stiffening effect of a cable**
- **Boasted to be the "strongest" suspension bridge at the time**

Williamsburg Bridge, 1904

Williamsburg Bridge

- **Regarded as the ugliest suspension bridge (doesn’t help that it is next to the stunning Brooklyn Bridge)**

Brooklyn Bridge, 1883

Williamsburg Bridge, 1904

Williamsburg Bridge

- **Carried traffic and trains throughout the 20th century**

- **But maintenance was neglected entirely for decades**

- **In 1988 the poor condition of the bridge became an emergency**

Photographs of the bridge throughout the next several slides were removed for copyright reasons.

Williamsburg Bridge, 1937

Decay of Williamsburg Bridge

- **Main cables were corroded badly (not galvanized)**
- **Pin joints in the main trusses were corroded**
- **Rusted girders**

Williamsburg Bridge, 1980's

Williamsburg Bridge Design Competition

Winning design by Jorg Schlaich, 1988

Estimated cost: $700 M

How to replace the Williamsburg Bridge?

- A vital link to Manhattan: the bridge could not be taken out of service

- Must use the same site: property for new approach spans is too expensive

Conclusion: Williamsburg Bridge Stays

At least 100 more years of service

1990-2005:
Rebuilding the Williamsburg Bridge

- **New cables, new girders, new roadways, new bearings, new paint, etc…**
- **Cost approximately $1 billion; more than a new bridge**

Williamsburg Bridge Rating

The Williamsburg Bridge is ranked as the most structurally deficient bridge in the USA carrying more than 50,000 cars per day.

-2002 report "The Nation's Bridges at 40." by The Road Information Program (www.tripnet.org).

Rebuilding the Williamsburg Bridge: Technical Problems

- **How to replace main cables?**
  - One strand bundle at a time
- **How to replace deck while traffic flows?**
  - Lightweight orthotropic steel deck placed at night
- **How to protect river and traffic from lead paint on the bridge?**
  - Contain large areas with plastic

Designing for Maintenance

- **Develop a maintenance plan for your structure**
- **Design components which are accessible and replaceable**
- **Avoid toxic materials which are hazardous for future maintenance operations**

‘Architects and engineers are the ones who *deliver things to people*’

- *“We can only get there...if the key professionals who deliver things to people are fully engaged... [architects and engineers], not the politicians, are the ones who can ensure that sustainable development:*
- *is operational*
- *is made to work for people*
- *delivers new ways of investing in our infrastructure, new ways of generating energy and providing a built environment*
- *delivers new ways of using consumer durables.*
- *There is no point along the sustainable development journey at which an engineer will not be involved.*
    - *(address to RAE, June 2001)*

CO_2 Emissions in the US

- US: 5% of world population, 25% of greenhouse gases
- UK: commitment to cut CO2 emissions 60% by 2050 (well beyond the goals of the Kyoto Protocol)

Kyoto Protocol and CO_2

- To meet Kyoto Protocol: ~33,000 lbs of CO_2/year/person (-7% from 1990)
- But individual contributions are only 1/3 of per capita contributions – rest is industry, agriculture, etc.
- So individual's annual goal would be 11,000 lbs (though many scientists are calling for much greater reductions)

Kyoto Protocol and CO_2

- To meet Kyoto Protocol: ~11,000 lbs of CO_2/year/person (-7% from 1990)
- This is equivalent to:

Kyoto Protocol and CO_2

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- This is equivalent to:

  2 coast to coast flights

Kyoto Protocol and CO_2

- **To meet Kyoto Protocol: ~11,000 lbs of CO_2/year/person (-7% from 1990)**
- **This is equivalent to:**

Driving about 11,000 miles

Kyoto Protocol and CO_2

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- This is equivalent to:

16 cubic yards of concrete

Kyoto Protocol and CO_2

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- **This is equivalent to:**

14 cubic feet of steel

Kyoto Protocol and CO_2

- To meet Kyoto Protocol: ~11,000 lbs of CO_2/year/person (-7% from 1990)

- This is equivalent to:

5 cubic feet of aluminum

Kyoto Protocol and CO_2

- To meet Kyoto Protocol: ~11,000 lbs of CO_2/year/person (-7% from 1990)

- This is approximately equivalent to:
  - Fly coast to coast twice (economy class)
  - Drive 11,000 miles (20 mpg)
  - Use 16 yds^3 of concrete
  - Use 14 ft^3 of steel
  - Use 5 ft^3 of aluminum

Kyoto Protocol and CO_2

- **Driving an SUV which gets 20 mpg:**
- **Using this material = driving this distance (approximately)**
  - **1 yd^3 of concrete = 700 miles**
  - **1 ft^3 of steel = 800 miles**
  - **1 ft^3 of aluminum = 2200 miles**

Kyoto Protocol

- **Aims to reduce CO_2 emissions by 7% over 1990 levels (though the UK has just committed to going much further – 60% reductions of current emissions)**

- **Would limit personal carbon emissions to 11,000 pounds of CO_2/year**

- **This quantity of CO_2 is produced by:**
  - **Two coast-coast flights (economy class)**
  - **Driving 11,000 miles (with 20 mpg fuel efficiency)**
  - **Casting 16 cubic yards of concrete**
  - **About 14 cubic feet of structural steel**
  - **About 5 cubic feet of virgin aluminum**

Kyoto Protocol

- **Aims to reduce CO_2 emissions by 7% over 1990 levels (though the UK has just committed to going much further)**
- **This requires approximate CO_2 emissions of 33,000 lbs/year for each person in the US**
- **Only about 1/3 comes from personal decisions, the rest is due to industry and services**
- **Architects and engineers contribute to the "*industry and services*"**

Construction and the Environment

In the United States, buildings account for:

37% of total energy use
(65% of electricity consumption)
30% of greenhouse gas emissions
30% of raw materials use
30% of waste output (136 million tons/year)
12% of potable water consumption

Source: US Green Building Council (2001)

Buildings: The real SUV's

In the United States, buildings account for:

-37% of total energy use (65% of electricity consumption)

-30% of greenhouse gas emissions

Photographs of buildings at night.

Images removed for copyright reasons.

Coal is the Future of US Energy

Enough coal to meet US energy needs for ~200 years

Coal: $30/ton

True cost: ~$150/ton

Energy and Buildings

Need	Current Solution	Sustainable Solution
Lighting	Lights	Daylight
Heating	Power grid	Better insulation Renewable energy
Cooling	Air-conditioning	Natural ventilation

What is required? → *Better DESIGN*

Embodied Energy and Operating Energy for Buildings

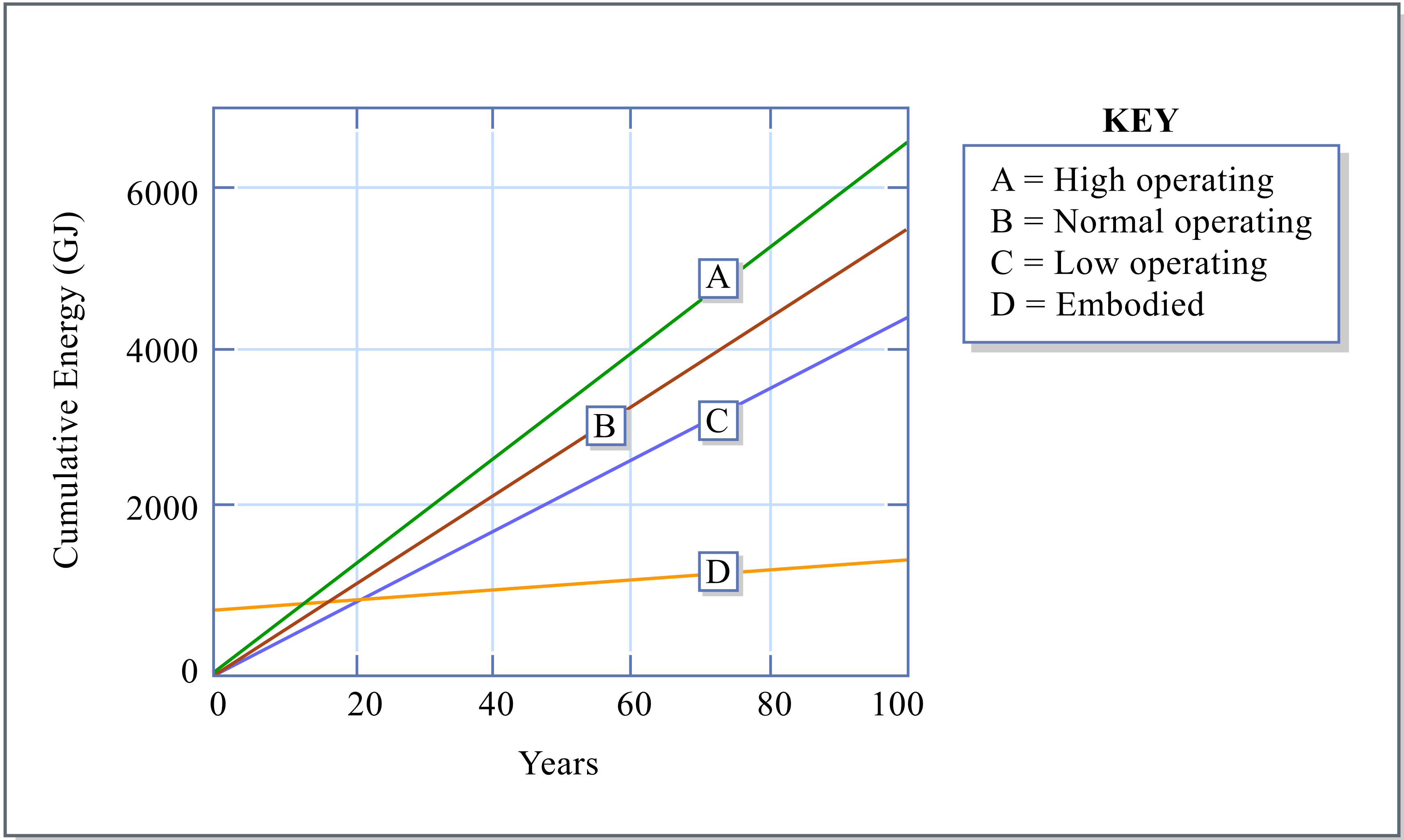


Figure by MIT OCW.

Typical Building Embodied Energy

Breakdown of Initial Embodied Energy by Typical Office Building Components Averaged Over Wood, Steel and Concrete Structures [Cole and Kernan, 1996].

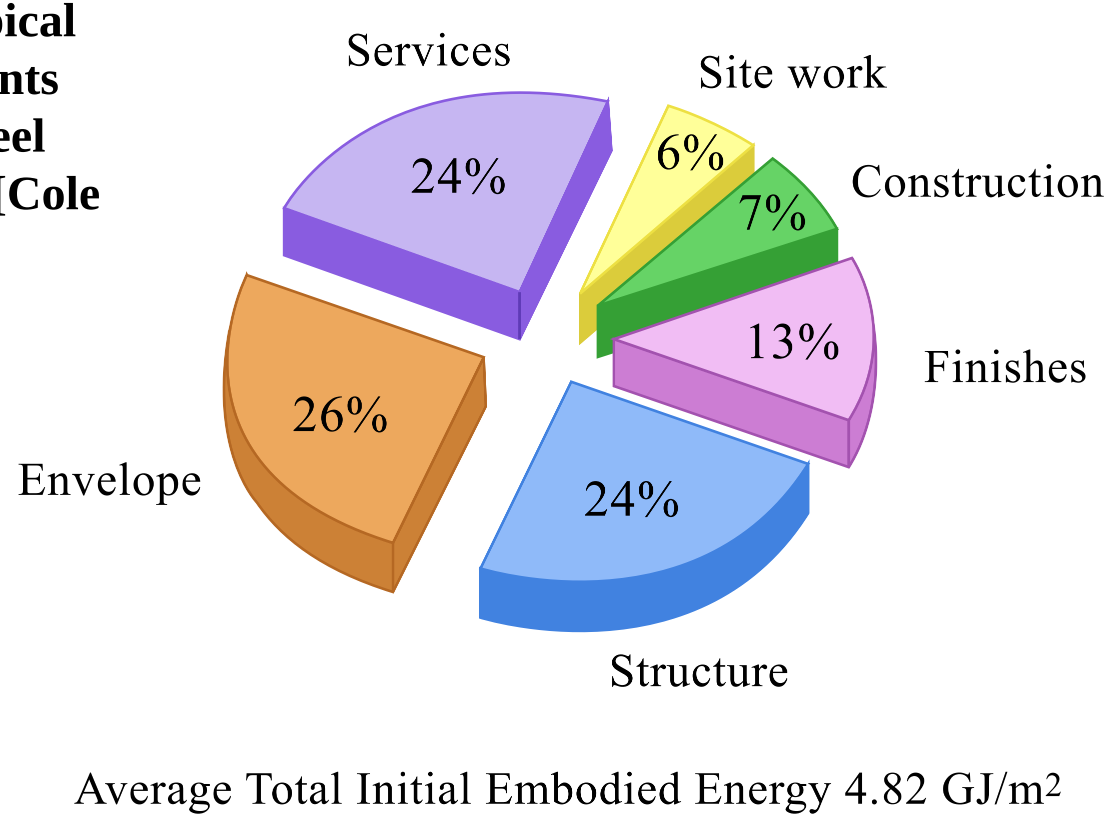


Figure by MIT OCW.

Range in Embodied Energy

Material	Density	Low value	High value
	kg/m³	GJ/m³	GJ/m³
Natural aggregates	1500	0.05	0.93
Cement	1500	6.5	11.7
Bricks	~1700	1.7	16
Timber (prepared softwood)	~500	0.26	3.6
Glass	2600	34	81
Steel (sections)	7800	190	460
Plaster	~1200	1.3	8.0

Source: BRE, UK, 1994

Choosing Materials

- Environmental Impact
- Durability
- End of Life

Is concrete a green material?

- **Concrete is made from local materials.**
- **Concrete can be made with recycled waste or industrial byproducts (fly ash, slag, glass, etc).**
- **Concrete offers significant energy savings over the lifetime of a building. Concrete's high thermal mass moderates temperature swings by storing and releasing energy needed for heating and cooling.**

Energy Required for Concrete

Component	Percent by weight	Energy %
Portland cement	12%	92%
Sand	34%	2%
Crushed stone	48%	6%
Water	6%	0%

Each ton of cement produces ~ 1 ton of CO_2

Is steel a green material?

Image removed for copyright reasons.

Steel Recycling

2000 STEEL CONSTRUCTION RECYCLING	
	Estimated Rate
Structural Beams and Plates	95%
Reinforcement Bar and Others	47.5%

Figure by MIT OCW.

(Steel Recycling Institute)

Environmental Advantages of Steel

- Lower weight reduces foundation requirements
- Highly recycled and can continue to be recycled indefinitely
- Durable, if protected from corrosion
- Can be salvaged for reuse

Energy Consumption for Steel

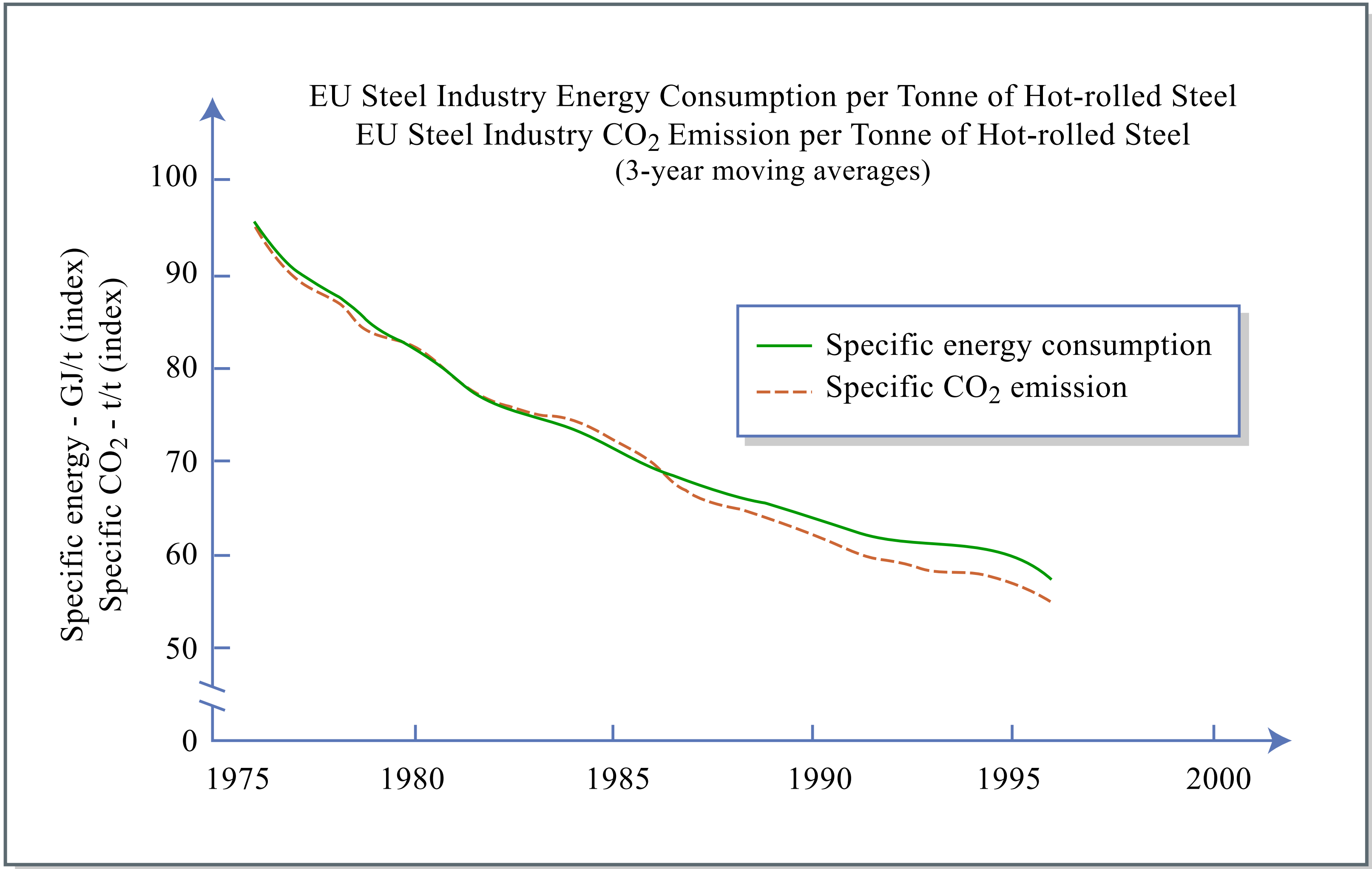


Figure by MIT OCW.

Environmental Disadvantages of Steel

- **Very high energy use, predominantly from fossil fuels → produces pollution**
- **Lightweight, so lower thermal mass compared to concrete → requires more insulation**
- **Is susceptible to corrosion**

The Greenest of Them All?

Only one primary building material:

- -comes from a renewable resource;
- -cleans the air and water;
- -utilizes nearly 100% of its resource for products;
- -is the lowest in energy requirements;
- -creates fewer air and water emissions; and is
- -totally reusable, recyclable and biodegradable.

And it has been increasing in US net reserves since 1952, with growth exceeding harvest in the US by more than 30%.

-American Wood Council

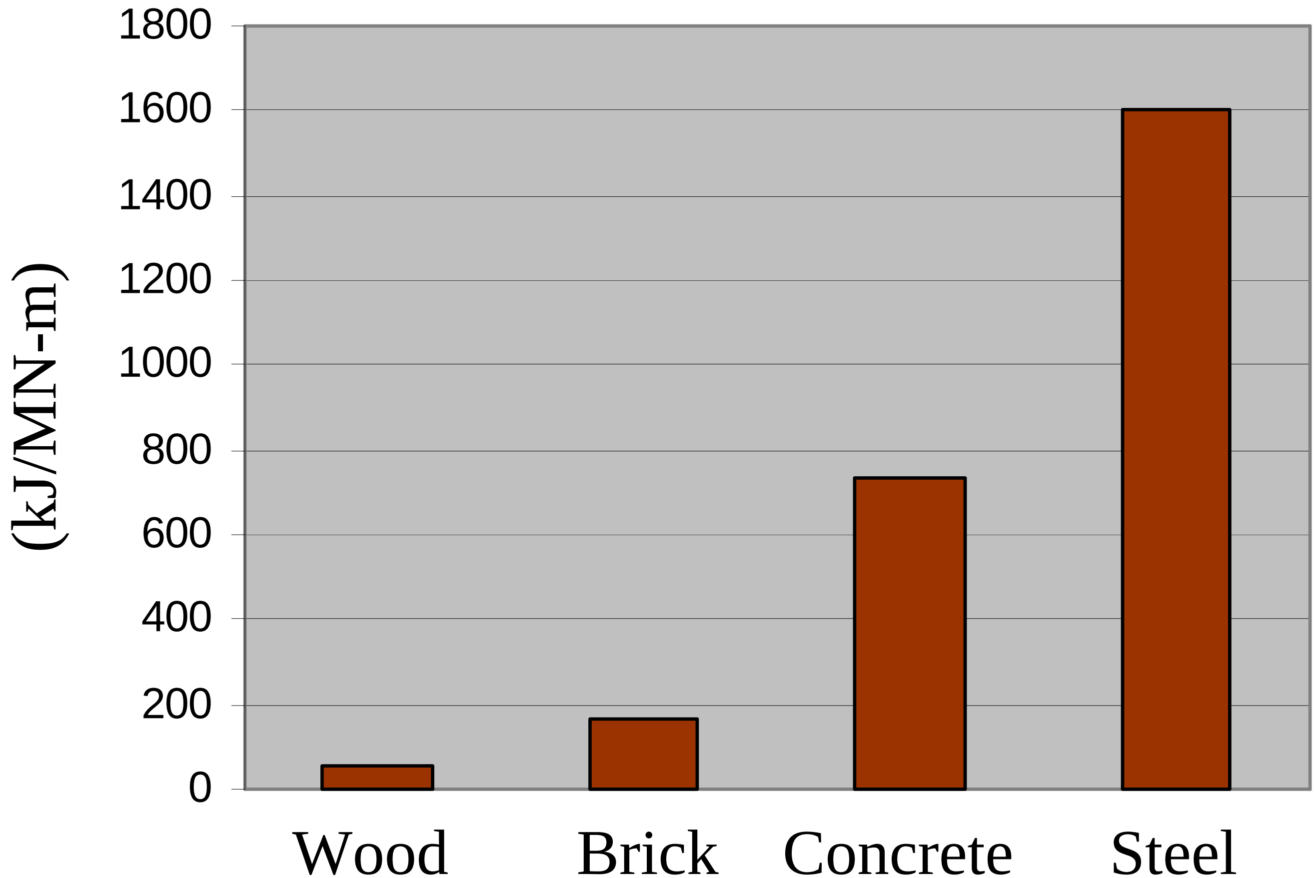
Planting trees?

- **A healthy tree stores about 13 pounds of CO_2 per year -- NOT MUCH!**
- **Would require nearly 3,000 trees per person to offset CO_2 emissions**
- **Specifying timber reduces CO_2 emissions compared to steel and concrete, but carbon sequestration is a small contribution to this reduction**
- **Main advantage is that wood does not produce nearly as much CO_2 as steel and concrete**

High vs. Low Embodied Energy?

- **Materials with the lowest embodied energy intensities, such as concrete, bricks and timber, are usually consumed in large quantities.**
- **Materials with high energy content such as stainless steel are often used in much smaller amounts.**
- **As a result, the greatest amount of embodied energy in a building can be either from low embodied energy materials such as concrete, or high embodied energy materials such as steel.**

Embodied Energy per Stiffness



Steel and Concrete

- Energy intensive materials
- High associated CO_2 emissions
- Dominant structural materials
  - Industry standards
  - Many engineers have not designed with other materials
  - Economies of scale
  - Steel provides ductility, the ability to absorb energy before failing
- Many other materials can serve in place of steel and concrete

Spending on Construction

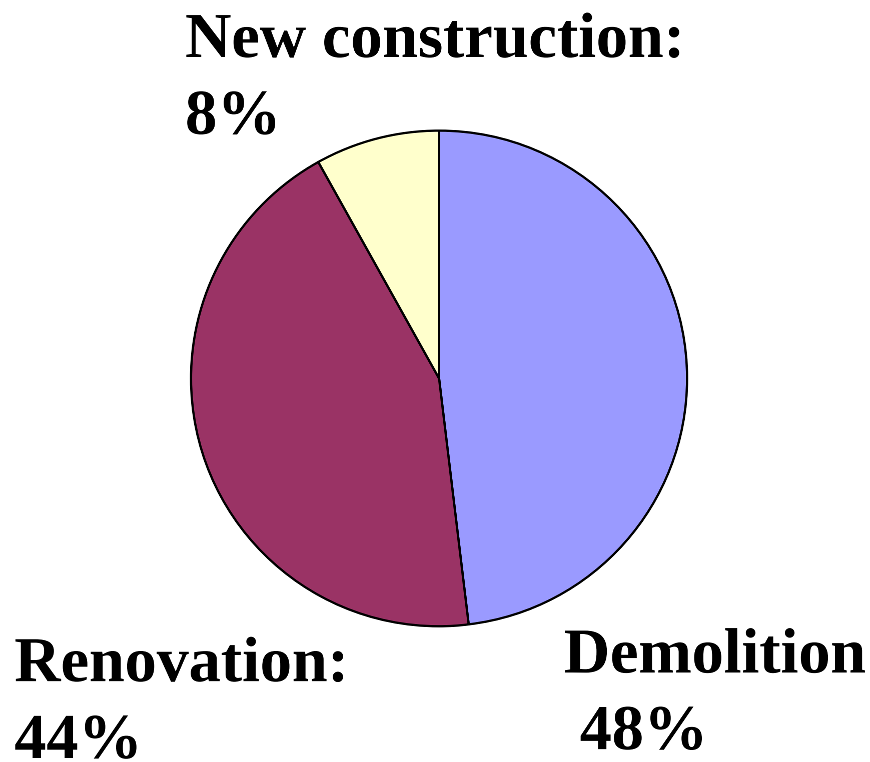
In industrialized nations, construction contributes more than 10% of the Gross Domestic Product (GDP)

An estimated 47% of total spending on construction is for renovation.

Source: Daratech (2001)

Construction Waste

- US Environmental Protection Agency (EPA) estimates 136 million tons of waste generated by construction each year
- Most from demolition or renovation and nearly half the weight is concrete



Reducing Waste

Design for Less Material Use
Use materials efficiently and maximize program use by combining spaces. (i.e., build smaller)

Design Building for Adaptability
Design multipurpose areas or flexible floor plans which can be adapted for use changes.

Recycle Construction Waste
Wood, metal, glass, cardboard etc. can be salvaged in the construction process. Materials should be used and ordered conservatively.

Energy Savings from Recycling

	Energy required to produce from virgin material (million Btu/ton)	Energy saved by using recycled materials (percentage)
Aluminum	250	95
Plastics	98	88
Newsprint	29.8	34
Corrugated Cardboard	26.5	24
Glass	15.6	5

Source: Roberta Forsell Stauffer of National Technical Assistance Service (NATAS), published in *Resource Recycling*, Jan/Feb 1989).

Use Recycled Content Products and Materials

<u>High recycled content:</u>

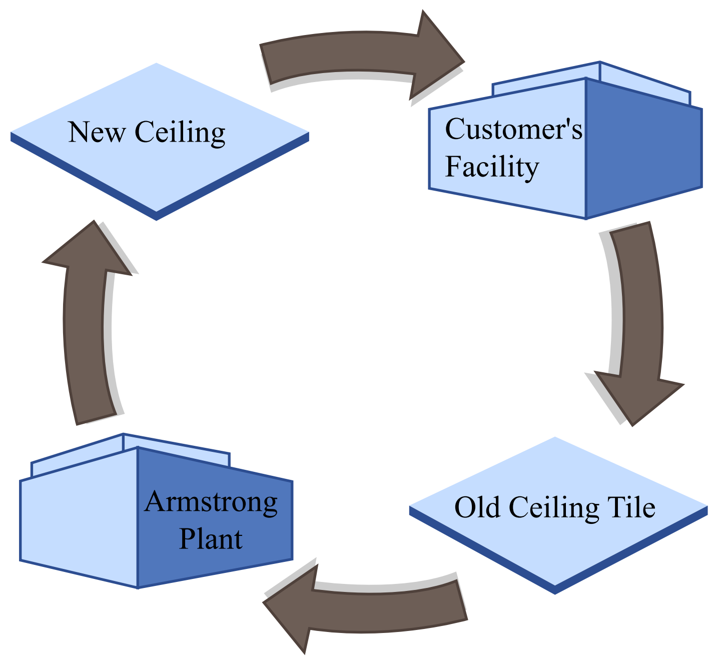
Paper on both the face and the back of all drywall is a 100% recycled product.

Structural steel uses mostly recycled material (though it is still energy-intensive and responsible for harmful pollutants.)

<u>Example of an item that you can specify:</u>

Armstrong ceiling tiles contain 79% recycled material (cornstarch, newsprint, mineral wool, recycled tiles). Both the ceiling tiles and the suspension systems can also be reclaimed and recycled rather than dumped in a landfill.

Armstrong Ceiling Tile



Mineral fiber ceilings from renovation projects can now be efficiently reclaimed and reused through the Armstrong Ceilings Reclamation and Recycling Program.

Armstrong Ceiling Recycling Program: A solution for ceiling disposal

Figure by MIT OCW.

Separating Waste

Photographs of construction waste (wood and concrete).

Images removed for copyright reasons.

Australia: Waste Avoidance and Resource Recovery Act (2001)

Web site dedicated to Construction & Demolition waste minimization: onSITE

http://onsite.rmit.edu.au/

(Source of material for this lecture.)

Ecological Comparison of Materials

- **Each material has environmental advantages and disadvantages**
- **Choice of material will depend on the site and design problem**
- **Embodied energy is only one of many considerations**

Design Matters

- 19th Century: Efficient use of materials
- 20th Century: Maintenance matters
- 21st Century: End of life matters

Demolition: Lessons from History

- Sustainable structures must consider the "end of life" of the structure
- ~24% of solid landfill waste in the US is generated by the construction industry
- Up to 95% of construction waste is recyclable, and most is clean and unmixed

Photographs removed for copyright reasons.

Source: **2002 Buildings Energy Databook http://buildingsdatabook.eren.doe.gov/**

Two Extreme Approaches to Sustainable Structures

1. **Permanence:** Very high quality construction, with materials which can be reused in future construction

2. **Temporary:** Less expensive construction, with a short life span. Materials must be low-impact.

Designing for Permanence: The Roman Tradition

A series of photographs were removed for copyright reasons.

Pons Fabricius in Rome, 62 BC

Temporary Bridges:
The Inca Tradition

Keshwachaka in Huinchiri, Peru
~1400 AD

Inca Bridge Construction: An Annual Festival

Day 1: Ropes made from local grass or plant fibers

Day 2: Old bridge is cut and new ropes are installed

Day 3: Roadway and handrails are added and bridge is complete

Grass Bridge Has Survived for 500 Years

-Maintenance plan is tied to the community

-Materials are locally available and environmentally sound

Two Sustainable Bridge Types

Inca suspension bridge	Roman arch bridge
High stresses	Low stresses
High maintenance	Low maintenance
Short lifetime	Long lifetime
Low initial cost	High initial cost
Renewable materials	Reusable materials
Low load capacity	High load capacity

The Structure of the Future?

- **Efficient: Materials are recycled, reusable, or low-energy**
- **Maintainable: components can be replaced or improved or reused**
- **Adaptable: Can respond to changing needs and loads throughout its lifetime**

Traversina Bridge, Jorg Conzett

Japanese Pavilion, Germany, 2000

- **Recycled paper tubes**
- **Minimal foundations**
- **Recycled at end of the Expo**

Stansted Airport Terminal

- Steel tubes can be disassembled
- Modular system for adaptation
- Can be recycled or reused at end of life

The Importance of History

- **Case studies can illustrate successful and unsuccessful designs**
- **The designs of yesterday are the problems of today**
- **How do we design with the future in mind?**

Design Questions to Consider

- In choosing structural system(s):
  - Flexibility of plan?
  - Can your building be adapted for alternative layouts?
  - Is the structural system economical?
  - Does it utilize local expertise?
  - How does the system help with natural lighting, natural ventilation, or thermal performance?

Design Questions to Consider

- In choosing materials:
  - What is the source for the materials?
  - What happens at the end of life of the materials?
  - Do the materials contribute to your other design goals? (transparency, thermal mass, etc.)

Beddington Zero Energy Development (Bed-Zed), UK, 2001

Photographs removed for copyright reasons.

Must consider site and building orientation to optimize daylight, ventilation, thermal insulation, etc.

www.bedzed.org.uk

Or you could treat architecture as sculpture…

Consideration of site and building orientation to optimize daylight, ventilation, thermal insulation, etc.???

Conclusion

In choosing a structural system and the materials for a building, consider:

1. **CONSTRUCTION**

2. **OPERATION**

3. **DEMOLITION**

‘Architects and engineers are the ones who *deliver things to people*’

- ***“We can only get there...if the key professionals who deliver things to people are fully engaged... [architects and engineers], not the politicians, are the ones who can ensure that sustainable development:***
  - ***is operational***
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  - ***delivers new ways of investing in our infrastructure, new ways of generating energy and providing a built environment***
  - ***delivers new ways of using consumer durables.***

- *There is no point along the sustainable development journey at which an engineer will not be involved.*

Royal Academy of Engineering, UK, June 2001

Sustainable design is good design

Global responsibility of engineers in the United States

Conclusions

- **Each material has environmental advantages and disadvantages: good design is local**
- **Recycle or reuse materials to decrease waste**
- **Consider end of life in the initial design**
- **History suggests sustainable solutions: Inka structures (temporary) and Roman structures (permanent) can both be sustainable**

Conclusions

- **Construction industry generates enormous waste annually**
- **Individual designers can reduce this waste significantly**
- **Energy intensive materials like steel and concrete can be used more efficiently**
- **Alternative materials should be explored**

Future Challenges

- **Education of architects and engineers**
  - **Teaching design and analysis**
  - **Assessment of existing structures**
  - **Environment as a design constraint, not an opponent**

- **Maintenance and disposal plan for new structures**

- **Code improvements for the reuse of salvaged structures and new uses of traditional materials**

Further Information

US Green Building Council:
www.usgbc.org

Department of Energy:
www.sustainable.doe.gov