The first and traditional question in material selection is:
What material will do the job?

This makes us look at materials properties:

- Is it strong enough? Or, flexible enough?
- Is it light enough?
- Does it have the right surface properties?
- Does it conduct heat or electricity?
- Does it require maintenance?
- etc.

A few environmentally conscious examples:

- Selecting a material for better thermal insulation
- Developing a more efficient photovoltaic cell for renewable energy generation
- Developing a carbon-fiber composite for a windmill blade or for a lighter car.

But, one should also ask the following questions:

- Where does this material come from? Is the source renewable?
- What are the impacts during production?
- Is the material harmful to its users?
- Where does it go after use? Is it recyclable or compostable?
For most of human history and especially in the early history of the U.S., the paradigm was:

- There is plenty of material out there, but the labor pool is limited.
- Hence, economical progress is limited by the workforce and don’t mind limits on materials.

But, we have now realized that we live on a finite planet, and the converse has become true:

- There are plenty of people out there, but materials are limited.
- Hence, economical progress is tied to materials (and energy) availability.

→ “Long-term shift from labor productivity toward resource productivity.”
(Paul Hawken)

Questions before us now:

- Is there enough for everyone?
- What shall we do when we run out of this or other non-renewable material?
- How do we keep materials in the industrial loop without dissipation, degradation?
- How do we switch to renewable materials?

And, more fundamentally:
- Do we need to stay wedded to this notion of “economic progress”?

The title of this report is rather telling...
Materials consumption versus wealth

Materials consumption reflects economic output. In other words, developed countries form a materials-based economy.

What if the entire world wanted to be like North America and Europe? South Korea? China? India? Brazil? Russia? Mexico?

It turns out that material intensity is also a function of population density up to a point.

Why? This is largely a reflection of the need for infrastructure:
More land → longer distances → longer roads and more bridges
Also: More land → tendency to build bigger houses.
Use of Natural Resources (in USA)

![Graph showing the use of natural resources in the USA from 1800 to 2000.](image)

**Figure 4.** U.S. flow of raw materials by weight, 1900-99. The use of raw materials dramatically increased in the United States throughout the 20th century (modified from Matsos and Wagner, 1998, fig. 3).


Materials are typically used for:

- Essential needs, such as shelter, clothing, food, health care
- Transportation (infrastructure, vehicles)
- Communication (fixed installations, mobile devices)
- Miscellaneous activities (wants?), such as sports and tourism
- Packaging

Needs & Activities → Products of all kinds → Function & Service

↑

Processed materials

↑

Raw materials

For every activity, we can ask:

1. Is this a need or a want? If it is a want, can we do without?
2. Can the same function or service be provided by less material?
3. At the limit, could the function or service be fulfilled with no material?
Systematic approach to material usage:

- Avoidance by no longer engaging in the activity
- Avoidance by focusing on the service rather than the product
- Avoidance of a toxic by substitution with a milder substance
- Reduction by dematerialization
- Reuse of products through second-hand markets
- Recycling of materials following collection and dismantling

Questions:

1. Are there signs of dematerialization?
2. Are there factors that promote dematerialization?
3. Are there factors that play against dematerialization?
4. How far can we drive dematerialization?

In answering these questions, think about:

- Environmental pressures? On resource side, on waste disposal side
- Technological changes?
- Cultural habits?
- Economic factors?
POSITIVE FACTORS

Environmental pressures:
- Need to reduce impact → less extraction → less use
- Air and water pollution → avoidance of toxics
- Climate change → energy efficiency → less fuel
- Landfill pressure → do with less, smaller stuff, less packaging

Technological changes:
- Better alloys and composites → less metal
- Better fibers → longer lasting carpets etc. → less frequent replacement
- E-mail → less physical mail

Economic factors:
- Running out → scarcity → rising price → conservation & elimination
- Smaller product → less procurement → reduced manufacturing cost
- Smaller product → less embedded energy → energy savings
- Smaller product → increased appeal → more sales → more profits

Regulatory factors:
- Ban on certain substances
- Mandated energy savings and recycle contents
- Banning grocery plastic bags in San Francisco → reusable canvas bags

ADVERSE FACTORS

Physical limits:
- Size of human person, fingers etc. → limits on how small things can be
- Too small → not robust enough → unsafe and unwanted

Technological limits:
- Cannot make computer microchips smaller than a certain size
- Size of internal combustion engine, batteries, fuel cell, …

Quality:
- Less material → weaker product → shorter life → more frequent replacement
- → more material overall

Technological changes:
- Printers, photocopiers, fax machines → more liberal use of paper
- New personal electronics → new accessories
- → new activities, more products
- Microwave oven → smaller ovens but in addition to conventional oven!

Societal factors:
- Personal preferences, such as documents on paper rather than on screen
- Dispersion of population → more roads, bridges
- → more cars and more fuel
- Lack of environmental awareness (paper bags vs. plastic bags)
- Competing motives (ex. SUVs)
Dematerialization of products

↓

Fancier materials being used
(alloys, coatings, etc.)

↓

Less recyclability

↓

Greater extraction and processing
of new materials

A DOUBLE-EDGED SWORD!

A sign of dematerialization: The automobile

Some of the contents in US cars

Net 1970-1995: − 890 kg of carbon steel + 205 kg of alternates = − 685 kg/car
(Average mass of an American car was 1426 kg in 1995.)
But, there is a phenomenon that acts against dematerialization…

- On one hand, we make better, smarter materials
- This allows us to use less or use the same for a longer time
- But, on the other hand, there are more of us
- And, each one of us consumes more.

The total amount used of a material =

Amount per product \times Number of products

The concept of **INDUSTRIAL METABOLISM** (Robert U. Ayres, 1994)
Analogy between Industrial Metabolism and Material Cycling in Nature

Energy aspect of recycling

Conclusion: Aluminum is definitely worth recycling.

What about other materials?
Energy required for production of various materials
(in MJ per kg)

<table>
<thead>
<tr>
<th>Material</th>
<th>Primary production</th>
<th>Secondary production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>40</td>
<td>18.1</td>
</tr>
<tr>
<td>Copper</td>
<td>60</td>
<td>45</td>
</tr>
<tr>
<td>Aluminum</td>
<td>280</td>
<td>40.3</td>
</tr>
<tr>
<td>Zinc</td>
<td>53</td>
<td>15.9</td>
</tr>
<tr>
<td>Lead</td>
<td>41.1</td>
<td>8.0</td>
</tr>
<tr>
<td>Titanium</td>
<td>430</td>
<td>140</td>
</tr>
<tr>
<td>Nylon</td>
<td>119</td>
<td>32.1</td>
</tr>
<tr>
<td>Fiberglass</td>
<td>66.5</td>
<td>40.0</td>
</tr>
<tr>
<td>PVC</td>
<td>65.4</td>
<td>29.3</td>
</tr>
<tr>
<td>Rubber</td>
<td>67.6</td>
<td>Not possible</td>
</tr>
</tbody>
</table>

Economic aspect of material extraction:
The more dilute the material in the environment, the higher its price on the market.
Price is related to the difficulty of extraction from a dilute mix:

\[ E = -kT \left[ \ln(1 - c) - \frac{c}{1 - c} \ln(1 - c) \right] \]

The thermodynamic minimum energy required for the purification of a mole of substance in relative concentration \( c \) in a mix is equal to

Now, let's look at the waste streams. How concentrated are they?

**FIGURE 8.** Concentration distributions of lead in waste streams undergoing recycling and concentration distributions of lead in all industrial hazardous waste streams (1996). The concentration below which only 10 percent of recycling takes place is noted. (Allen & Behmann, *Wastes as Raw Materials*, 1994, page 79)
Figure 10 The Sherwood plot for waste streams. The minimum concentration of metal wastes undergoing recycling (see Figures 8 and 9) is plotted against metal price. The Sherwood plot for virgin materials is provided by comparison. Points lying above the Sherwood plot indicate that the metals in the waste streams are undersized, that is, waste streams undergoing disposal are richer than typical virgin materials. Points lying below the Sherwood plot indicate that the waste streams are vigorously recycled. (Allen & Behmanesh, Wastes as raw Materials, 1994, p. 88)
Barriers to recycling
(according to Frosch, 1997 + additional thoughts)

- Material is diffused in the environment
  (ex. rubber on roads, solvents in the air)
- Material is embedded in obsolete product and hardly separable
  (ex. copper wires in cars)
- Material is mixed with impurities
  (ex. zinc in steel, adhesives on used plastic bottles)
- Material is more concentrated in nature than in waste streams
  (ex. sulfur)
- Recycling is not economically profitable
  (low and fluctuating prices, disposal may be cheaper)
- Lack of information about possible uses
- Regulations against some “hazardous wastes”
  (cases of recycling followed by dumping after new law has taken effect)
- Cultural habits
  (throw-away culture)

Materials in construction

Questions:
- Which materials?
- How much?
- From where?
- To where after demolition

In addition to requiring substantial amounts of energy for their operation, construction of residential and commercial buildings accounts for a significant fraction of the materials that are produced and utilized each year.

For example, about $3 \times 10^9$ tons/year of natural aggregates (crushed stone, gravel & sand) are used in the United States, with 60% going to road construction and 40% to buildings. These 40% amount to almost 4 ton per person per year.

Metals and wood are the other primary materials used in buildings. About 15% of iron and steel production in the US going to the construction industry (of which ~50% is from recycled sources). About 60% of forest products (lumber, plywood, veneer, pulp products and fuel wood) are used in building construction and operation.

(Source: D. T. Allen & D. R. Shonnard, Sustainable Engineering, 2012)
A major question is then:

Could we use less material for our buildings?

There are two primary ways to address this question.

1. Build smaller.
2. Build smarter.
1. Build smaller

Larger houses consume more resources than smaller ones. They use more wood, more carpet, more drywall, and more concrete. They cover more ground and generate more construction debris. In use, they require more energy to heat and cool.

The size of a house has a greater impact on energy and resource use than any other factor, including insulation, equipment efficiency, and windows.

http://oikos.com/esb/52/smallefficient.html

And size has been increasing over time under the impulse of affluence.

According to the National Association of Home Builders, the average home size in the US was 2,700 ft² in 2009, up from 1,400 ft² in 1970.

Ways to reduce the size of one’s house without feeling cramped:

- **Share space between different uses.**
  Examples: Home office and guest bedroom combination, hall or stairway as a library, mudroom doubling as laundry.

- **Add height space.**
  High vertical spaces add an airy feeling.

- **Use the entire building volume.**
  Example: Space under the roof can be used for visual appeal instead of being an empty attic, loft space or heated storage.

- **Reduce circulation paths.**
  Shorten or eliminate hallways, and have traffic cross rooms, so the extra space adds to the visual size of the room.

- **Build furniture into rooms.**
  Bookcases, benches and eating nooks use less space when part of the structure. Large storage drawers can be installed under stairs and beds (as they do onboard ships).

- **Remove formal spaces.**
  Most people gather in kitchens and family rooms. Formal living and dining rooms are seldom used. So why have two spaces dedicated to essentially the same activity?

- **Use bedrooms for sleeping.**
  Bedrooms should be used for sleeping, dressing and little more. “Sanctuary” bedroom suites are wasted space.
Ways to reduce the size of one's house - continued

- **Invite natural light.**
  Careful selection, sizing and location of windows and small skylights can flood a small space with natural light without increasing energy use. Daylight brings comfort.

- **Bring in the outdoors.**
  Locate windows and glazed doors next to decks, patios, courtyards and porches to extend the sense of living space past the outer walls.

- **Reveal the structure.**
  Structural elements such as exposed beams and posts need not be concealed and can be used as substitutes for floor space consuming furniture.

- **Use color.**
  Most small spaces benefit from lighter colors or white wall paint, because these give a spacious feeling.

- **Tie spaces together.**
  Similar materials, such as flooring, wall coverings and trim, tie spaces together visually, giving the overall impression of greater space.

---

2. **Build smarter**

The idea here, of course, to be more clever with the materials we use.

An example:

Corelam™ is a unique wood product that uses less material to deliver equal or greater strength than typical plywood products of the same dimensions.

The added stability comes from corrugation, which has been used for over a hundred years with metal and plastic but had not been applied successfully to wood until now.
Another thoughtful use of material

(+ keep in mind that corrugated cardboard is already full of holes!)

General rules:

- Curved and honeycomb geometries make strong structures with less material;
- Corollary: Use materials that include air bubbles in their makeup, such as some ceramics.
- Give preference to recycled materials and/or fast growing wood types (ex. bamboo).

An interesting use of a local and renewable material:
Bamboo


Companion video:

Strawbale synagogue in California

"Wealth appears to be a materializer" (Wernick et al., 1997)

Some dematerialization has taken place, but there are forces opposing it.

Energy efficiency appears easier than material efficiency.

Unlike for energy, one needs to consider closing the loop with materials.