Lecture: Systems Analysis Methodologies

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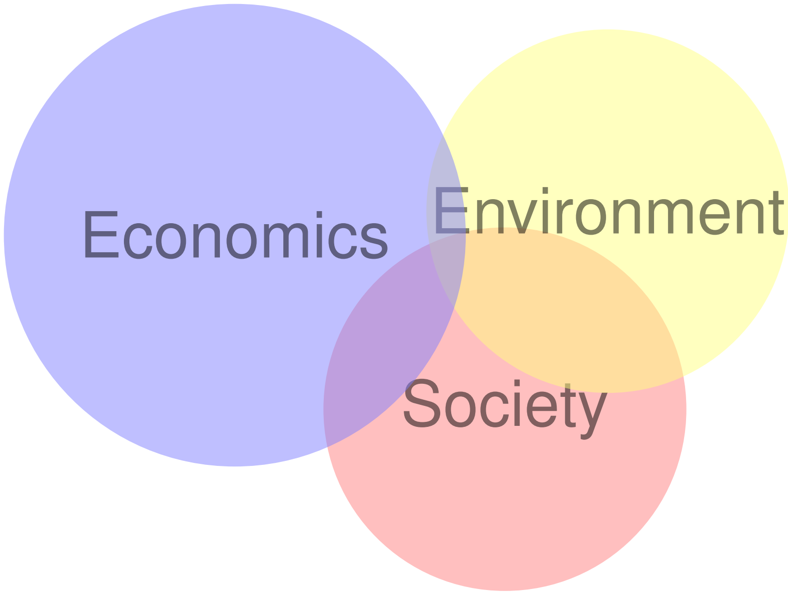
Outline

- Scoping study
- Systems analysis - increasing detail
- Life cycle analysis
- Simulation models
- Risk analysis and uncertainty
- How are all these connected?

INTRODUCTION

- Many issues for sustainability requiring balance
- We need to quantify to proceed
- Deal with complexity and uncertainty
- This is the goal “Systems Analysis”
- End result often involves very, very large computer codes
- How do we make such computer models?



Scoping study characteristics

- We'll see more of this in a fuel costs example next week.
- Basic guidelines for a scoping study:
  - Highly simplified
  - Mostly linear analysis - add separate costs
  - Very few feedback effects
- Advantages
  - Relatively simple to understand
  - Good overall picture
  - Identification of weaknesses

Systems Analysis is the next step in evaluation

- Assume a favorable scoping study
- Next step is a detailed systems analysis
- All elements are analyzed in much greater detail
- For example in our nuclear plant scoping study we gave the fuel price in $/kg
- In a system analysis model these costs are further broken down
- Fuel costs:
  - Mining costs
  - Conversion costs
  - Enrichment costs
  - Finance costs

Modularization of systems analysis

- Each of these may be further analyzed one or two levels deeper.
- Input data will be based on experience and future projections.
- The analysis will account for uncertainties.
- All lower level contributions are combined to form one module of the systems code
- $\Rightarrow$ the fuel cost module.

SA INCLUDES NON-LINEAR EFFECTS

- A critical feature in SA is the inclusion of interdependencies.
- Systems analysis are not linear.
- They include feedback effects.
- For example consider mining costs:
  - Plenty of Reserves – no problem, linear relation works.
  - Reserves dwindle – other issues arise
  - Fuel costs will rise
  - Will new fuel be found, if so how much?
  - How will this affect the projected cost of fuel?

BEWARE OF COMPLEX CODES.

- Systems analysis code contains a large number of complex modules
- Often hard to understand the whole picture, often expert in part of the picture.
- Should be more reliable than a scoping study thought.
- Warning:

Be very careful using complex systems analysis codes!!

SA is not only about money

- Investors are not the only people to carry out systems analysis
- Investors focus on financial returns
- Architectural engineers focus on technical credibility, schedule, and cost
- Environmentalists focus on pollution, waste disposal, greenhouse gasses, etc.
- Government focuses on the public good

GOVERNMENT IMPACT ON SA IS THROUGH REGULATION

- Desirability of a regulation is in the eye of the stakeholder.
- Everyone is a lobbyist.
  - Financial institutions.
  - Engineering firms.
  - Environmental groups.
  - Industrial groups.
- Consideration of impact of regulation is part of any SA.
- There often is an uncertain political aspect to a regulation.

Structure of a Systems Analysis

- Number of approaches to systems analysis
- Method below is fairly typical
- Goal of the analysis – answer the question

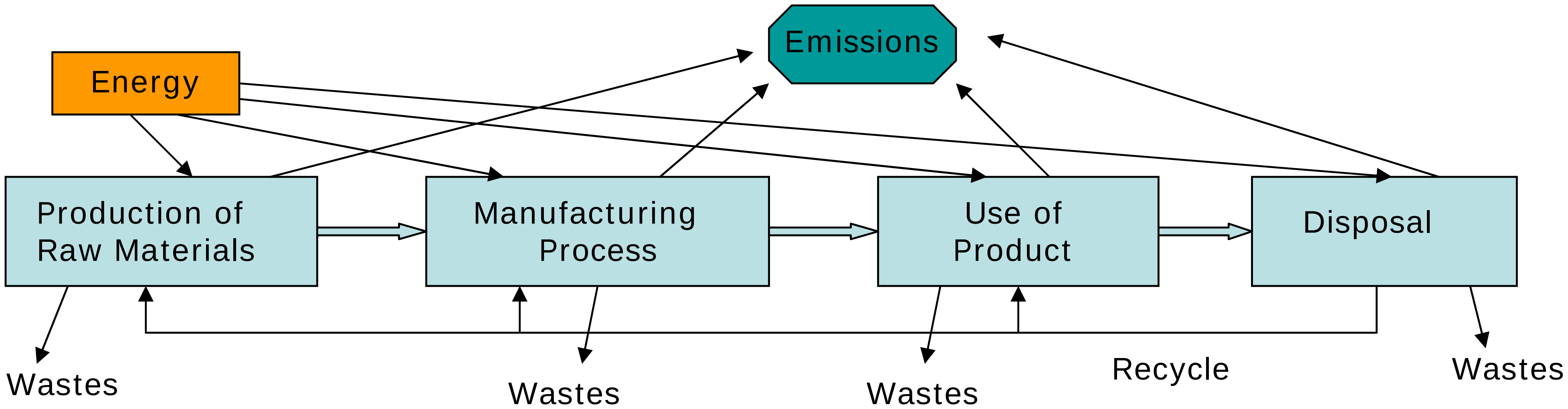
Does it make sense to build a new power plant (of type X)?

- The end product – a large, complex, hopefully all inclusive, simulation code.

The Simulation Code

- Technical aspects from a life cycle analysis
- Regulation aspects from a risk analysis
- Include feedback effects
- Combine to create a financial analysis

Life Cycle Analysis (LCA) elements



- Comprehensive cradle-to-grave, wells-to-wheels, dust-to-dust analysis
- Includes
  - Raw materials
  - Materials processing
  - Manufacturing
  - Distribution
  - Repair and maintenance
  - Waste disposal
  - Decommissioning

MacDonald's Styrofoam or paper?

Trees (natural?)

↓

Paper (good ?)

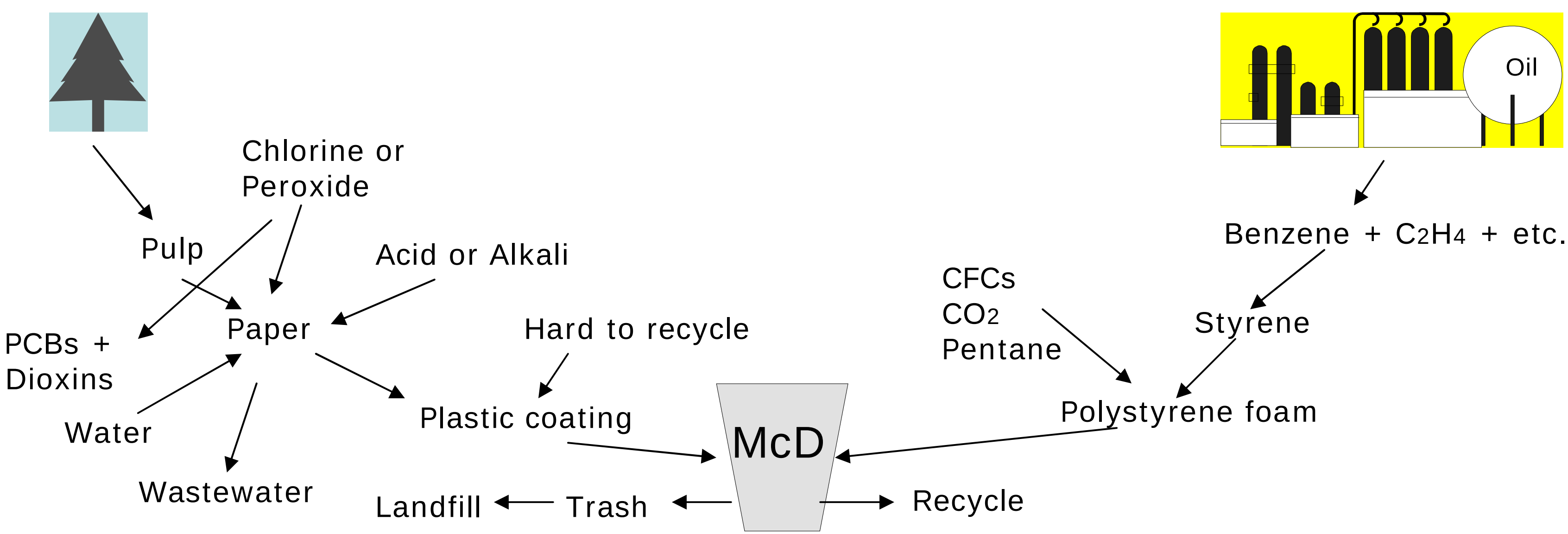
Oil (bad?)

↓

Chemicals (worse)

↓

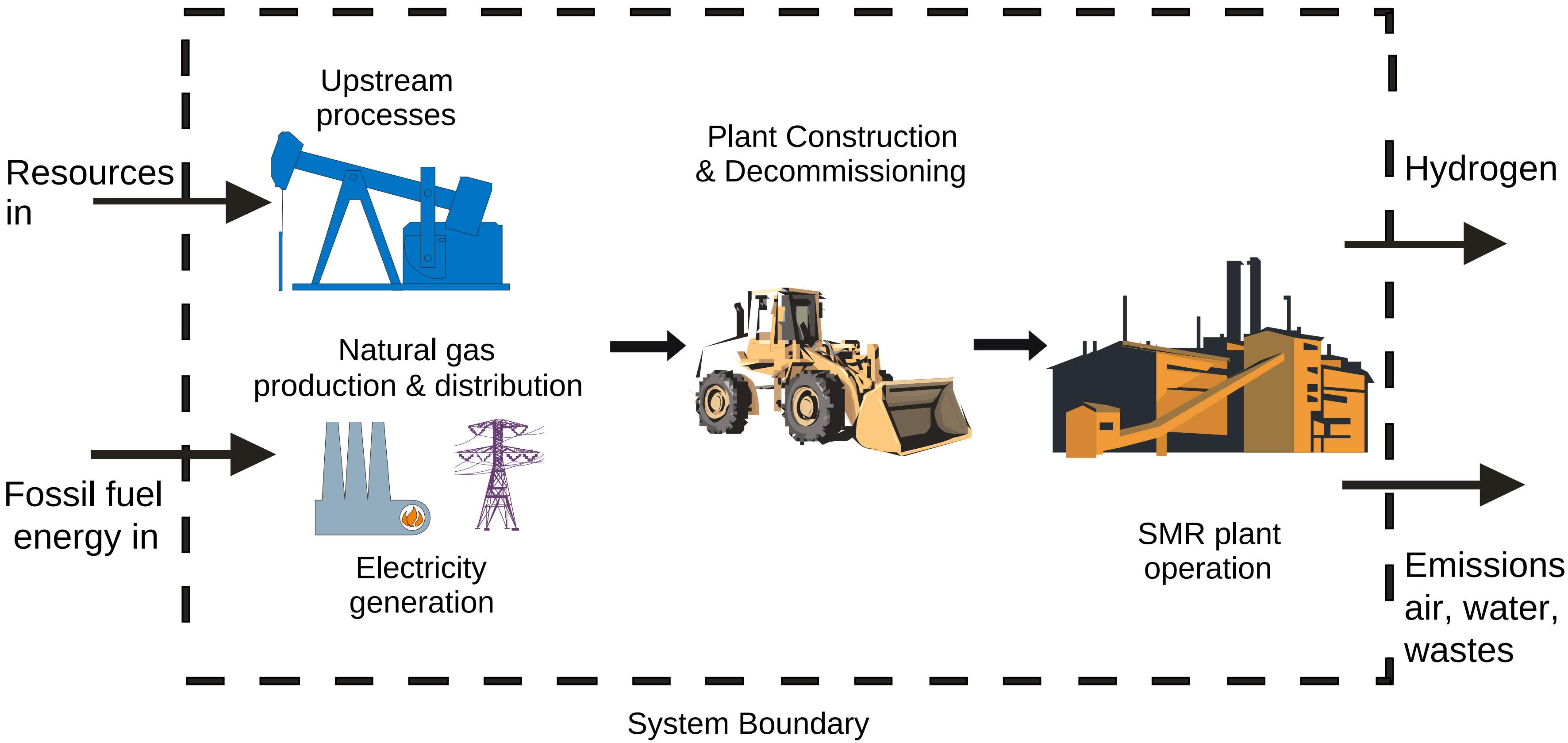
Styrofoam (??)



Hydrogen Production Example

- **Make from steam methane reforming?**
- **Make from water electrolysis using wind power?**

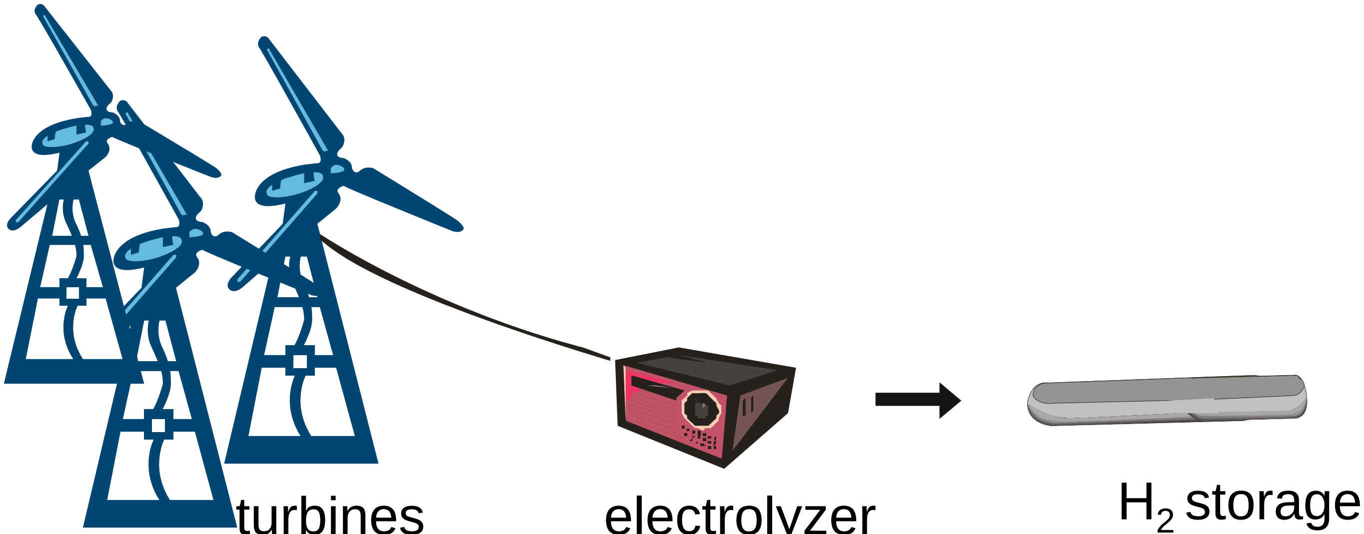
Steam Methane Reforming System Boundary Definition



SMR Results

- H_2 is a clean fuel, but its production from natural gas has environmental consequences
- H_2 plant itself produces few emissions, except CO_2
- CO_2 is the largest air emission (98 wt%) and accounts for 77% of the GWP
- 0.64 MJ of H_2 produced for every 1 MJ of fossil energy consumed

Wind/Electrolysis Study



Wind turbines:

- **Atlantic Orient Corporation (50kW x 3)**
- **Class 5 wind data from upper Midwest site (North Dakota)**

Electrolyzer:

- **Stuart Energy (30 Nm³/hr nominal capacity)**

Cars fueled: fleet of 46 at 3 kg/car/week

GWP and Energy Balance - Wind/Electrolysis

Preliminary results:

- **GWP = 650 g CO_2-eq/kg H_2**
  - **Only 5% of the greenhouse gas emissions from SMR**
- **Energy balance = 20 MJ of H_2 produced for every 1 MJ of fossil energy consumed**
  - **31 times more than the net energy balance from SMR**
- **Emissions are from equipment manufacture**
  - **Majority from concrete bases for wind turbines**
  - **Water consumption in electrolysis accounts for nearly all resources**

Hydrogen Production Choice?

- **Wind power offers significant reduction in GHG emissions**
- **For transportation, there is a mismatch between wind turbine energy availability and the large concentrated populations of cars**
- **Costs for hydrogen from wind power are MUCH higher than those from SMR**
- **For SMR, more fossil energy is consumed than H_2 energy produced**

Accuracy reflects uncertainties

- Technical accuracy is good
- Based on established engineering principles
  - Amount of fuel per year
  - Amount of stainless steel pipe
  - Average lifetime of valves
- Converting technical into $ more difficult
  - Interest rates
  - Inflation rates
  - Cost of fuel

An LCA of nuclear fuel cost including scarcity

- Cost of nuclear fuel including scarcity
- Reference case: U=$2000/kg
- Breakdown from the MIT study for cost per kg
  - Ore $437
  - Enrichment $117
  - Fabrication $825
  - Storage and Disposal $351
  - Total $2040

Some Reference Numbers

K_F = Fuel cost	\$2000/kg-U
W_{th} = 1 GWe Therm. En.	$2.1 x 10^{10}$ kWhr/yr
B = Burn rate	$1.1 x 10^{6}$ kWhr/kg
$M_F = W_{th}/B$ = Fuel/yr	$2.0 x 10^{4}$ kg-U/yr
$C_F = M_F x K_F$ = 1st yr fuel	\$42 M/yr
COE_{Fuel} = Fuel cost/kWhr	0.56 cents/kWhr

Focus on the cost of ore

- 10 kg ore yields 1 kg ready to use U
- Cost of ore is thus $44/kg-ore
- Ore reserves at this price = R_i
- R_i not well known
- Assume 50 years of reserves for 250 nukes
- Then

$$R_i = 10 \times 50 \times 250 \times M_F = 12.5 \times 10^4 M_F = 2.5 \times 10^9 \text{ kg-ore}$$

- Each nuke reduces reserves by $10 M_F t$ kg-ore

Dwindling Reserves

- Cheap reserves as a function of time

$$R_c(t) = R_i - 10NM_F t$$

- Cost of ore will increase rapidly as reserves dwindle
- Simple model

$$C_{ore}(t) = C_i \exp\left[k_1\left(\frac{R_i}{R_c} - 1\right)\right] = C_i \exp\left[k_1\left(\frac{10NM_F t}{R_i - 10NM_F t}\right)\right]$$

- $k_1 = 2.3$

Two Additional Effects

- Number of nuclear plants may change with time
- As cost of ore goes up new reserves may be found
- Both effects have an impact on the amount of reserves

The Number of Nukes

- Three effects determining N
  - Replacement of old nukes
  - Replace old coal plants with CO_2 free nukes
  - US electricity demand will increase each year – meet new demand with nukes
- Old nukes replaced by new nukes
- Old coal replacements = N_{coal}/T = 6.25/yr
- New demand = % increase x total plants = 5

The Number of Nukes (cont)

- Combine terms

$$N(t) = \text{Existing Nukes} + \text{Coal Replacement} + \text{New capacity}$$

$$= \quad N_{nuke} \quad + \quad \frac{N_{coal}}{T_p} t \quad + \quad 0.05 N_{nuke} t$$

$$= 100 + 11.3\,t$$

- Here, $N_{nuke} = 100$, $N_{coal} = 250$, $T_p = 40$ yrs, t is measured in years

New Reserves

- Reserves go down $\rightarrow$ cost of ore goes up
- Cost of ore goes up $\rightarrow$ search for new ore
- New reserves cost more than initial reserves
- But you lose more because of increasing demand than you gain with new reserves

New Reserves (cont)

- A simple model

$$R_i(t) = R_{i0} + k_3 \frac{C_{ore}(t) - C_i}{C_{ore}(t)} R_{i0} = 2.5 \times 10^9 \left(1 + 2\frac{C_{ore} - 44}{C_{ore}}\right)$$

- Here R_{i0} = $2.5\text{x}10^9$ kg-ore, C_i = \$44 / kg-ore, and k_3 = 2
- Note the feedback loop
  - $C_{ore}(t)$ depends on $R_i(t)$
  - $R_i(t)$ depends on $C_{ore}(t)$

Equations for the cost of ore are non-linear

- Known reserves and cost of ore are inter-related

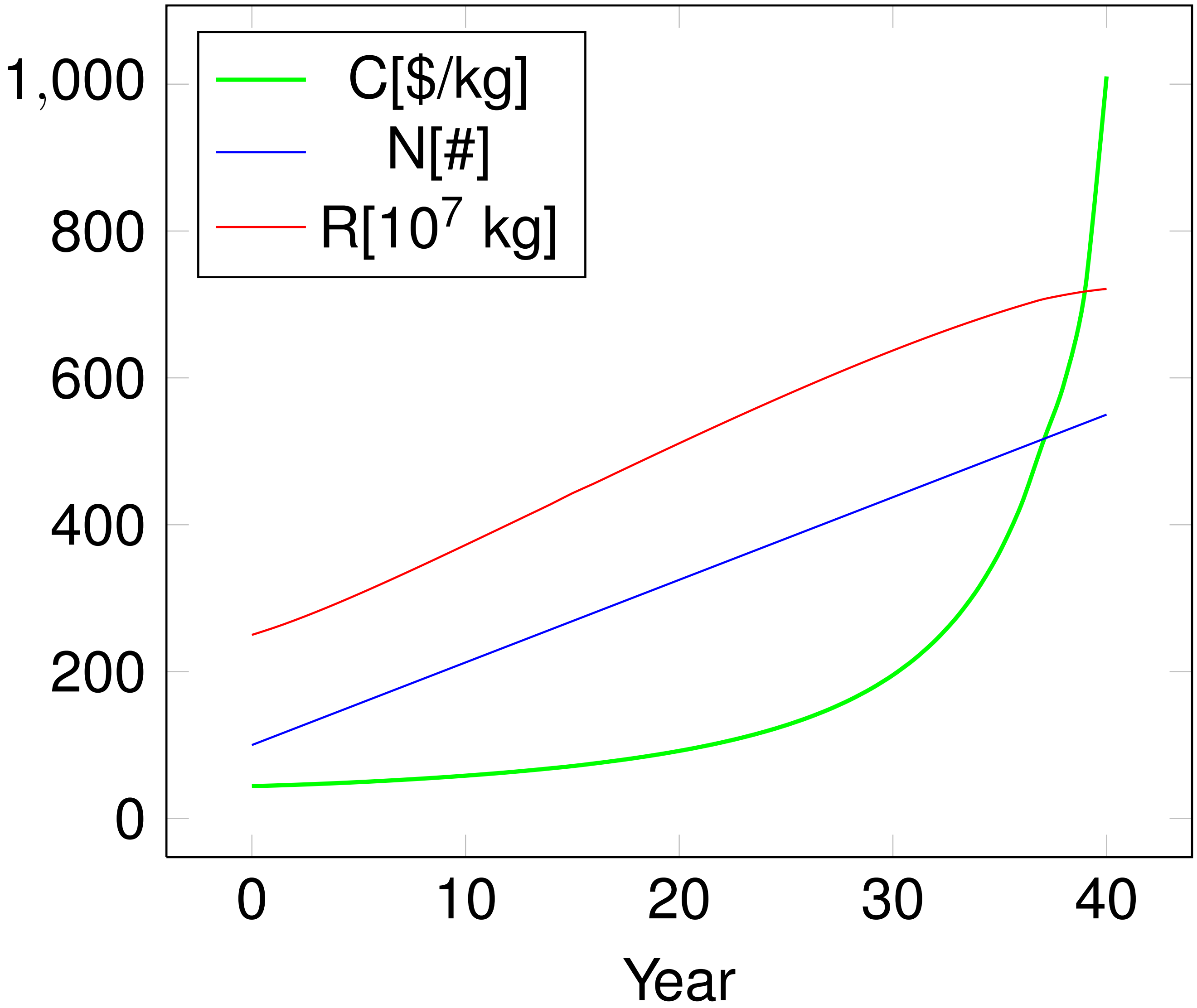
$$C_{\text{ore}}(t) = C_i \exp\left[k_1\left(\frac{10N(t)M_F t}{R_i(t) - 10N(t)M_F t}\right)\right]$$

$$N(t) = N_{i0} + \left(\frac{N_{\text{coal}}}{T_p} + k_2 N_{i0}\right) t$$

$$R_i(t) = R_{i0}\left(1 + k_3 \frac{C_{\text{ore}}(t) - C_i}{C_{\text{ore}}(t)}\right)$$

$$k_1 = 2.3, k_2 = 0.05, k_3 = 2$$

Cost of ore from systems analysis



- Note the singular response around 40 years. What causes this?
- What does a plot of R vs C look like?

Conclusion

- Cost of ore increases by 30
- Ore is 1/5 the cost of uranium
- COE of uranium = 0.56 cent/kWhr
- This yields 3.8 cents/kWhr
- Not as bad when you calculate the present value
- Still – it could be a problem
- Uncertainty: what is the sensitivity to k_1, k_2, k_3

Risk Analysis

- Risk analysis involves accidents to people or mechanical failures
- Too many injuries or failures lower the capacity factor and reduce revenue
- We want to minimize risk but it is not possible to achieve zero risk
- Qualitatively risk can be written as

$$\text{Risk} = \text{Frequency} \times \text{Consequence}$$

Types of Risk

- Risk can be continuous or discrete
- Continuous: exposure to toxic fumes
- Discrete: steam pipe explosion
- Consequences could cause minor injuries
- Consequences could cause death
- Consequences could involve land or water contamination
- Even if no human or ecological damage, mechanical failures lower capacity factor

Avoiding Risk

Three basic approaches:

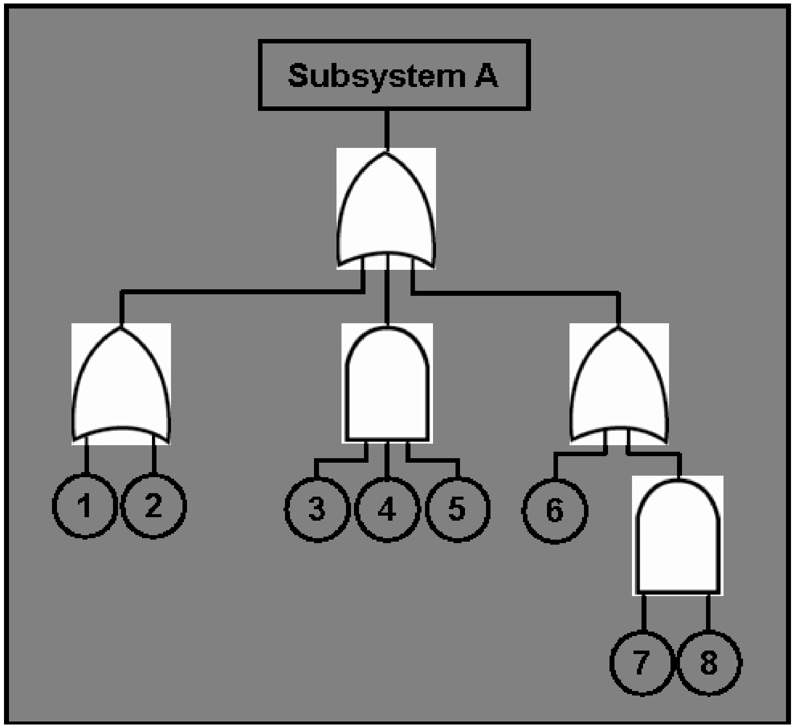
- Ultra robust design to minimize failure
- Redundancy – one system fails, another takes over
- Increased shut-downs for maintenance and repairs

DETERMINING RISK

- How do we determine risk?
- This is the realm of risk analysis
- Single component failures relatively easy
  - Qualification data available
  - History of real world experience
  - Can predict the mean time between failure
- Single small failures often harmless
- Single gigantic failures very rare

Complex Failures

- Largest danger: often a sequence of minor failures leads to major catastrophe
- For example: TMI, Challenger
- Analysis requires sophisticated tools
  - Fault tree analysis
  - Event tree analysis
  - Uncertainty analysis
- Probability of a severe accident
- Greater for a sequence of minor failures
- Smaller for a single major failure



Fault Tree example

WHAT TO DO?

- Recommendations vary by group
- Builders tend to underestimate risks to keep the cost down
- Example: Don’t worry – the Big Dig is safe
- Others tend to overestimate the risks to avoid or delay construction
    - Example: Nuclear is unsafe – don’t build it.
    - Example: Wind kill birds – don’t build it.
- Often the arbiter of risks are government agencies – the EPA, NRC, FDA, etc.
    - Desire risk informed regulations
    - Regulations consistent with severity of the risk

An Illustrative example

- How does risk affect construction cost of a power plant?
- Assume initial capital cost includes all regulations associated with risk
- As construction proceeds, new risks may be identified
- These can lead to new regulations
- New regulations lead to construction changes
- Change orders increase time and cost of construction

The Construction Model

- Assume the initial capital cost is C_{cap}
- Assume the initial construction time is T_c
- New regulations often occur randomly
- For simplicity assume that new regulations occur at the rate *r* per year
- Each new regulation increases cost by ΔC
- Each new regulation increases time by Δt
- Goal: calculate the new cost of the plant including new regulations

The New Construction Period

- New construction time T_c' = original time T_c plus extra regulation time $N\Delta t$
- $N = rT_c'$ = total number of changes
- Mathematically

$$T_c' = T_c + N\Delta t = T_c + rT_c'\Delta t$$

- Solve for T_c'

$$T_c' = \frac{T_c}{1 - r\Delta t}$$

- Note that $r\Delta t < 1$ for completion

The New Cost

- A similar argument holds for the new cost

$$C'_{cap} = C_{cap} + N\Delta C = C_{cap} + \frac{rT_c}{1 - r\Delta t}\Delta C$$

- Note that Δt and ΔC are related
- Make Δt larger – fewer workers needed, leads to lower costs
- But they are paid over a longer time
- Fixed costs (e.g. insurance, benefits, etc.) lead to a net increase in C_{cap} due to delays

Model for ΔC

- Increment includes hardware and labor

$$\Delta C = \Delta C_{hard} + \Delta C_{labor}$$

- Labor costs increase as Δt increases
- Incremental labor costs are assumed to scale linearly with initial labor costs C_{labor}

$$\Delta C_{labor} = k_1 C_{labor} \frac{\Delta t}{T_c}$$

- k_1 is a constant about equal to 1

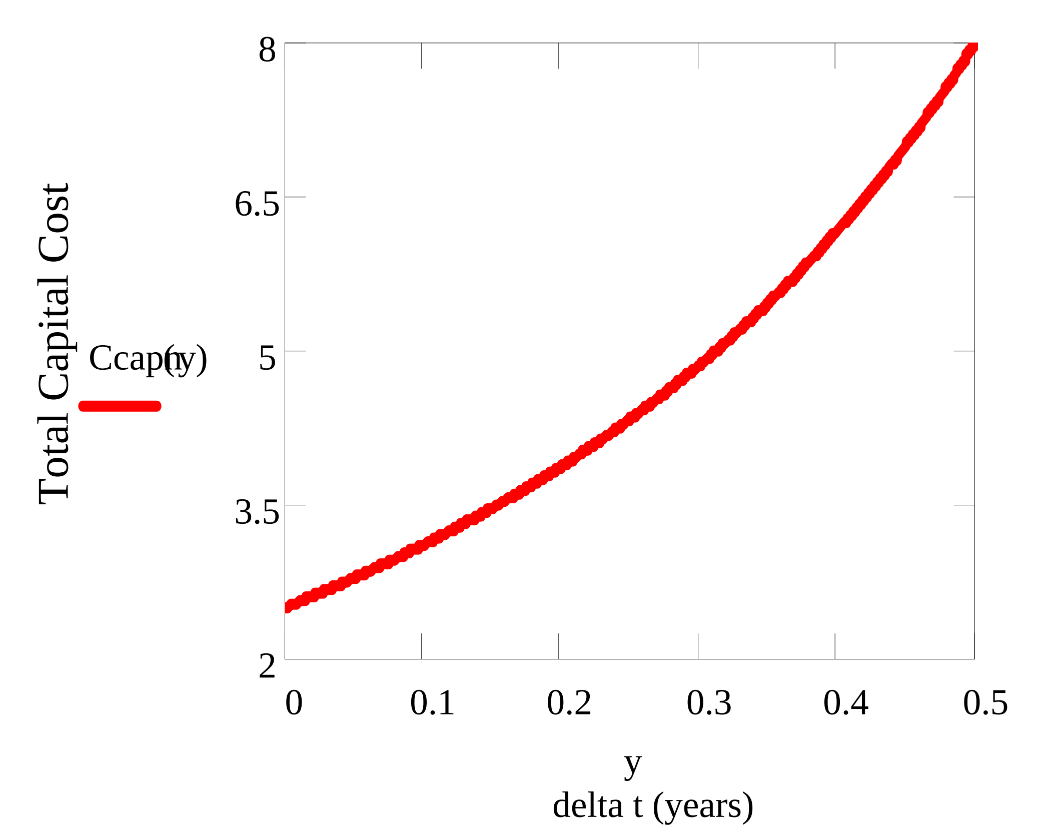
The Bottom Line

- The new construction cost is given by

$$C'_{cap} = C_{cap} + \frac{rT_c}{1 - r\Delta t}\left(\Delta C_{hard} + k_1 C_{labor}\frac{\Delta t}{T_c}\right)$$

- The best strategy
- Finish construction as soon as possible even if it means borrowing more money up front

Capital Cost vs. Δt



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