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Decision-Making under Uncertainty and Risks

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Profile

- Senior Lecturer in Computational Aided Engineering and Director Strategic Engineering Lab
- Project Lead, JLR – Imperial Sustainable Modern Luxury Lab
- Instructor Economics & Finance, Data Science, Optimisation
- Associate Editor *ASME Journal of Mechanical Design* and *IISE Transactions*
- MIT PhD Engineering Systems and SM Technology & Policy, McGill Alum (Honours BSc Physics)

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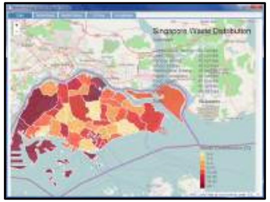

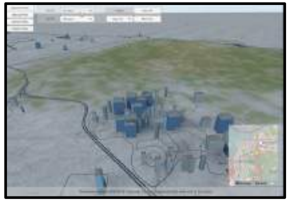

Selected Publications

- C. Caputo and M.-A. Cardin, "Analyzing Real Options and Flexibility in Engineering Systems Design using Decision Rules and Deep Reinforcement Learning," *ASME Journal of Mechanical Design***,** 2022.
- A. M. Caunhye and M.-A. Cardin, "An Approach based on Robust Optimization and Decision Rules for Analyzing Real Options in Engineering Systems Design," *IISE Transactions*, vol. 49, pp. 753-767, 2017
- Y. Deng and M.-A. Cardin, "Integrating Operational Decisions into the Planning of Mobility-on-Demand Systems under Uncertainty," *Transportation Research Part C: Emerging Technologies,* vol. 86, pp. 407-424, 2018
- M.-A. Cardin, Y. Deng, and C. Sun, "Real Options and Flexibility Analysis in Design and Management of One-Way Mobility-on-Demand Transportation Systems Using Decision Rules," *Transportation Research Part C: Emerging Technologies,* vol. 84, pp. 265-287, 2017

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PART 1

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Uncertainty Recognition

With credit to R. de Neufville, MIT

Causes of Uncertainty

- Underlying variability of phenomenon
- Difficulties in measurement or estimation
- Unforeseen or “unpredictable” circumstances
- Limits to valid measurement
  - for example: behavioral patterns

Recognition of Uncertainty and Complexity

- Uncertainty: Wide Range of Possible Futures

- The forecast is “always wrong”
  - Risks: the bad things that may happen
  - Opportunities: the flip side, or good things that may occur

Recognition of Uncertainty

- The usual error: search for best forecast

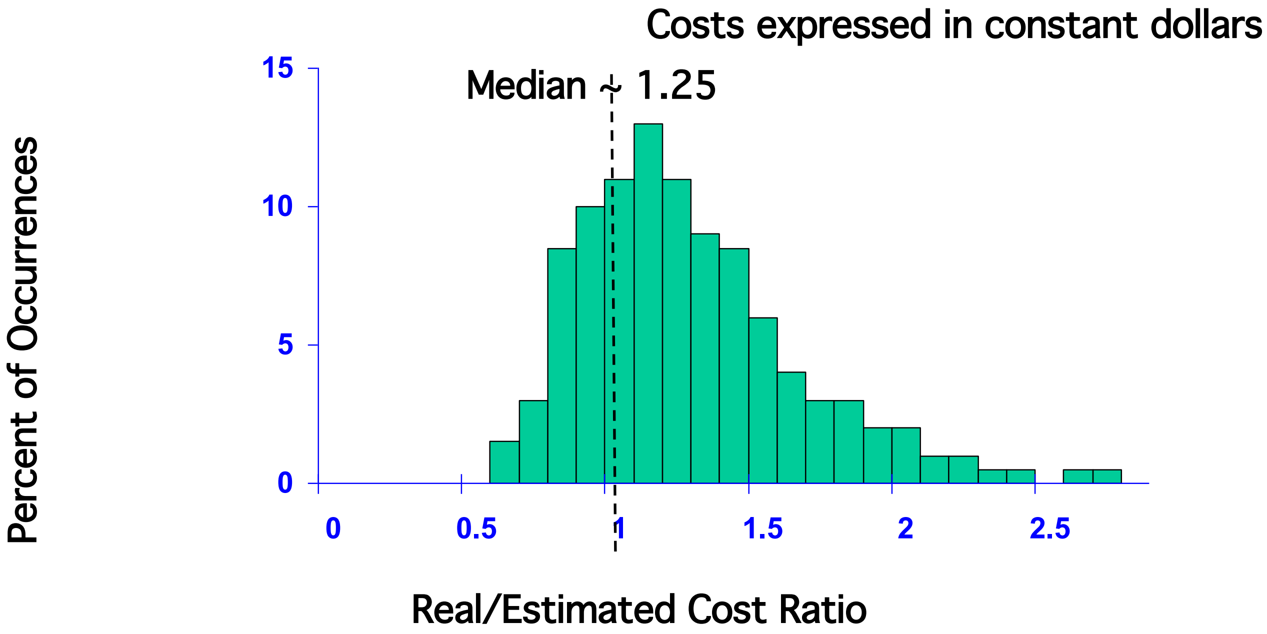
- However: the forecast is “always wrong”
  - What happens can be far in time, in practically every case, from what is forecast
  - Examples: costs, demands, revenues, production

- Need to start with a distribution of possible outcomes to any choice or decision

Evidence

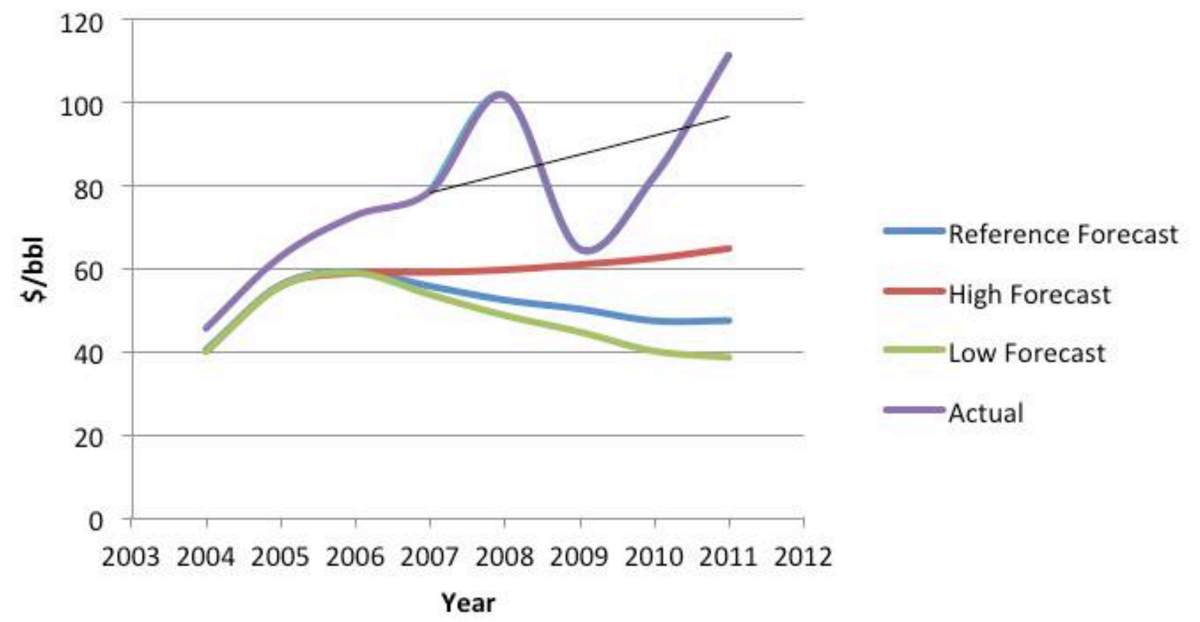
1. Costs
2. Price
3. Production
4. Demand

Ratio of Real to Estimated Costs



Repaving of runways

Oil Price Forecasts



Source: EIA Annual Energy Outlook 2006, BP Statistical Review of World Energy June 2012 Per Julia Kimmerly, 2012

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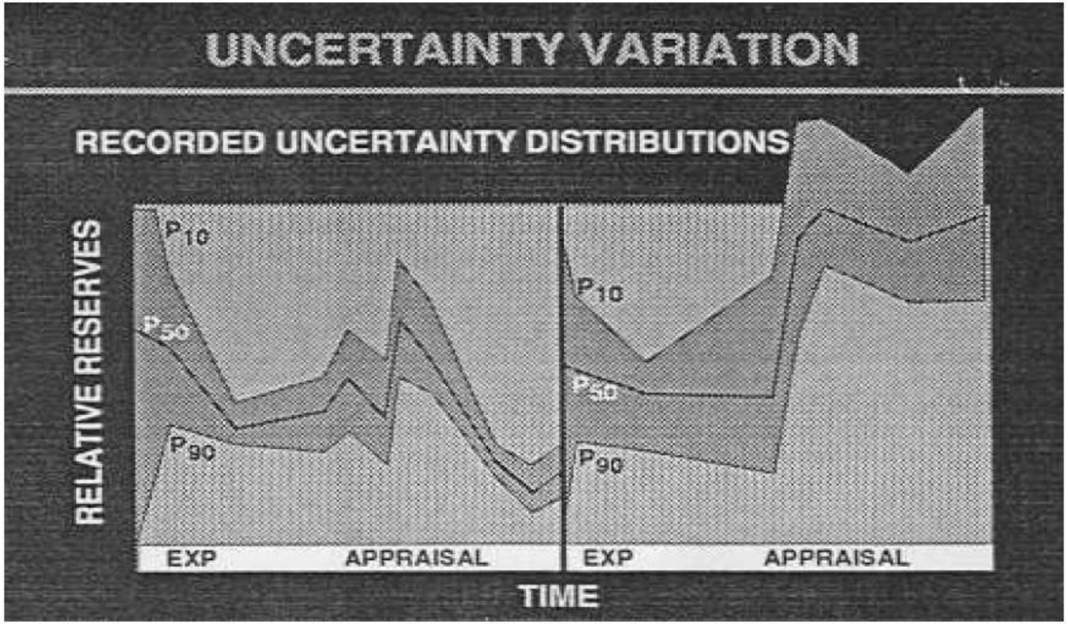
Variation in Estimates of Original Oil in Place



Source: Lin (2009) from BP sources

Apple iPhone Sales

Year	Actual Sales (millions of units)	Forecast Sales (millions of units)	Error
2007	1.4	3.2	128.57%
2008	11.6	12.4	6.90%
2009	20.7	25.7	24.15%
2010	40	36	-10.00%
2011	72.3	48.5	-32.92%
2012	125	134	7.20%
2013	150.3	143	-4.86%
2014	169.2	176	4.02%
2015	231.2	235	1.64%
2016	-	220	-
2017	-	224	-

Source: Angwei Law, 2016 –IDS.333 Wall St. analysts + Apple Reports

Why We Can't Predict Well: Surprises!

- Surprises
  - All forecasts are extensions of the past
  - Past trends always interrupted by disruptions, discontinuities:
    - Major political changes
    - Economic booms and recessions
    - New industrial alliances or cartels

- Exact details of such surprises cannot be anticipated, but surprises will surely exist!

Why We Can't Predict Well: Ambiguity

- Ambiguity
  - Analysis can look at many ranges of historical records
  - From any set of historical data, many extrapolations possible
    - Different explanations (independent variables)
    - Different forms of explanation (equations, models, theories)
    - Different number of periods examined
  - Many of these extrapolations will be "good" to the extent that they satisfy usual statistical tests e.g., correlation
  - Yet these extrapolations will give quite different forecasts!

Consequences

- Resulting problem: wrong design, wrong plans
  - Wrong size for plant, production capacity, system, or technology
    - Iridium, IUT Global, Ghost cities, see next
  - Wrong type of facility
    - Although “forecast” may be “reached”
    - Components that make up forecast generally not as anticipated, thus requiring
    - Quite different facilities or operations than anticipated

Rearview Mirror Analogy

- Relying on forecasts is like driving by looking in a rearview mirror

- Satisfactory for a while, so long as trends continue, but soon one runs off the road…

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Flaw of Averages

With credits to R. de Neufville, MIT

Mathematics of the Flaw

- Jensen's Law:

$$E[f(x)] \geq f[E(x)] \text{ if } f(x) \text{ is convex}$$

- Notation: $E(x)$ = arithmetic average or expectation of x

- In words:
  - $E[f(x)]$ = average of possible outcomes of $f(x)$
  - $f[E(x)]$ = outcome calculated using average x

In English…

Average of all possible outcomes associated with several uncertainty scenarios…

…generally does not equal…

…value obtained from using the average uncertainty scenario

Consequences in Practice

- Because most systems response, economic performance, production, are not linear:
- Unless you work with probability distributions, you will get the wrong answer, wrong decisions, wrong plans
- Answer from a realistic description differs – often greatly – from answer you get from average or any single forecast
- This is because gains when things go well do not balance losses when things do not (sometimes they're more, sometimes less)

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Activity 1: Reflection

Reflections

- Take 5 min. to reflect on the questions below, then share with group
- How do you deal with risks and uncertainty at your firm?
- What are the most important challenges/difficulties in doing so?
- Think of a case where uncertainty had considerable impact on project performance, whether good or bad
- What could have been done differently?

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PART 2

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Motivating Example

The Iridium System

- Space-based mobile communication system
- Developed by Motorola in the 1990s for ~$4 billion
- Capacity planning for 1 millions subscribers
- 66 LEO satellites deployed between 1996-97
- No contingency for rapid rise of land-based cell phones
- Declared bankruptcy in early 2000s

Flexibility Concept

What is Flexibility?

- Flexibility provides ability to change and adapt readily in face of uncertainty
- Inspired from Real Options theory, but emphasizes importance of system and design thinking
- Example strategies
  - Abandon/decommission
  - Defer investment
  - **Expand/contract capacity**
  - Phase deployment
  - Switch technologies
- Focus on design
  - "In" systems: requires careful engineering considerations
  - "On" systems: from managerial standpoint

Example Waste-to-Energy System

Benefits:

- Initial capital cost reduction
- Better use of financial and material resources i.e. build *if and when needed*

→ MORE SUSTAINABLE

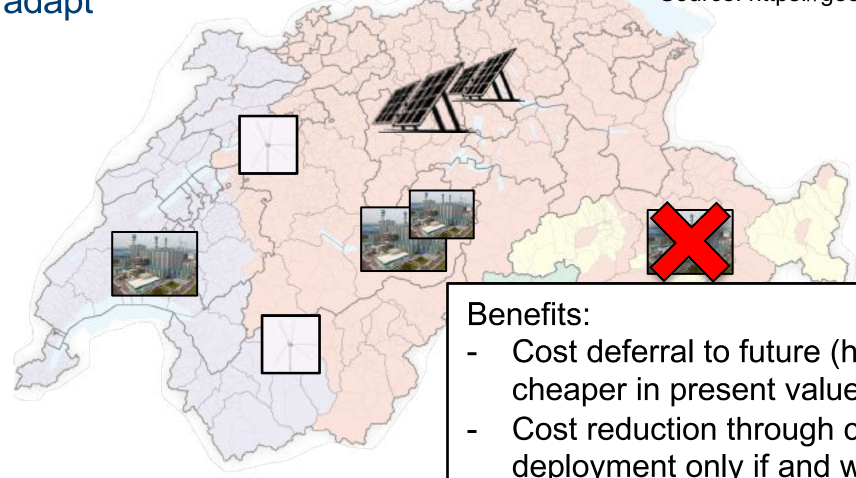
- Ability to capture upside opportunities e.g. higher demand than expected, and protect from downsides e.g. disruptions

→ MORE RESILIENT

What is Flexibility?

Energy System

Source: https://geovisualist.com



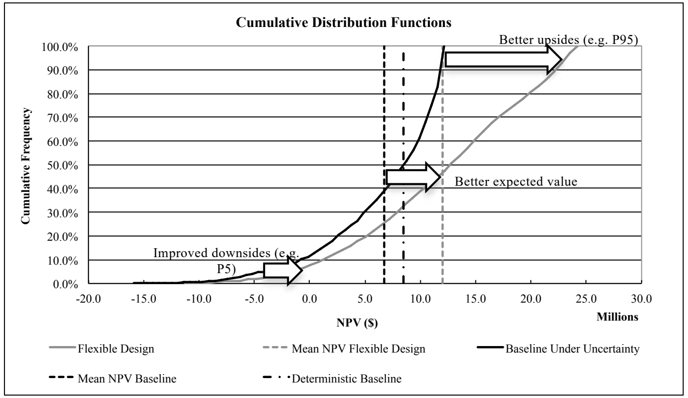
- Flexibility provides ability to change and adapt readily in face of uncertainty

- Many strategies
  - **Abandon/decommission**
  - Defer investment
  - Expand/contract capacity
  - **Phase deployment**
  - Switch technologies
  - Etc.
- Focus on design
  - “In” systems: requires careful engineering considerations
  - “On” systems: from managerial standpoint

Benefits:
- Cost deferral to future (hence cheaper in present value terms)
- Cost reduction through capacity deployment only if and when needed, and cutting down losses
- Capitalize on upside opportunities i.e. greater demand than planned
- + all benefits for each site as described in previous slide

Why Flexibility Matters?

- Markets and increasingly global, inter-connected, and complex
- Uncertainty affects economic performance
  - Markets volatile, demographics and regulations change, technology evolve
- Flexibility **can improve expected performance by 20%-30% (routinely)** compared to standard methods, sometimes 100% or more, **along sustainability and resilience**
  - Protects from downsides (insurance)
  - Position for upsides (stock option)
  - Improves expected performance
  - Significant for > £100 million projects
- Deterministic analysis may lead to failure
  - IUT Global, and many others
  - Iridium, Ghost cities…
- **Growing needs in industry, government, policymaking**



A Unifying Decision-Making Paradigm?

- ## Sustainability
  - More efficient, better use of resources
  - Less capacity wasted, pollution
  - Improved performance for already sustainable “green” systems

Source: shutterstock.com

Source: shutterstock.com

Source: NASA

- ## Resilience
  - Quick recovery of pre-disruption performance – sometimes even better!

- ## Flexibility as unifying paradigm
  - Helps consider both sustainability and resilience principles at same time
  - Helps focus design effort and operational decision-making on unifying concept
  - Contributes new systems thinking to address important challenges

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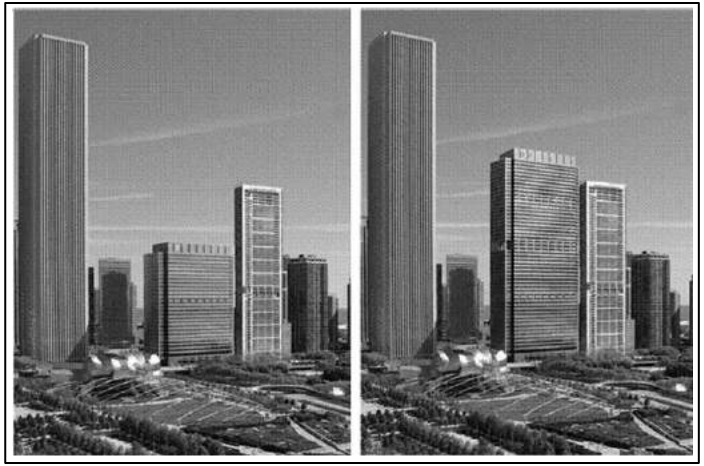
Real-World Example Projects

Health Care Services Corp. Bldg, USA

- Original building erected with 30 stories (1997)
- 24 storey expansion completed in 2010
- Original design
  - Extra strength to carry double load
  - Empty spaces for possible future elevators
  - Planning permissions from City
- 2.3 million sqf, 2nd largest in

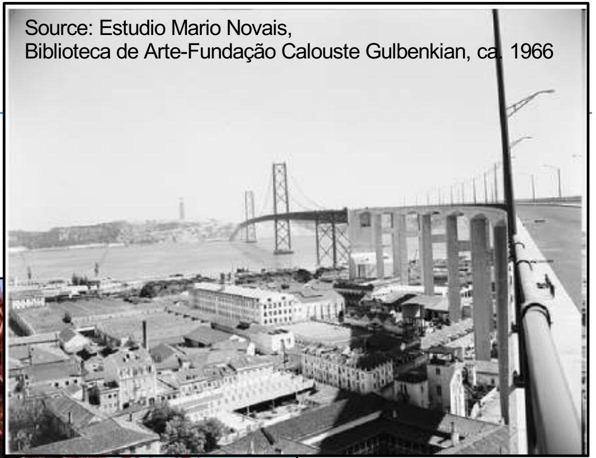
Chicago after Sears tower!



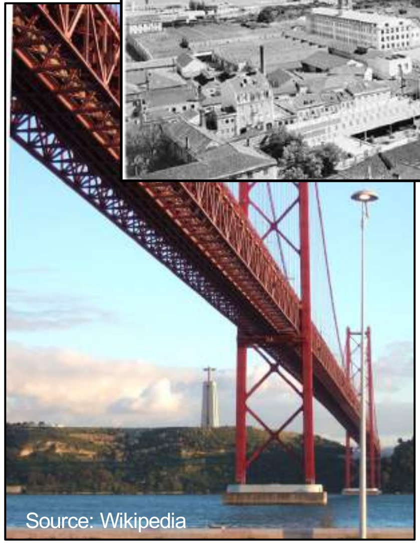
Source: Goettsch Partners, Pearson and Wittels (2008)

Ponte 25^{th} de Abril, Portugal

- Built during dictatorship in 1966
  - Extra strength for second deck
  - Allowance for possible rail service (pre-built station)
- 30 years later, situation very different
  - Portugal now part of EU
  - Receives funds from community, especially for Metro
  - New conditions lead to new solutions, considering uncertainty and flexibility



Source: Estudio Mario Novais, Biblioteca de Arte-Fundação Calouste Gulbenkian, ca. 1966



Source: Wikipedia

Source: Wikipedia

NHS Nightingale Hospital, UK

- First temporary field hospital constructed in the UK during COVID
- Completed in just 9 days in early 2020, first wave of pandemic
- Built over the vast ExCel London Centre
- Part of vast campaign to repurpose internal space and redeploy resources for critical care patients
- Good example of **flexibility enabling resilience**


Aerial view in 2015

March 2020

Source: Wikipedia

IUT Global, Singapore

- Waste-to-energy (WTE) system
- Designed to convert 800 tons food waste into biofuels and power 10,000 homes
- Waste amounts collected never reached expectations
- Only powering 500 homes in 2011, then shut down

Source: https://sggreendrinks.wordpress.com

Source: Carla Hajjar, Forbes

Ghost Cities, China

- Ordos City, Inner Mongolia
- Construction began in 2004
- Plan was to create sprawling metropolis for 1 million inhabitant
- Gleaming apartment blocks, malls, government buildings
- Many years later, acres of large residential, commercial and government building were still largely unoccupied, six-lane highways deserted
- Situation started changing in 2017

Source: BBC

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Example Tools and Methods

Flexibility Framework

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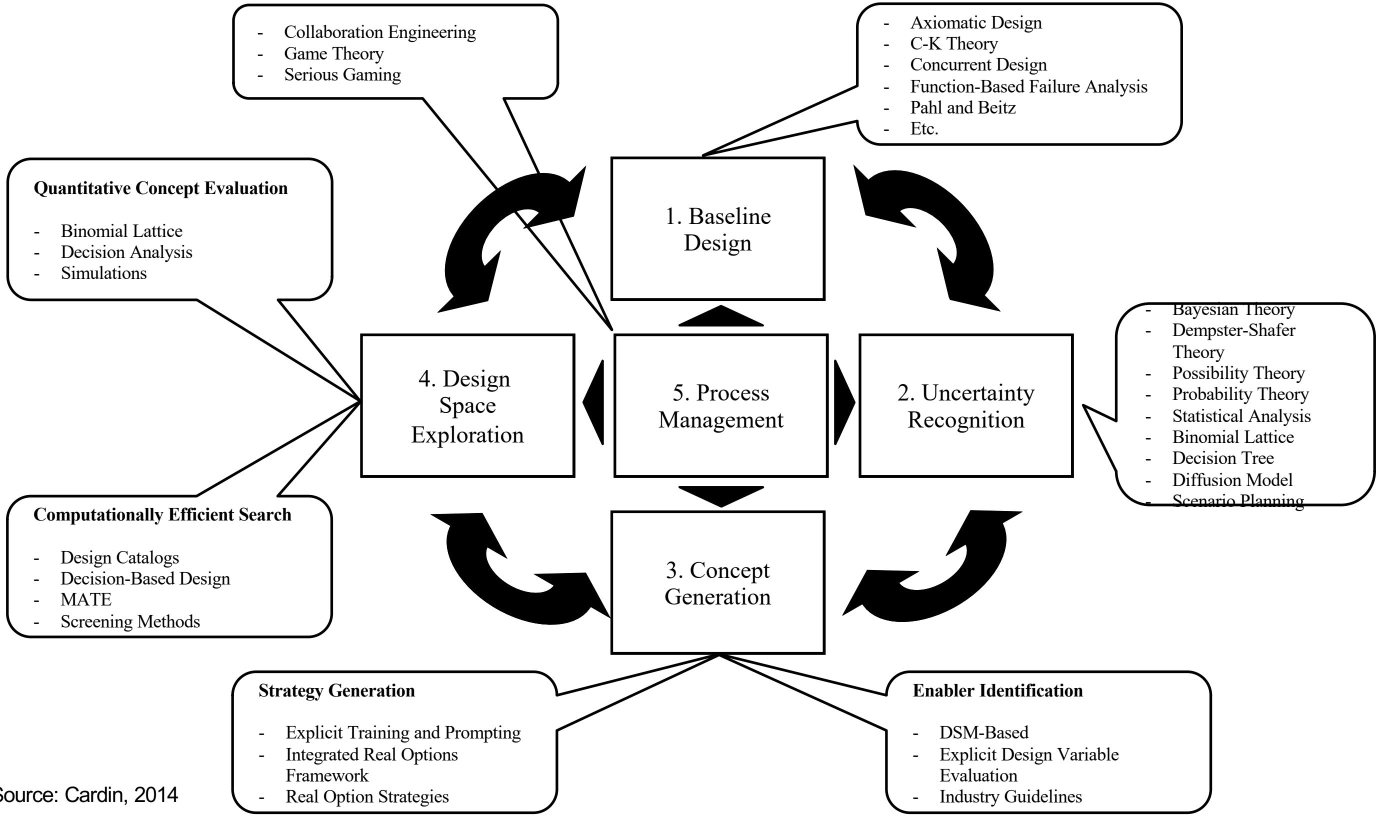
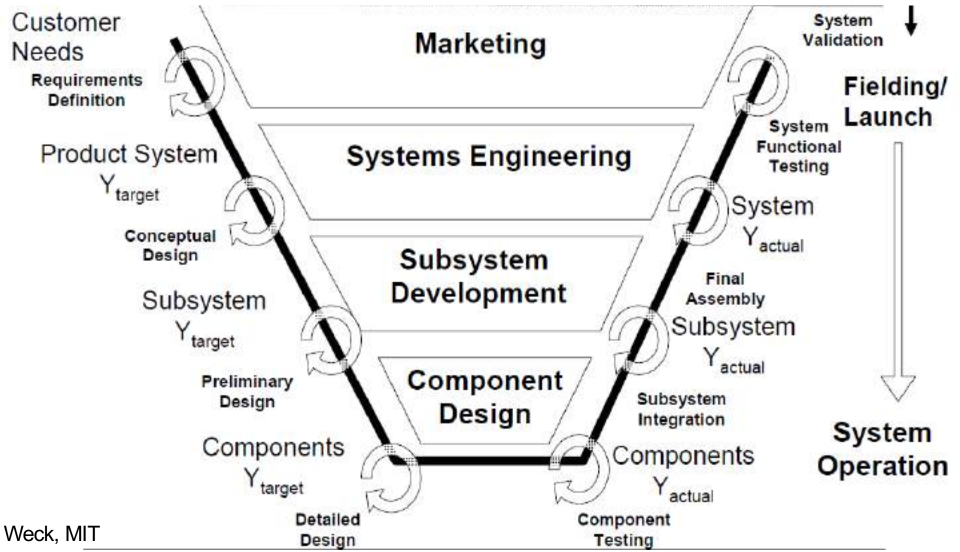


Source: Cardin, 2014

Phase 1: Baseline Design

V-Model in Systems Engineering



Source: O. de Weck, MIT

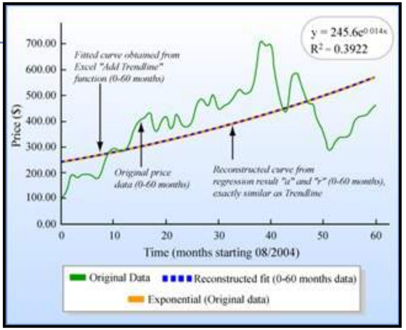
Phase 2: Uncertainty Recognition

- Formal
  - Probability theory
  - Statistical theory
  - Expert elicitation/Delphi
- Practical
  - Decision Tree
  - Diffusion models
  - Scenario planning
  - Simulation

$$p(A \mid B) = \frac{p(B \mid A)\, p(A)}{p(B)}$$

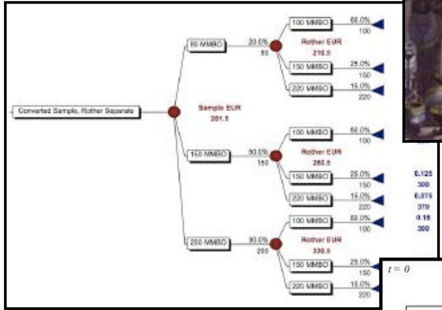
Data/Regression

Source: ocw.mit.edu



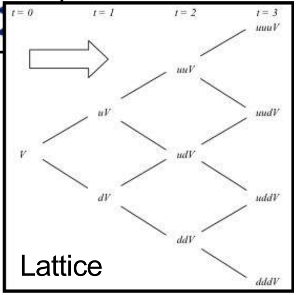
Expert Elicitation

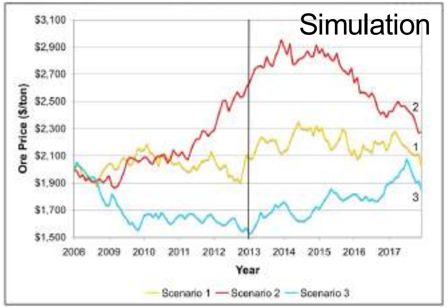
Source: www.crystalinks.com



Decision Tree

Source: Babajide et al., 2009





Source: Cardin et al., 2008

Phase 3: Concept Generation

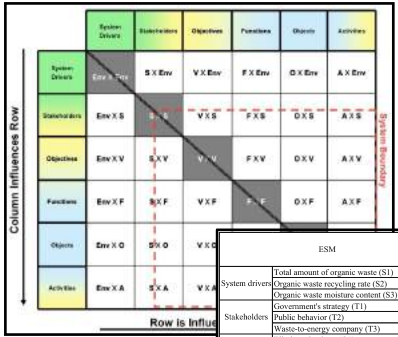
- Concept Generation
  - Real Option strategies
  - <Mechanism, Type>
  - Explicit training/prompting
- Enabler Identification
  - Change Propagation Analysis
  - Engineering System Matrix

Source: www.cs2designgroup.com

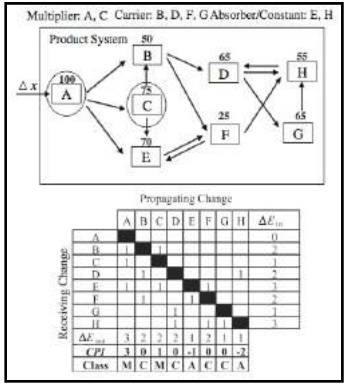
Prompting (Cardin et al., 2013)

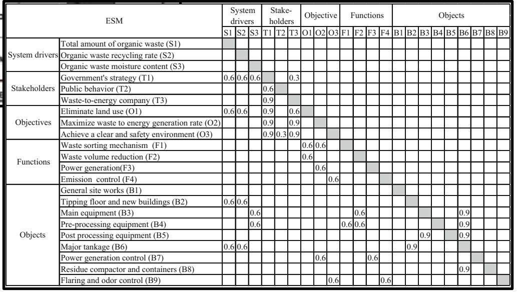
1. *Main uncertainty sources?*
2. *Best flexible strategies?*
3. *How to enable in design?*
4. *When to exercise?*

ESM (Bartolomei, 2007)



CPA (Suh et al., 2007)





ESM		System drivers			Stake-holders			Objective			Functions				Objects								
		S1	S2	S3	T1	T2	T3	O1	O2	O3	F1	F2	F3	F4	B1	B2	B3	B4	B5	B6	B7	B8	B9
System drivers	Total amount of organic waste (S1)																						
	Organic waste recycling rate (S2)																						
	Organic waste moisture content (S3)																						
Stakeholders	Government's strategy (T1)	0.6	0.6	0.6			0.3																
	Public behavior (T2)				0.6																		
	Waste-to-energy company (T3)				0.9																		
Objectives	Eliminate land use (O1)	0.6	0.6		0.9		0.6																
	Maximize waste to energy generation rate (O2)				0.9		0.9																
	Achieve a clear and safety environment (O3)				0.9	0.3	0.9																
Functions	Waste sorting mechanism (F1)							0.6	0.6														
	Waste volume reduction (F2)							0.6															
	Power generation(F3)								0.6														
	Emission control (F4)									0.6													
Objects	General site works (B1)																						
	Tipping floor and new buildings (B2)	0.6	0.6																				
	Main equipment (B3)			0.6								0.6								0.9			
	Pre-processing equipment (B4)			0.6							0.6	0.6								0.9			
	Post processing equipment (B5)																0.9			0.9			
	Major tankage (B6)	0.6	0.6													0.9							
	Power generation control (B7)								0.6				0.6										
	Residue compactor and containers (B8)																			0.9			
	Flaring and odor control (B9)									0.6				0.6									

Probabilistic ESM (Hu and Cardin, 2015)

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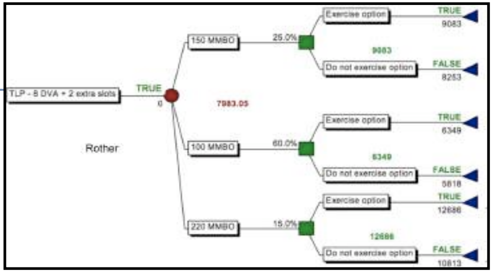
Phase 4: Design Space Exploration

- Quantitative concept evaluation (ROA)
  - Decision Analysis
  - Binomial Lattice
  - Decision Rule Based ROA
  - Stochastic optimisation

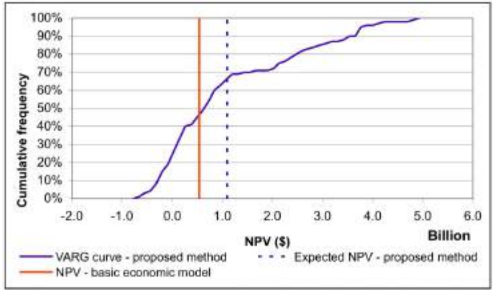
- Efficient/systematic search
  - Design catalogs
  - Screening Methods

Decision Analysis



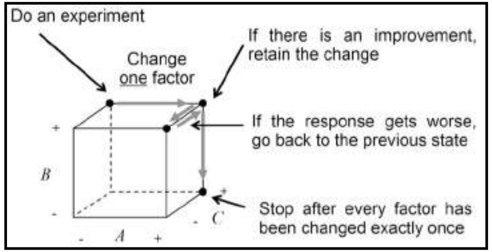
Source: Babajide et al., 2009

Source: Cardin et al., 2008

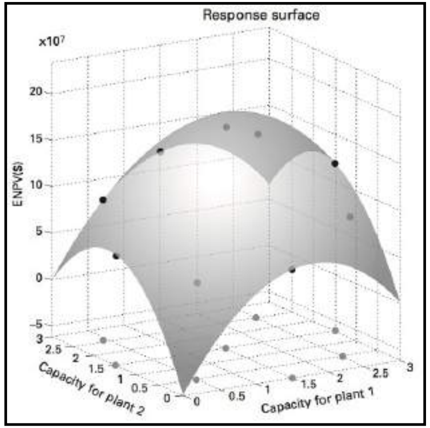


Simulations

Screening Methods



Adaptive One-Factor-At-a-Time algorithm by Frey and Wang (2006) used in design catalog approach



Source: Yang, 2009

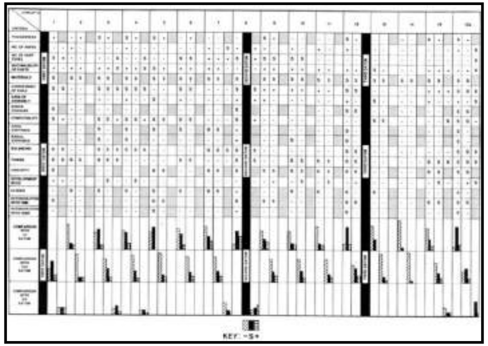
Phase 5: Process Management

- Collaboration Engineering
- Simulation Games
- Decision-Support Systems

Collaboration Engineering

Source: Kolfschoten, 2010

Pugh matrix
Source: Frey et al., 2009



Decision Support System

Simulation Game (Source: Cardin et al. 2015)

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Activity 2: Application

Reflections

- Take 5 min. to reflect on the proposed framework, then share with group (or on chat)
- What analytical methods do you use to tackle uncertainty and risks in project design, delivery, or operations?
- What benefits (or challenges) do you envision in using the framework in the future?
- What phase do you find most (or least) important and why?
- Think back about that same project mentioned in Activity 1
- How would that project have benefitted from using the framework?

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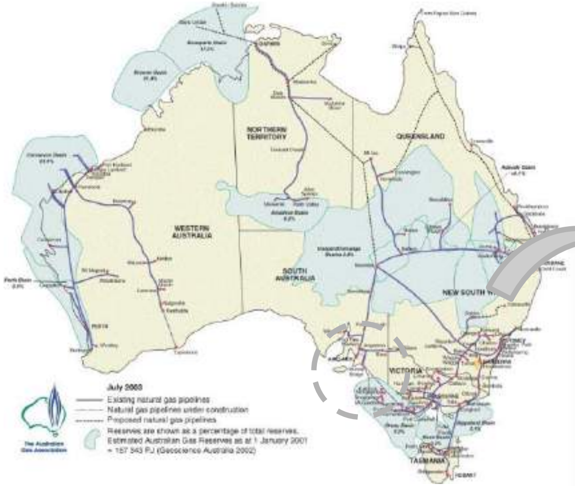
LNG Case Study

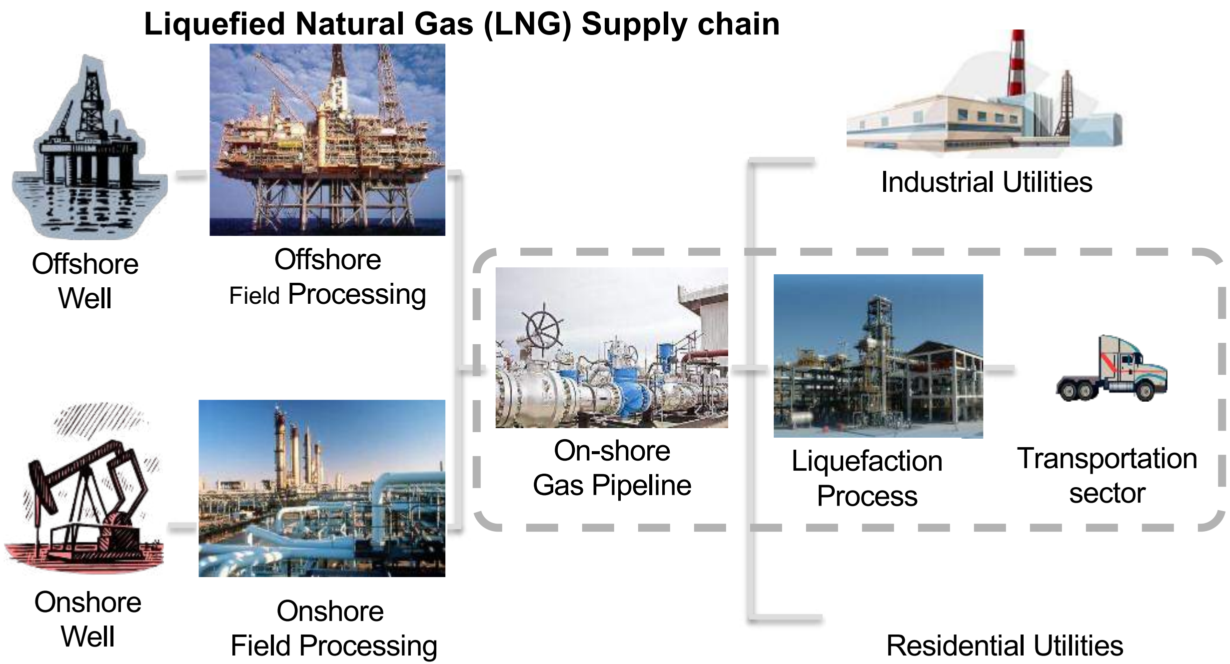
Time permitting

Geographical Location



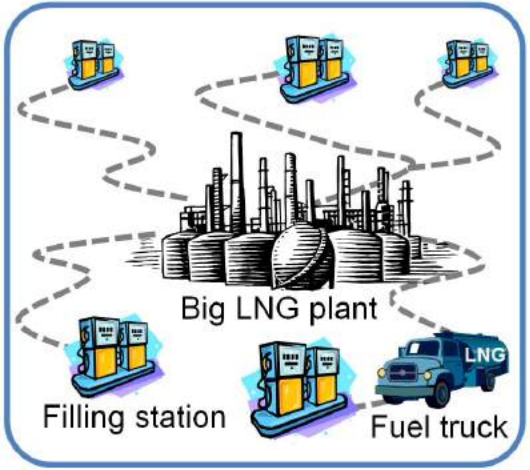
South east Australia

Scope


Liquefied Natural Gas (LNG) Supply chain
Offshore Well
Offshore Field Processing
Onshore Well
Onshore Field Processing
On-shore Gas Pipeline
Liquefaction Process
Transportation sector
Industrial Utilities
Residential Utilities

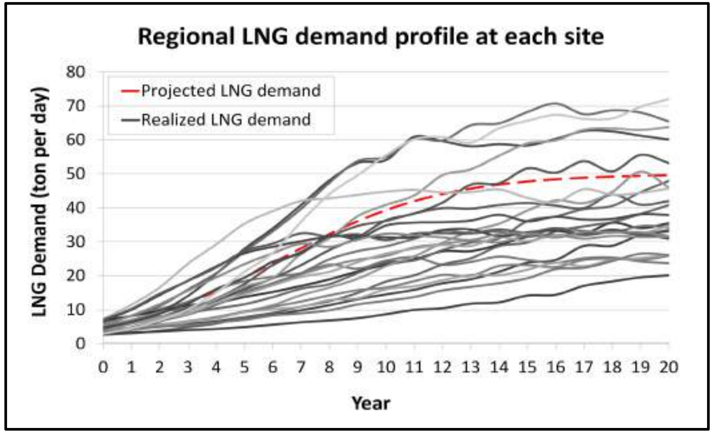
Phase 1: Baseline Design

- Start from known or existing system
- Builds upon organization's expertise as starting point
- Exploits existing methods e.g., V-model
- Needed to establish performance baseline (or benchmark)
- Build techno-economic model to quantify benefits and costs
  - E.g., Net Present Value, CO2e
- Here, centralized LNG production with transport to distribution points



Phase 2: Uncertainty Recognition

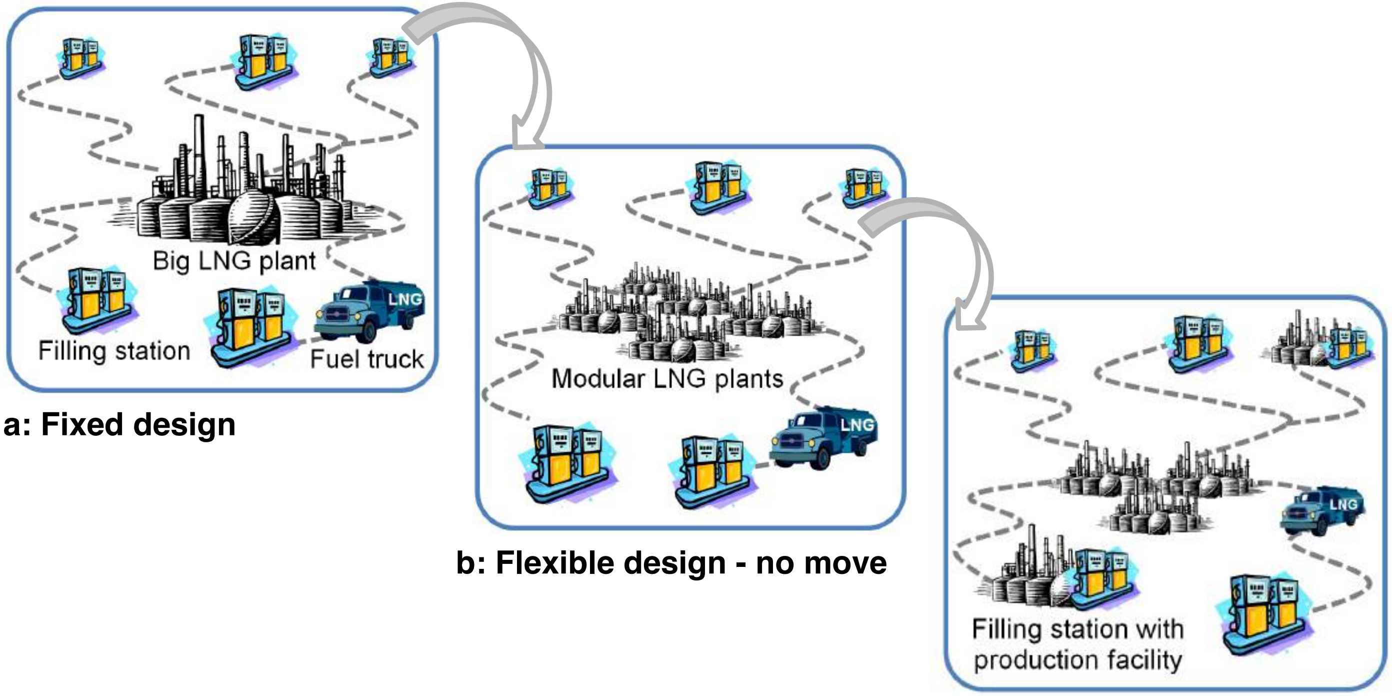
- Identify most impactful uncertainty sources
- Impossible to address them all, focus on most impactful
- Consider exogenous and endogenous sources
  - Exo: environment, markets, regulations, technologies
  - Endo: know-how, technical failures
- Choose modeling approach
  - Decision tree, Monte Carlo simulation, scenarios
- Here consider LNG demand for transport sector (many others possible)
- Use Monte Carlo simulation



Phase 3: Concept Generation

- Exploits designer's expertise with system
- Uses uncertainty as stimulus, consider both downside risks and upside opportunities
- Think creatively (and differently!) about system
- Strategy generation
  - Standard real options strategies
  - Integrated real options framework
  - Brainstorming, prompting, etc.
- Enabler identification
  - Design structure matrix
  - Industry guidelines
  - Design variable evaluation
- Here consider capacity expansion strategy

From Rigid to Flexible Design



a: Fixed design

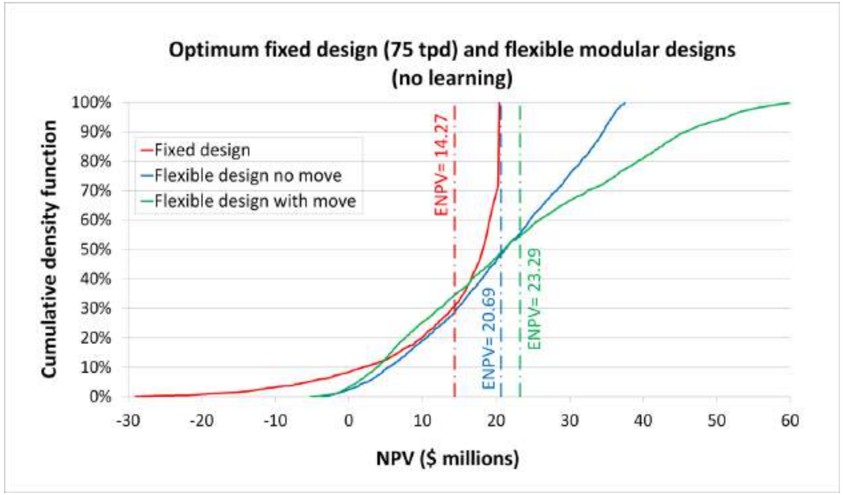
b: Flexible design - no move

c: Flexible design - with move

Phase 4: Design Space Exploration

- Once design variables and decision rules are identified, need to find best systems design consideration
- Computational design space consists of all possible combinations of design variables and decision rules
- Already big for complex infrastructures, considering uncertainty and flexibility makes it huge!
- For complex problems, may need advanced computational tools
- Here, use partial discrete enumeration

With Flexible Modular Design (with Move, no Learning)



Criterion	ENPV Value ($ millions)			Improvement (%)	
	Optimum fixed design	Flexible no move	Flexible with move	Flexible no move	Flexible with move
ENPV	14.27	20.69	23.29	45	63
$VaR_{10\%}$	1.82	5.40	3.74	197	105
$VaG_{90\%}$	20.46	34.54	45.78	69	124

Phase 5: Process Management

- System design involves many professionals
  - Engineers, managers, marketing, finance, etc.
- **Communication is key (no siloed decision-making)**
- Consider important socio-technical aspects of decision-making
  - Current market, regulatory framework, state-of-the-art technology
  - Parameter assumptions e.g., learning, economies of scale, volatility
  - Stakeholders e.g., suppliers, customers, share holders, competitors
- Create environment for collaborative design activities
  - Concurrent engineering
- Keep your “options” alive
  - May requires thorough documentation, as management may change
- Here, consider learning effects and different risk profiles for decision-making

Multi-criteria Decision-Making (Management)

Value of Flexibility = max[0, (ENPV of flexible design) – (ENPV of fixed design)]

Criterion	Fixed design	No move option	Move option	Value of flexibility	Best design
ENPV	14.27	36.93	**43.17**	28.80	Move
VaR, 10%	1.82	10.82	**11.06**	9.24	Move
VaG, 90%	20.46	63.17	**80.09**	59.63	Move
STD	**8.78**	18.91	25.31	0.00	Fixed
Capex	60.44	**27.50**	**27.50**	32.94	Flexible

(α = 0.95, LR = 10%, figures in $ Million)

Conclusions

- Decision-making requires explicit considerations of uncertainty in front-end analysis as it most impacts other project phases down the line
- Uncertainty considerations is important to consider in early design and planning
- Flexibility enables better economic performance, sustainability, resilience
- Many examples of flexibility (and lack thereof)
- Proposed framework decomposes analysis into several distinct, systematic phases
- Helps connect early and later phases in systems thinking process (V-model)
- Framework well-suited to stimulate multi-stakeholder discussions

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Thank You

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