The Darwinian Principle Applied to System Design

Theory and Applications for Strategic Engineering

Systems Thinking for Contemporary Challenges

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·GVERICKE·TORRICELLI·CHLADNI·
·HVYGENS·YOVNG·ARAGO·FRESNEL·
·DAGVERRE·KIRCHHOFF·ROWLAND·
DARWIN

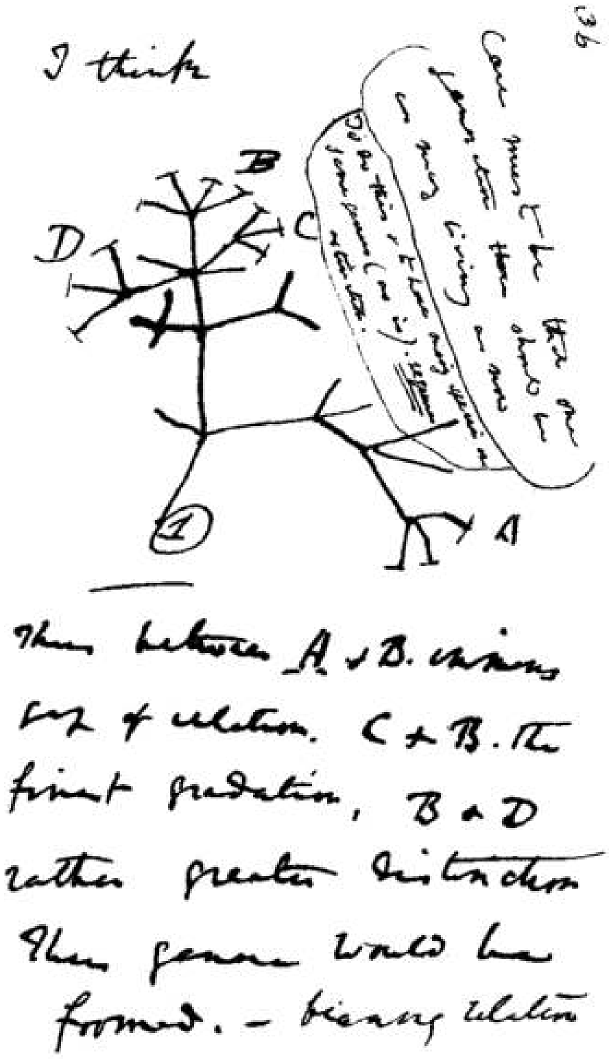
Charles Darwin (1809-1882)

- All species of life have evolved over time from common ancestors through the process of “natural selection”.
- **It is not the strongest of the species that survives, nor the most intelligent that survives. It is the one that is the most adaptable to change.**

On the Origin of Species (1859)

Questions for designers of systems?

- ❑ What happens to man-made systems that don't change easily?
  - ➢ It depends, can become "locked in"
- ❑ Why is "changeability" important?
  - ➢ Because future is uncertain, and designing to fixed requirements can be counterproductive
- ❑ Implications for System Design
  - ➢ Design for changeability – strategically designing products and systems for change



Case must be that one generation then should be as many living as now. To do this & to have many species in same genus (as is) requires extinction.

Thus between A & B. immense gap of relation. C & B. the finest gradation, B & D rather greater distinction Thus genera would be formed. — bearing relation

Darwin's first sketch of an evolutionary tree from his First Notebook on Transmutation of Species (1837)

Lock-In

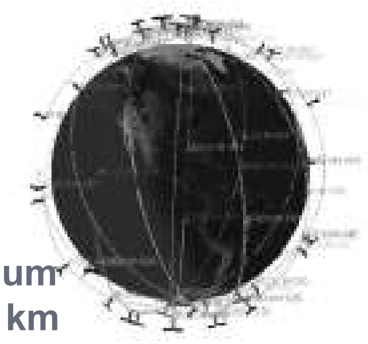
de Weck, O.L., de Neufville R. and Chaize M., “Staged Deployment of Communications Satellite Constellations in Low Earth Orbit”, *Journal of Aerospace Computing, Information, and Communication*, **1**, 119-136, March 2004

What is lock-in?

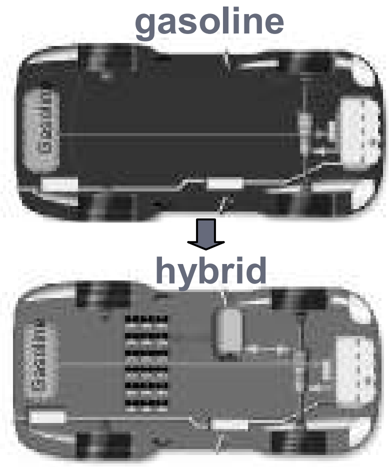
- Many large-scale complex systems suffer from **“lock-in”,** the inability to change/switch to a better configuration (or technology) despite superior solutions being known
  - Nuclear reactor technology [Cowan 1990]
  - Economic aspects of lock-in [Arthur 1989, Arrow 2000]
  - Political economic context [Nelson & Winter 1982]
  - Causes are still being debated [Liebowitz 1985]
  - Network externalities are important [Katz 1997, Witt 1997]
  - Trade-off between operating slightly inefficient fielded technologies and developing new technologies [Sarsfield 2001]
  - Political and organizational inertia [Puffert 2003]
  - Recent AA/TPP S.M. Thesis on lock-in [**Silver 2005**]

Examples of Lock-In

- **Communications Satellite Constellations** **[Chaize et al. 2003]**
  - Iridium Bankruptcy [1999, $5B], Globalstar similar fate
  - Oversized System based on optimistic market forecasts, could not easily adapt capacity, service, footprint …
  - How would you design them for evolution?



- **Automotive Platforms** **[Suh et al. 2005]**
  - General Motors, e.g. Epsilon Platform [2003-2013+]
  - Challenge in adapting platform to changing requirements over 10-15 year life: stretching chassis, incorporate new powertrain technologies, rigid tooling, too many constraints
  - O($10B) commitments for design, factory layout, tooling,…



- **NASA Launch Vehicles** **[Silver et al. 2005]**
  - NASA Space Shuttle Program [1972-present]
  - Original traffic model called for ~ 50 flights/year
  - Actual flight rate much smaller, technical issues, long turnaround times, high fixed cost, ~$4 billion/year

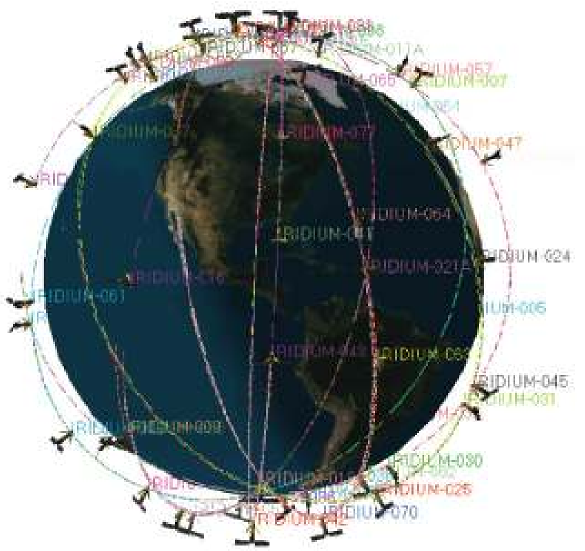
Iridium Satellite System

'Motorola unveils new concept for global personal communications: base is constellation of low-orbit cellular satellites',

Motorola Press Release on Iridium, London, 26 June 1990.

'Last week, Iridium LLC filed for bankruptcy-court protection. Lost investments are estimated at $5 billion.'

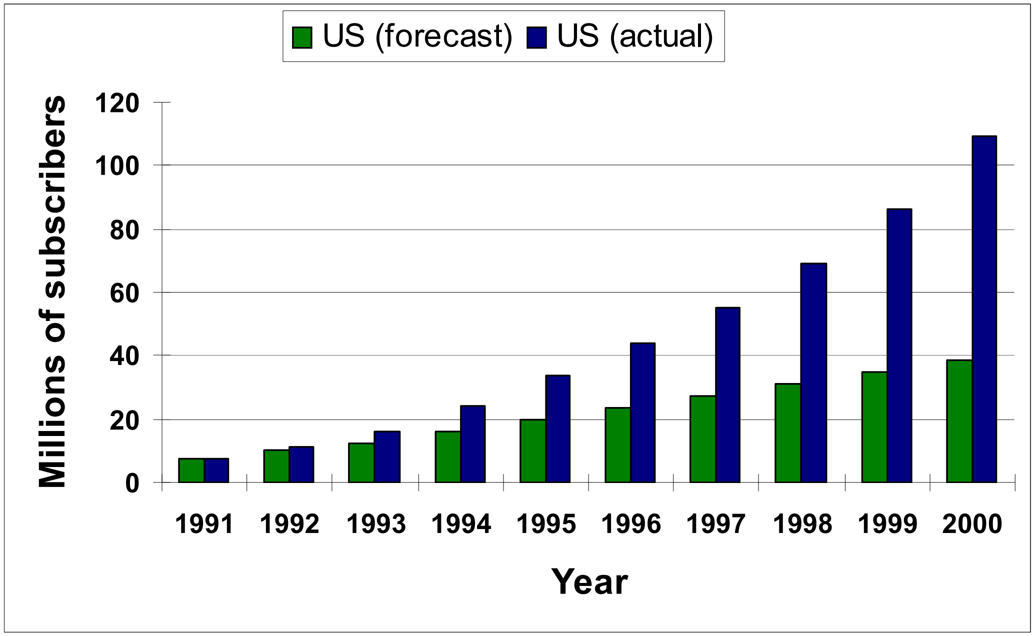
Wall Street Journal, New York, 18 August 1999.



- ❑ Lesson Learned:
  - Difficult to properly size capacity of large system
  - Market assumptions can change when 7-8 years elapse between conceptual design and fielding (1991-1998)

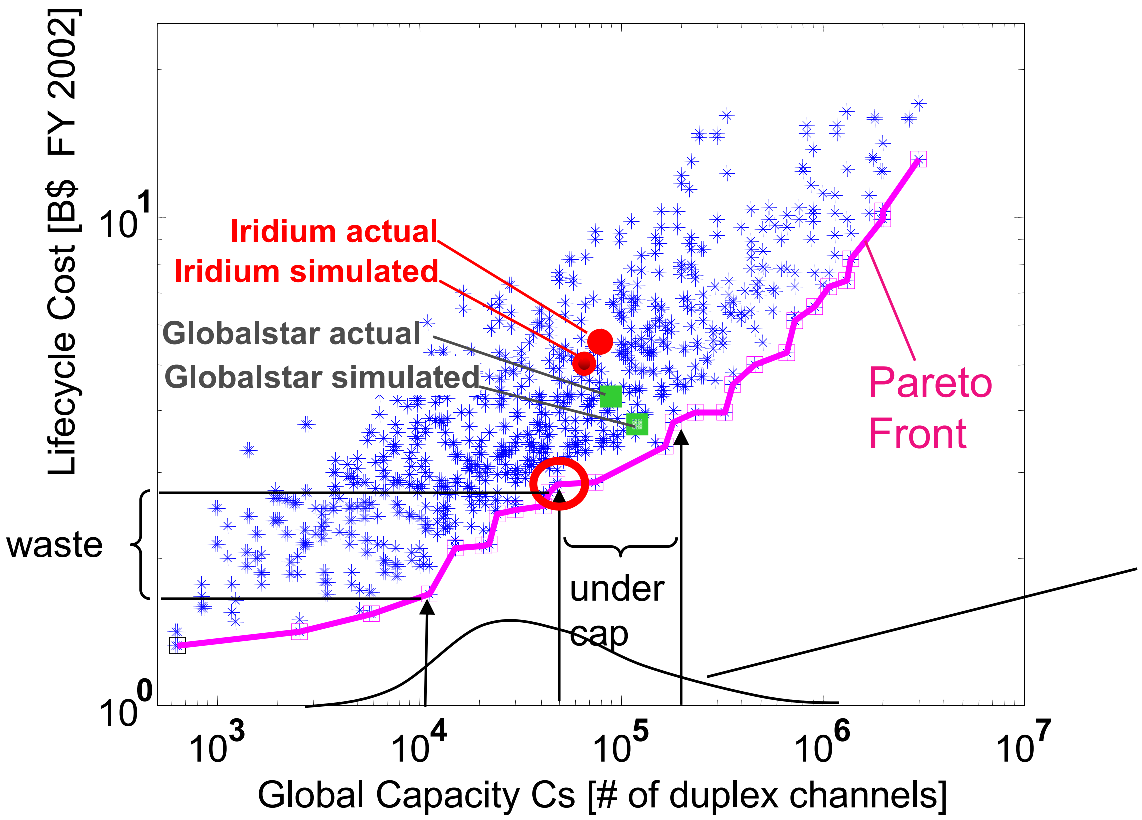
Forecasts are (usually) wrong

- Iridium was a technical success but an economic failure:
  - 6 millions customers expected (1991)
  - Iridium had only 50 000 customers after 11 months of service (1998)
- The forecasts were wrong, primarily because they underestimated the market for terrestrial cellular telephones:



Traditional Systems Engineering

- The traditional approach for designing a system considers configurations (architectures) to be fixed over time.
- Designers look for a Pareto Optimal solution in the Trade Space given a targeted capacity.



Demand distribution
Probability density function

$$P\{a < D \le b\} = \int_a^b f_D(\delta)\mathrm{d}D$$

$$0 \le f_D(D) \text{ for all } D$$

$$\int_{-\infty}^{\infty} f_D(\delta)\mathrm{dD} = 1$$

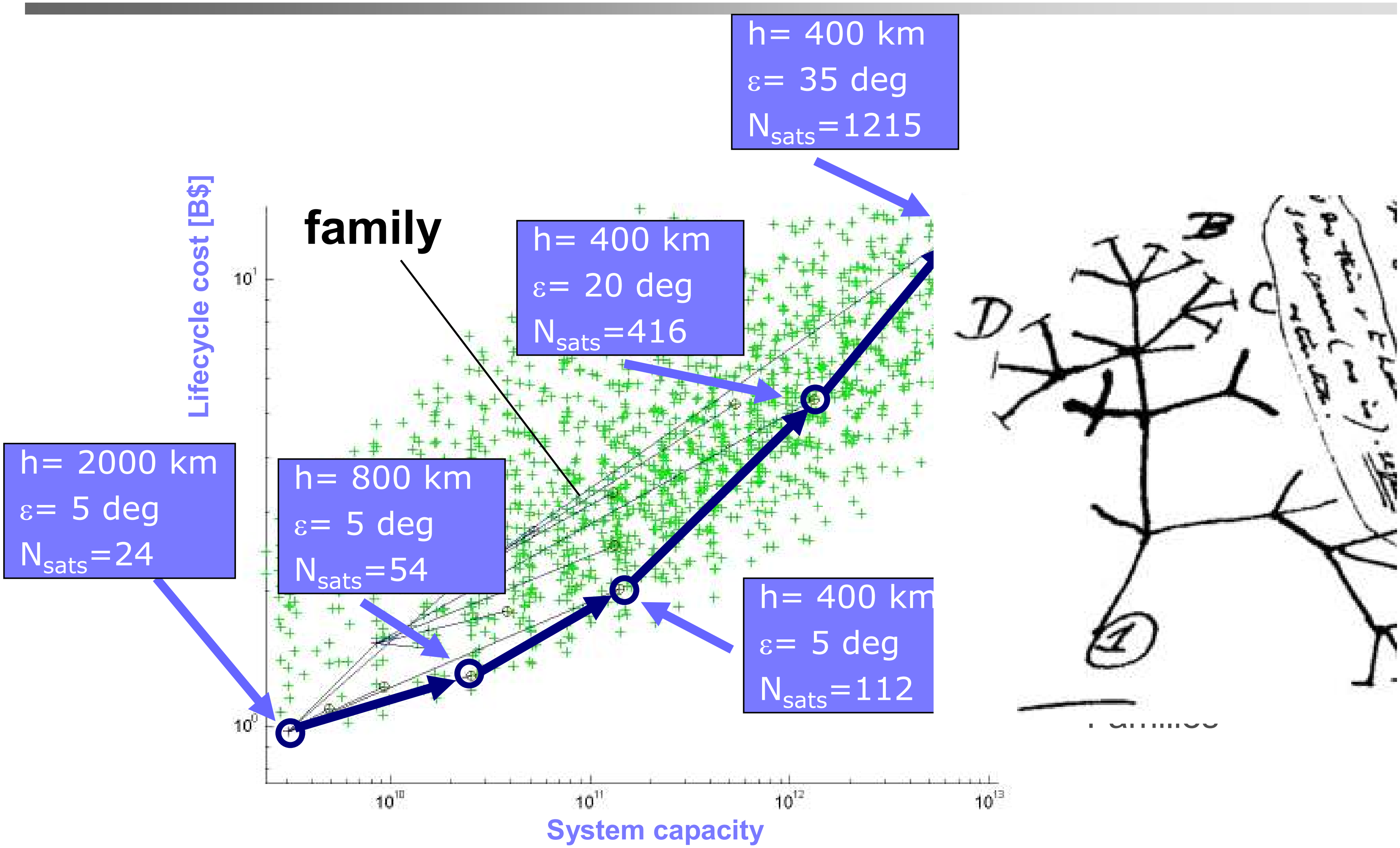
Staged Deployment – A Form of Evolution

- Adapt to uncertain demand with a staged deployment strategy:
  - A smaller, more affordable system is initially built
  - System has the flexibility to increase its capacity if needed

How do we design an evolvable system?

- *What should be the initial starting point?*
- *How many stages?*
- *When to trigger system expansion?*

Identify Feasible Paths



h= 2000 km
ε= 5 deg
N_{sats}=24

h= 800 km
ε= 5 deg
N_{sats}=54

h= 400 km
ε= 5 deg
N_{sats}=112

h= 400 km
ε= 20 deg
N_{sats}=416

h= 400 km
ε= 35 deg
N_{sats}=1215

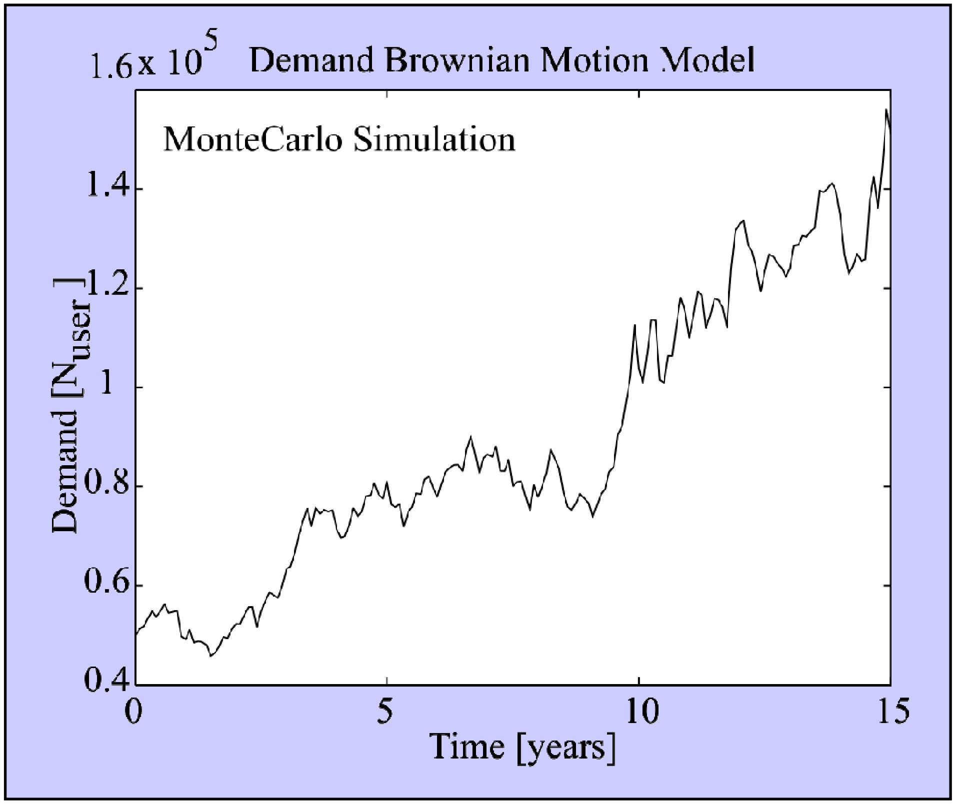
Generate Demand Scenarios (GBM)

S -stock price → N_{user} demand
Δt – time period
ε- SND random variable
μ, σ - constants

$$\frac{\Delta S}{S} = \mu \Delta t + \sigma \varepsilon \sqrt{\Delta t}$$

$$E\left[\frac{\Delta S}{S}\right] = \mu \Delta t$$

$$\mathrm{var}\left[\frac{\Delta S}{S}\right] = \sigma^2 \Delta t$$



- Demand can go up or down between two decision points
- Infinitely many scenarios can be generated based on this model

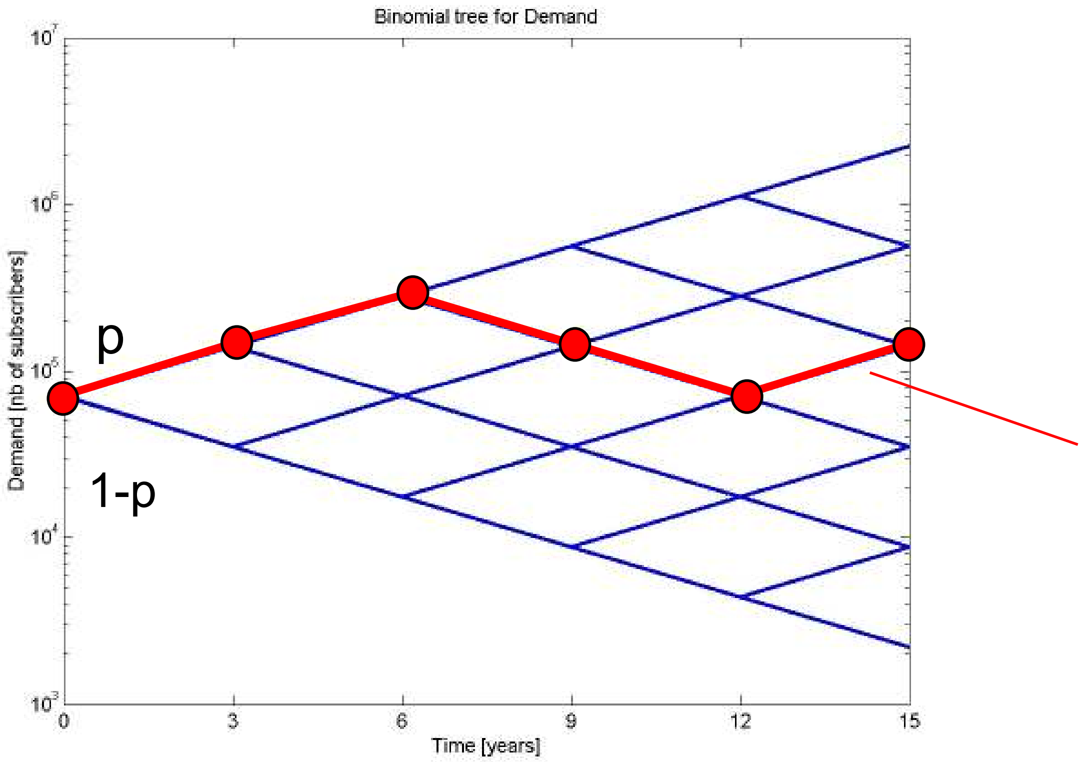
Discrete Demand Scenarios

$$u = e^{\sigma\sqrt{\Delta t}}$$

$$d = 1/u$$

$$p = \frac{e^{u\Delta t} - d}{u - d}$$

Discretized Random Walk



Total

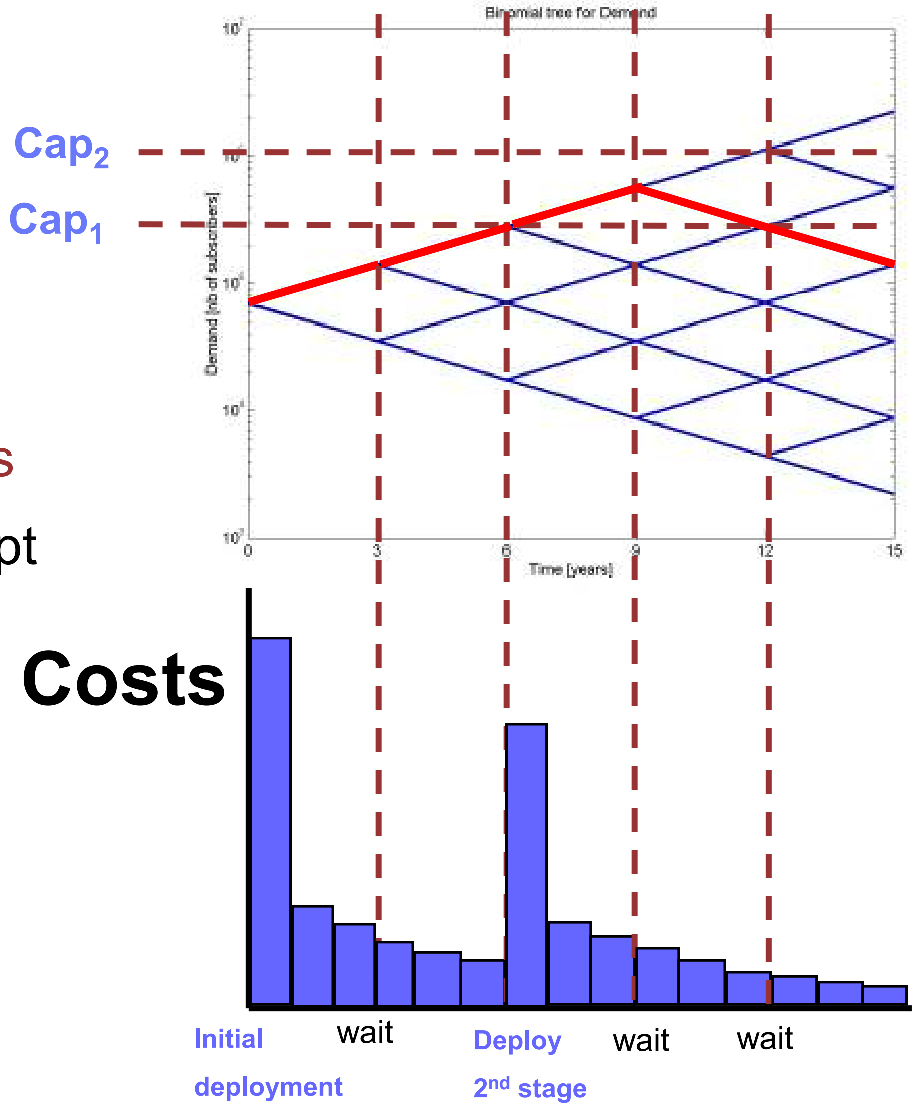
2^5=32 scenarios

Sample scenario

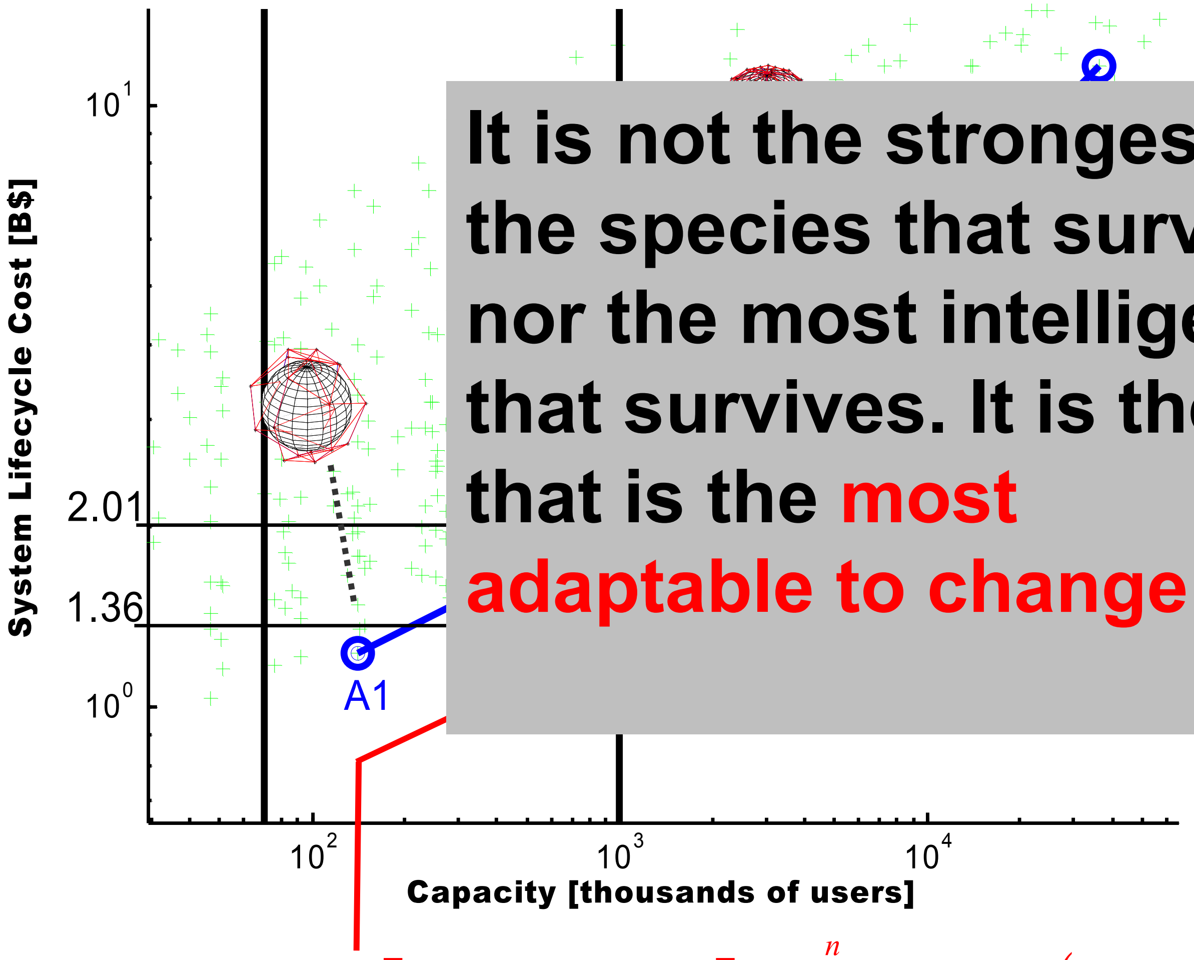
$$P(i) = p^k (1 - p)^{n-k}$$

Calculate Lifecycle Cost (="fitness")

- We compute the costs of a path with respect to each demand scenario
- We then look at the weighted average of every allowable path for cost over all scenarios
- Decision rule: We always adapt to demand when demand exceeds capacity
- The costs are discounted: the present value of LCC is considered



Identify optimal evolution path*



It is not the strongest of the species that survives, nor the most intelligent that survives. It is the one that is the most adaptable to change

- For a given targeted capacity, we pare our tion to the itional approach

  approach ws large savings % on average)

E[ΔLCC]=$650 million value of real option

$$E\left[LCC(path_j)\right]=\sum_{i=1}^{n} p_i LCC\left(scenario^i_{path_j}\right)$$

Uncertainty

de Weck O.L., Eckert C., "A Classification of Uncertainty for Early Product and System Design", ICED-2007-1999, *16th International Conference on Engineering Design,* Paris, France, August 28-31, 2007

Example: Automotive Assembly Plant

- DaimlerChrysler's PT Cruiser
  - Big sales success in 2000 and 2001
  - Capacity at Mexican plant exceeded
- Could not shift overflow production to Belvidere, Illinois, plant
  - Paint shop too low
  - $480 Million in pre-tax profits foregone

http://cgmedia.daimlerchrysler.com

Unexpectedly high demand, but cannot satisfy it due to rigid capacity constraints

Example: Military Equipment in Iraq

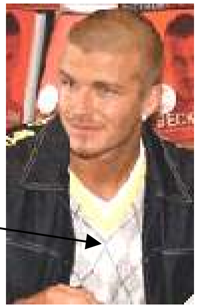
- **M-1 Abrams Tank**
  - Designed during cold war
  - Battle against Soviet Union in moderate European Climate
  - ~ 800 miles/year nominal

- 2004 Letter by **Lt. Gen Ricardo Sanchez**, top US Commander
  - M-1 Abrams Combat Readiness dropped to 78% from 90%
  - Driven 4000 miles/year (5 times nominal usage)
  - Sand is clogging up mechanisms; parts fail much earlier than expected; lack of spares; upset service contracts

Increased failures due to vehicle operated outside its original specifications

Example: Fashion and Consumer Products

- Robert **Pringle**, born in the 1780's, founded a sock, hosiery and underwear company in Harwick, Scotland in 1815.
- January 1999 – U.S. imposes **trade sanctions** on European luxury goods in retaliation of European subsidies for Banana imports



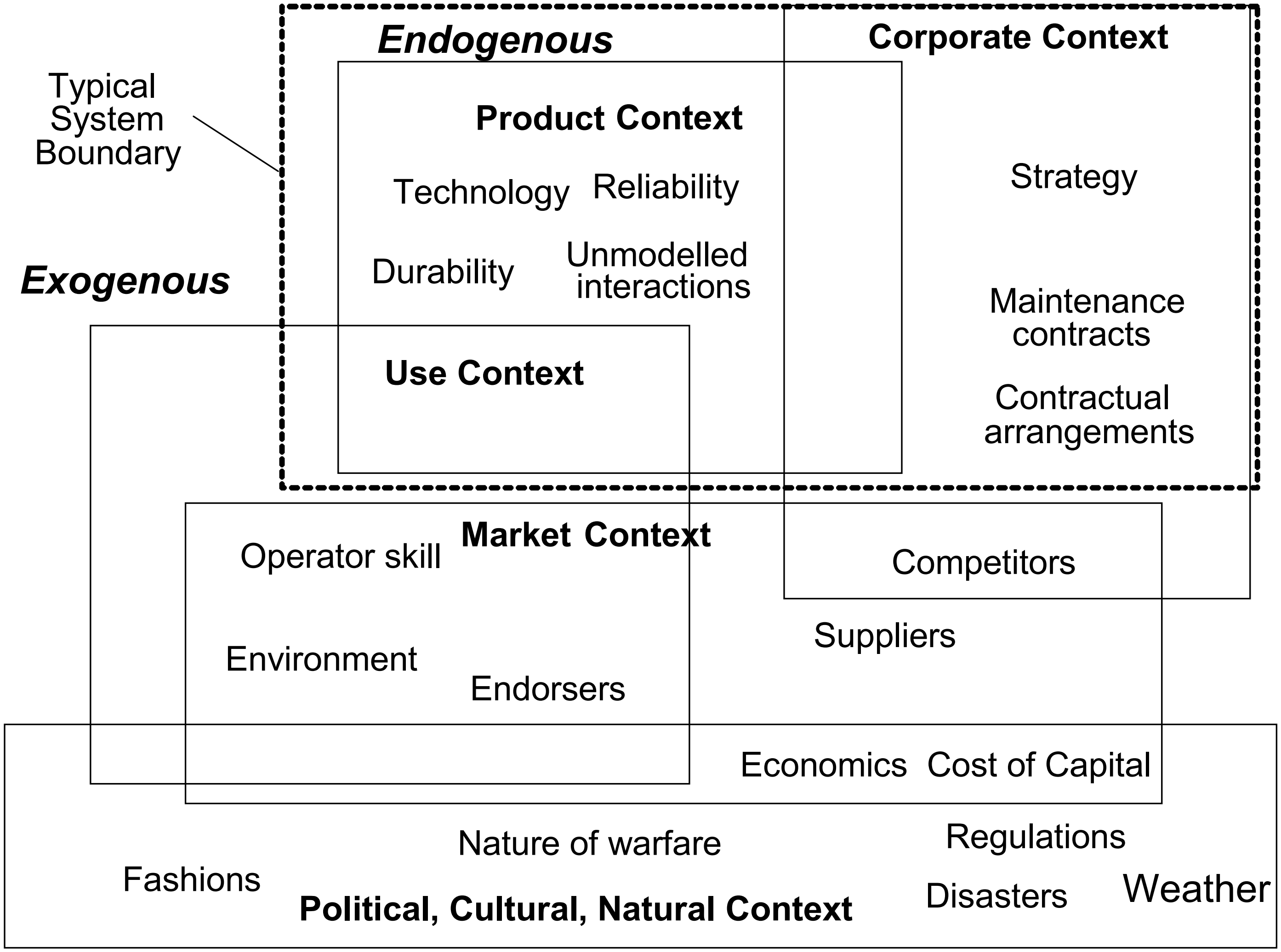
Cashmere Sweater

Among celebrities wearing Pringle Argyle patterned sweaters, is David Beckham.

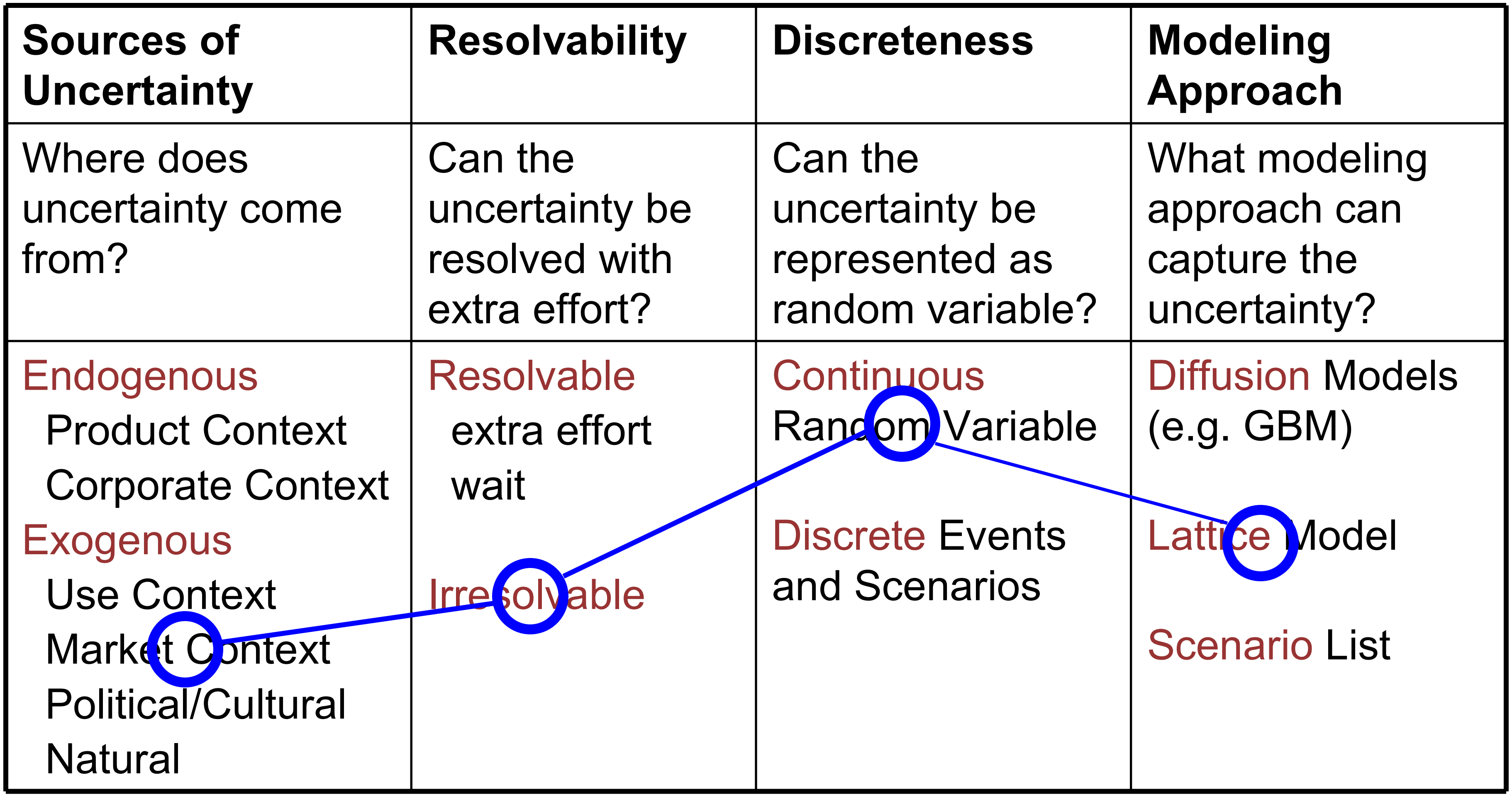
- Scottish cashmere garment manufacturers in financial trouble
- David Beckham on TV in a pink and gray cashmere sweater
- Instead of 500, sales rocket to over 20,000, saving the company

Unexpected Windfall during crisis

Sources of Uncertainty



Uncertainty “Checklist” in System Design



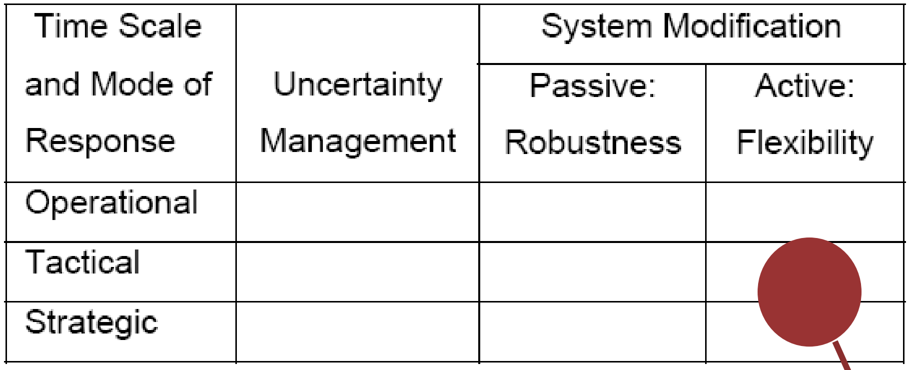
Sources of Uncertainty	**Resolvability**	**Discreteness**	**Modeling Approach**
Where does uncertainty come from?	Can the uncertainty be resolved with extra effort?	Can the uncertainty be represented as random variable?	What modeling approach can capture the uncertainty?
Endogenous Product Context Corporate Context Exogenous Use Context Market Context Political/Cultural Natural	Resolvable extra effort wait Irresolvable	Continuous Random Variable Discrete Events and Scenarios	Diffusion Models (e.g. GBM) Lattice Model Scenario List

Example: Iridium/Globalstar Case

Dealing with Uncertainty

- Considering uncertainty is important for systems and products that are characterized by:
  - large, irreversible investments
  - long lifecycles
  - large volatility in market, technology, regulations …
- Need to characterize the uncertainty … then what?
- How to respond ?
  - See Typology

Ref:de Neufville, R. et al: Uncertainty Management for Engineering Systems Planning and Design, MIT International Engineering Systems Symposium, Monograph, MIT, Cambridge, MA. March 2004. http://esd.mit.edu/symposium/pdfs/monograph/uncertainty.pdf



Time Scale and Mode of Response	Uncertainty Management	System Modification	
		Passive: Robustness	Active: Flexibility
Operational			
Tactical			
Strategic			

Table 1: Two-Way Typology of Ways to Manage Uncertainty in Engineering Systems Design

System Design for Changeability

Strategic Engineering

Silver M., de Weck O. "Time-Expanded Decision Networks: A Framework for Designing Evolvable Complex Systems", *Systems Engineering*, 10 (2), 167-186, 2007

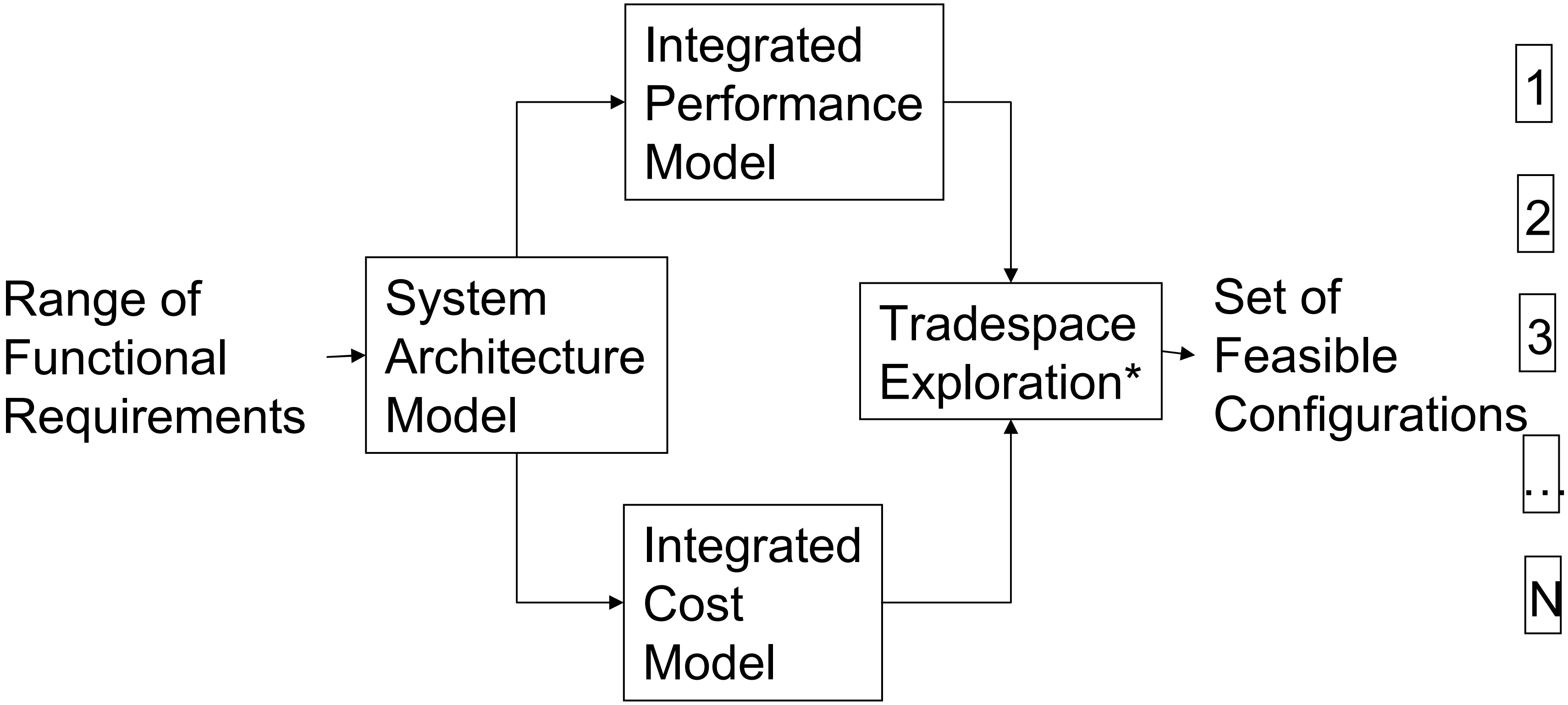
5-Step Framework for Strategic Engineering

- Step 1: Trade Space Exploration (initial Configurations)
- Step 2: Uncertainty Identification and Quantification
- Step 3: Change Propagation Analysis
- Step 4: Create Time-expanded Decision Network
- Step 5: Path Optimization in TDN

- Step 6: Identify popular “switches” – redesign to lower switching costs by embedding flexibility, as appropriate
- Iterate on Value-at-Risk (VAR)

1: Tradespace Exploration

Step 1: Define a set of initial configurations



* Design of Experiments, Optimization, Isoperformance

2: Uncertainty Characterization

- Continuous: Geometric Brownian Motion (GBM)
- Discrete: Lattice Models
- Discrete Scenarios

D - demand
Δt – time period
ε- SND random variable
μ, σ - constants

$$\frac{\Delta D}{D} = \mu \Delta t + \sigma \varepsilon \sqrt{\Delta t}$$

$$E\left[\frac{\Delta D}{D}\right] = \mu \Delta t$$

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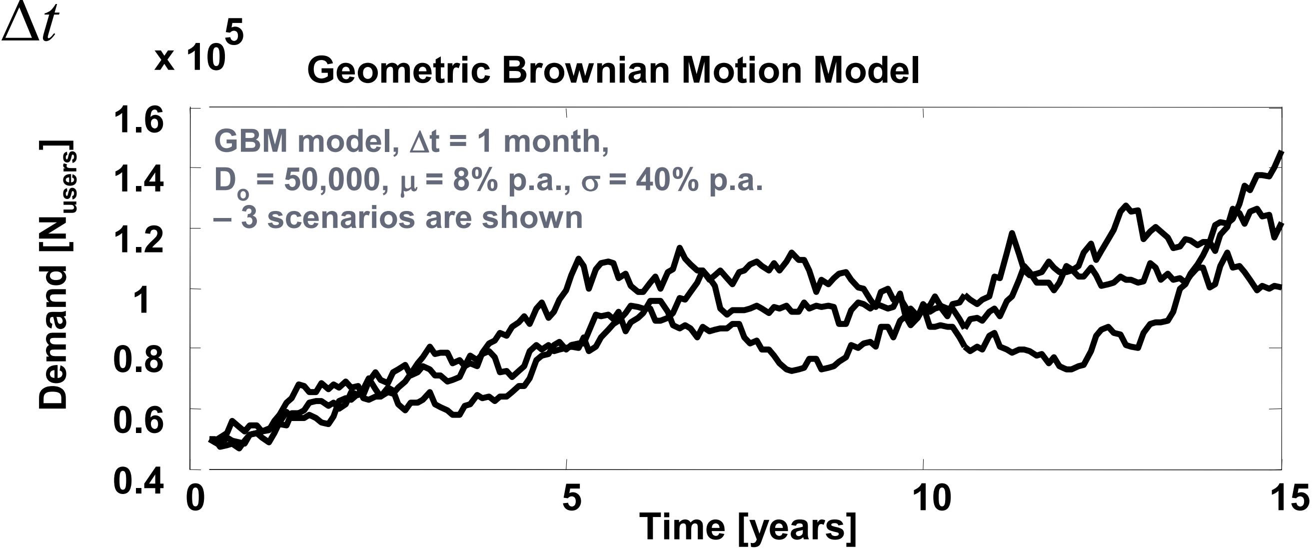
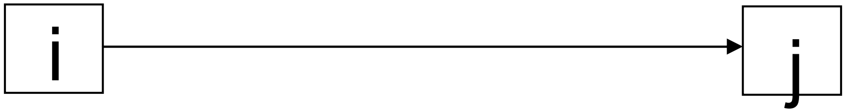


3: Change Propagation Analysis



Switching Cost from Configuration i to j implies

$$\Delta C_{ij} = \Delta C_{RD_{ij}} + \Delta C_{\inf_{ij}} + \Delta C_{\mathrm{var}_{ij}}$$

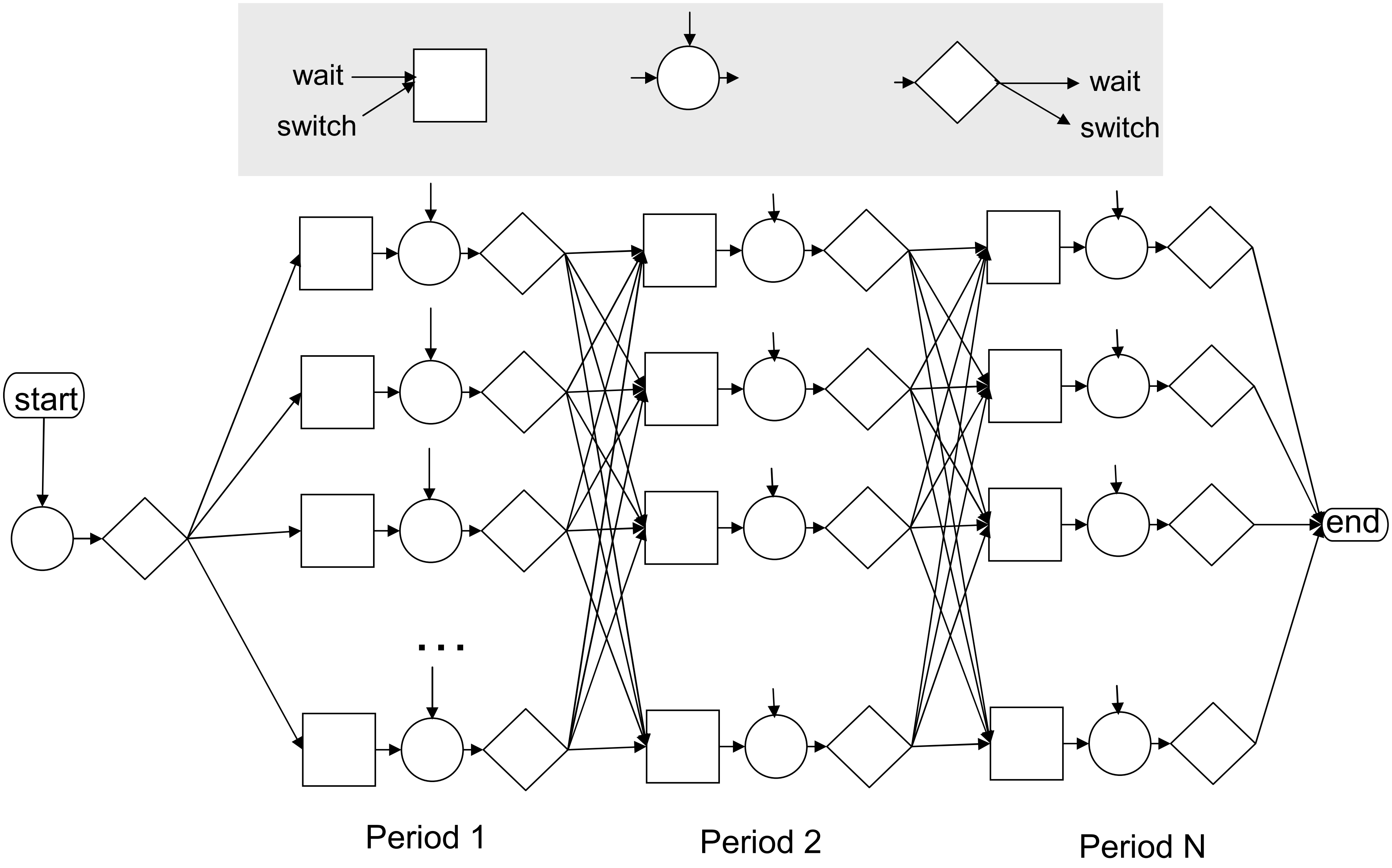
non-recurring
redesign
cost

change to
infrastructure
cost (incl. tooling)

variable
material
cost

Switching can also imply a time delay, which needs to be accounted for.

4: Time-expanded Decision Network

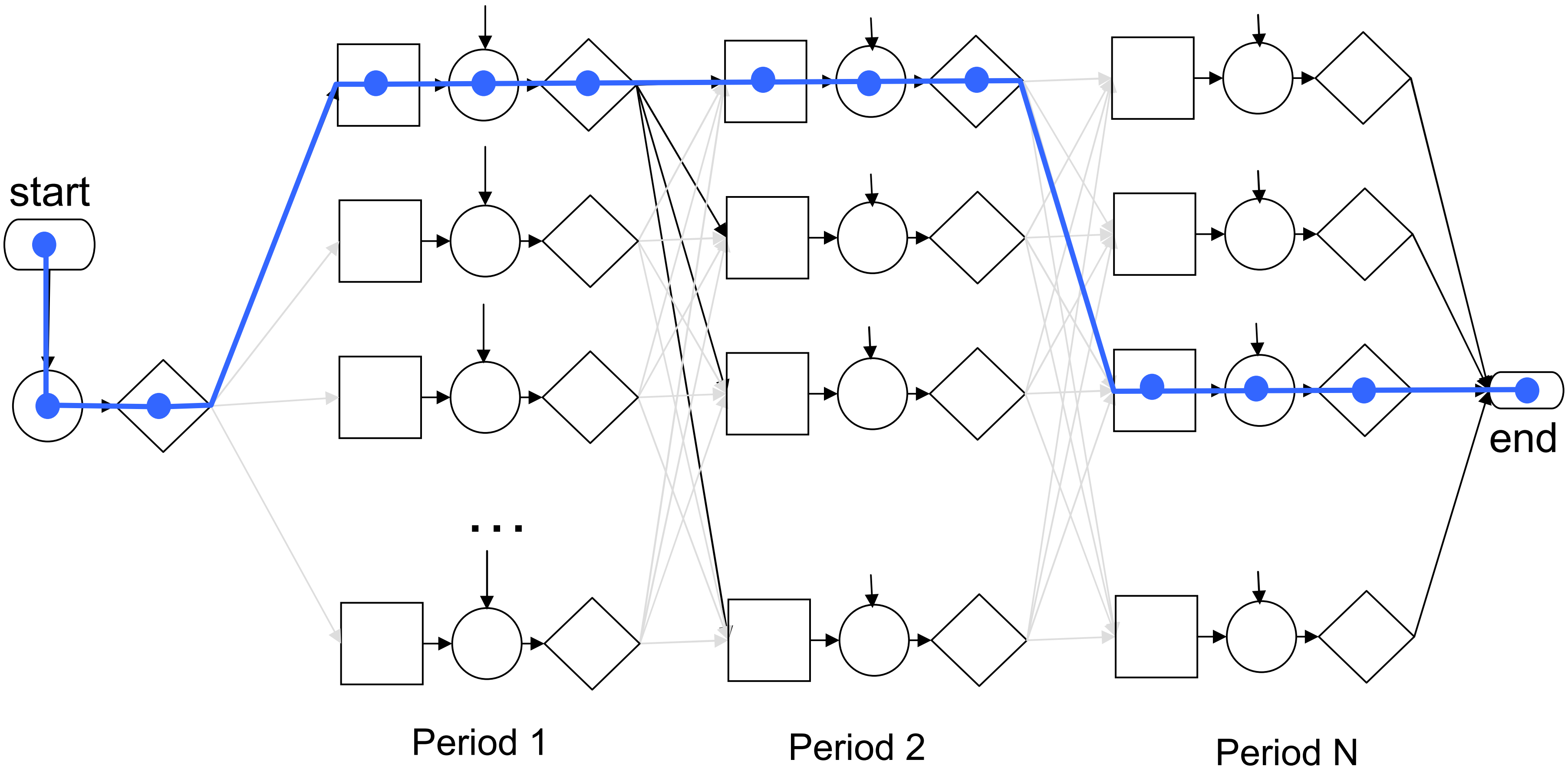


5: Path Optimization in TDN

For each uncertain scenario, find the optimal path through the TDN

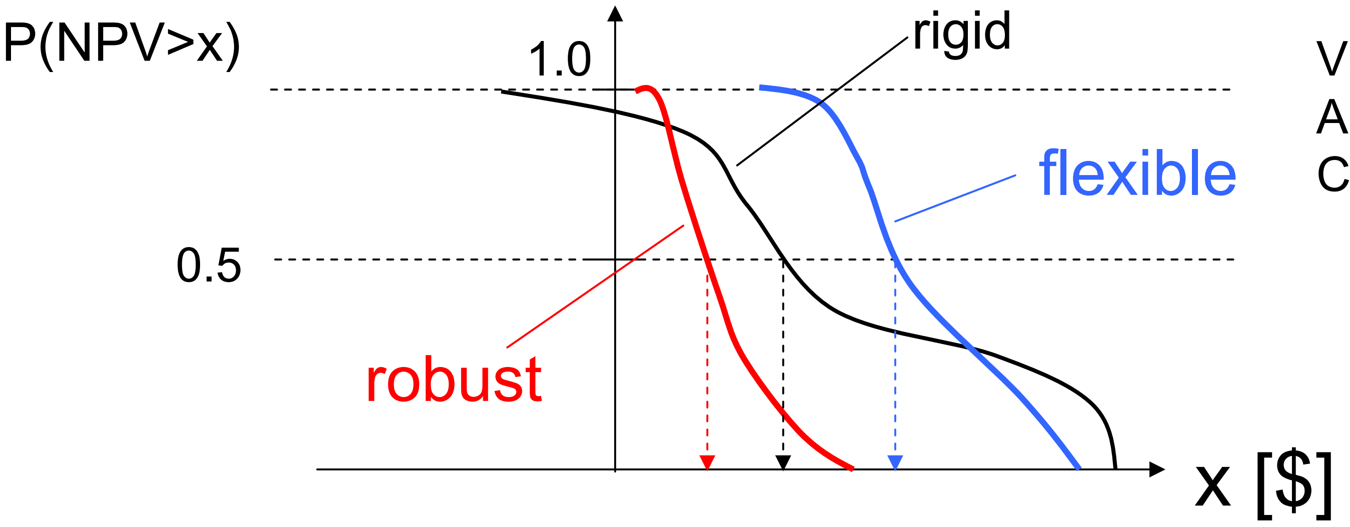
max NPV, min LCC, …

example



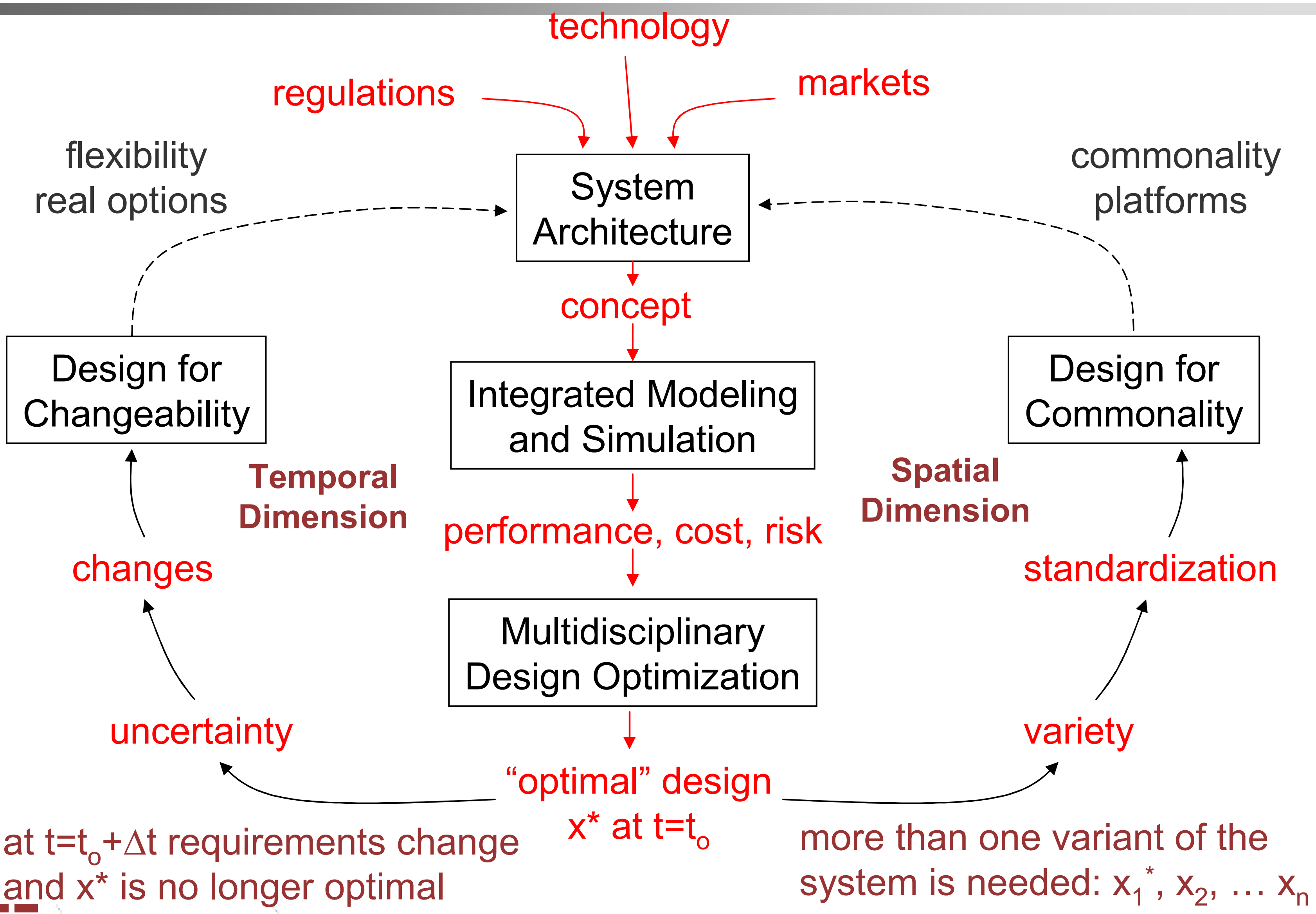
6: Find most popular "switches"

- Statistically find which switches are most used
- Embed flexibility in those transitions (= lower switching costs through redesign)
- Redefine initial configurations w/embedded flexibility (i.e. real options)
- Reoptimize TDN until convergence (use VaR)



Value at Risk
And Gain (VARG)
Curves

Strategic (Systems) Engineering – “the big picture”



technology

regulations

markets

System Architecture

flexibility
real options

commonality
platforms

concept

Design for Changeability

Integrated Modeling and Simulation

Design for Commonality

Temporal Dimension

Spatial Dimension

performance, cost, risk

changes

standardization

Multidisciplinary Design Optimization

uncertainty

variety

“optimal” design
x^* at $t=t_o$

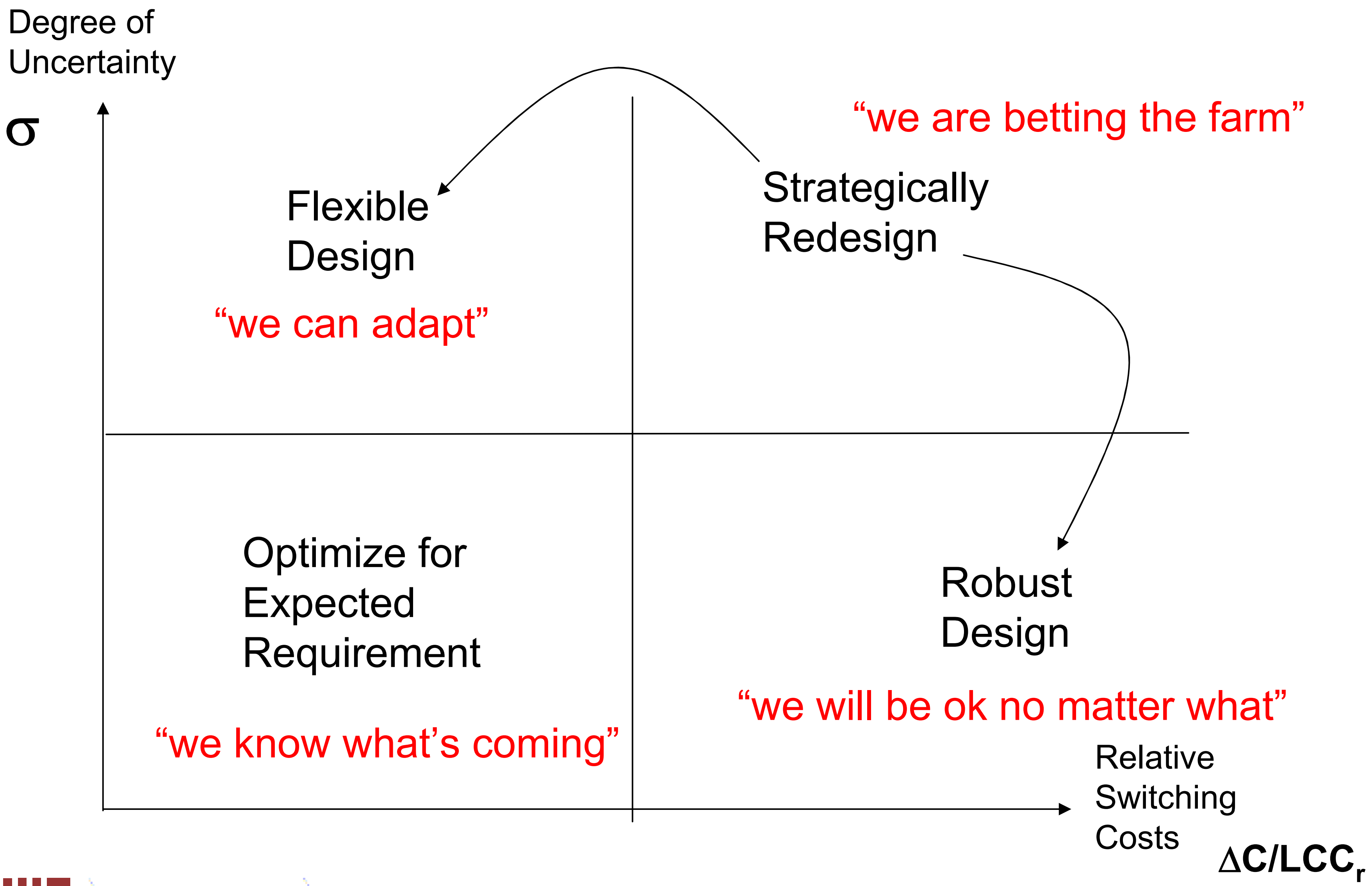
at $t=t_o+\Delta t$ requirements change and x^* is no longer optimal

more than one variant of the system is needed: $x_1^*, x_2, \ldots x_n$

Principles of Strategic Engineering

- A rigid design will be optimal (max NPV) if future events unfold exactly as forecasted
- A robust design can minimize the standard deviation of outcomes (reduce risk), but will usually also lower the expected NPV and max achievable NPV (limit opportunity)
- The larger the degree of uncertainty, the more valuable flexibility will be. Flexible designs can increase the E[NPV], while limiting downside and maximizing upside
- The larger the switching costs from one configuration to another the more likely that the current system will be
  - continued due to "architectural lock-in", despite operational sub-optimality

Strategic Engineering Map



Degree of Uncertainty

σ

Flexible Design

"we can adapt"

Strategically Redesign

"we are betting the farm"

Optimize for Expected Requirement

"we know what's coming"

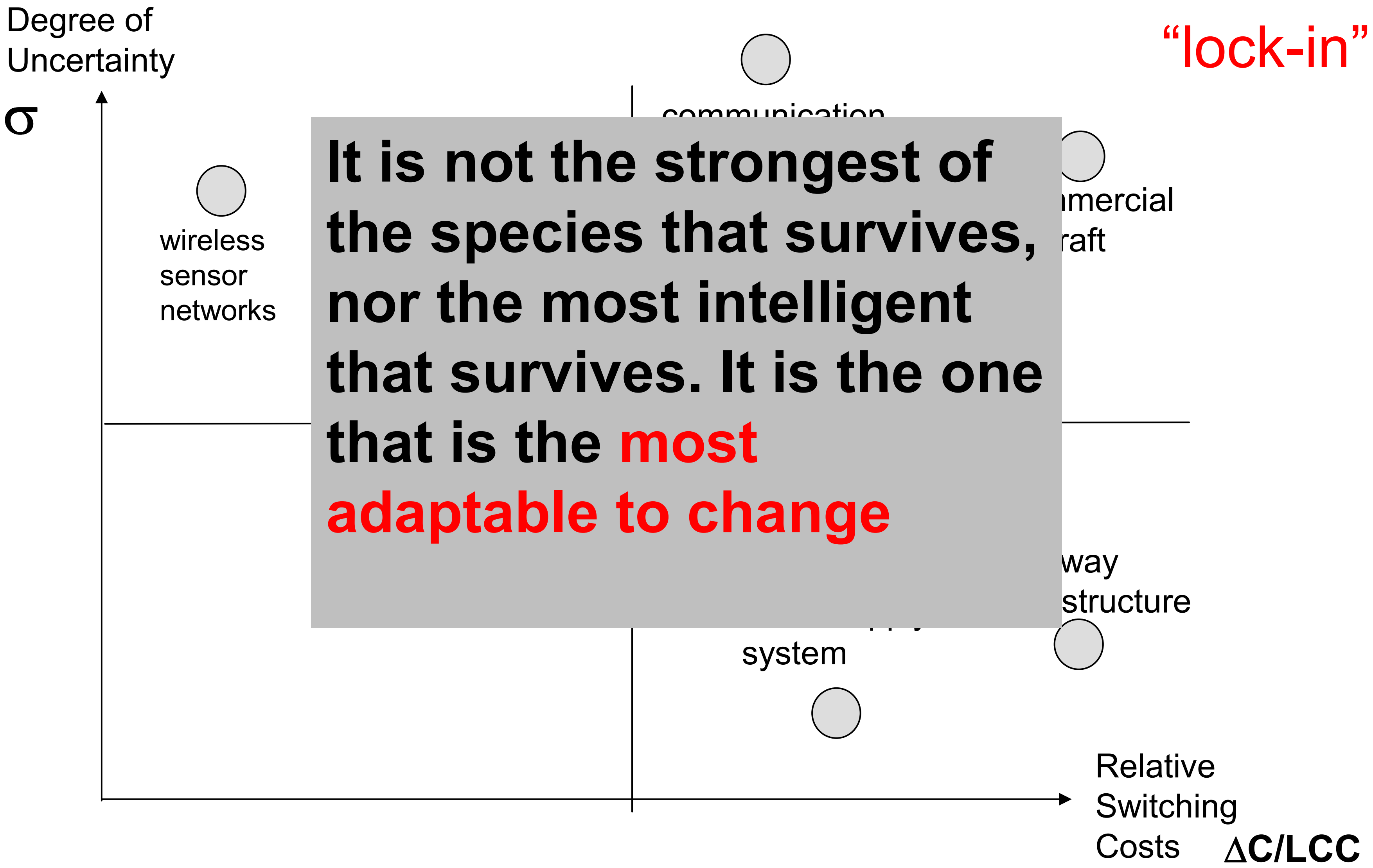
Robust Design

"we will be ok no matter what"

Relative Switching Costs

$\Delta C/LCC_r$

Future Work: Where do various systems fall ?



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More Information

http://strategic.mit.edu

- **Thinking strategically about engineering and design of systems is important when we face:**
  - **long lifecycles**
  - **exogenous uncertainty**
  - **large, (partially) irreversible investments**