Enabling Collaborative Decision Making through Applied Systems Engineering Tools, Methods, and Processes

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Abstract

Increasingly complex problems involved in systems development drive systems engineers to develop novel decision making processes. The breadth of complex problems demands the interaction of various stakeholders, including both decision makers and subject matter experts, each focusing on specific areas but all addressing a higher level common cause. The process brought forth in this tutorial integrates a series of methods, some widely accepted and others which are novel in nature, in order to enable a collaborative process for technology selection. Quality Function Deployment is used to capture customer desires and focus engineering level requirements. Multi-Attribute Decision Making is used to identify system configurations when multiple and competing objectives exist, which is a situation where traditional system optimization struggles. System modeling is a necessary step to analyze and understand the impact of various systems options. This seminar therefore introduces the process of surrogate modeling in order to rapidly access elements of modeling and simulation, a necessary step to analyze system options. The very integration of these applied systems engineering methods enables collaborative decision making throughout system development. A proof of concept is presented where each of these methods is applied in the technology selection portfolio analysis of renewable energy system options for a remote off-grid site.

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Biography

Tommer ENDER, USA, is a Research Engineer at the Electronic Systems Laboratory of the Georgia Tech Research Institute, and serves as Associate Head of the Systems and Controls Branch within the Systems Technology and Analysis Division. His primary area of research includes development of systems engineering tools and methods as applied to complex systems-of-systems, concerned with supporting decision making through a holistic treatment of various problems. His research focuses on the application of advanced design methods, uncertainty analysis, and multidisciplinary design optimization to defense related, hybrid energy, and other complex systems. In addition to conducting research, Dr. Ender is a course developer and lecturer for Georgia Tech's Professional Masters in Applied Systems Engineering, and teaches several professional development courses in systems engineering as part of Georgia Tech's Defense Technology Certificate Program. He earned a B.S., M.S., and Ph.D. in Aerospace Engineering from the Georgia Institute of Technology in 2001, 2002, and 2006, respectively.

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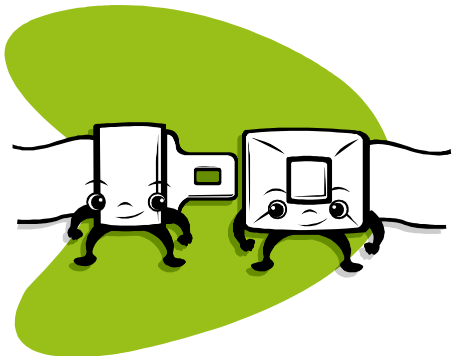
Objectives

- Show how complex, quantitative engineering level analysis is brought into and informs decision making
- Show how to best capture customer requirements such that engineering analysis is properly directed
- Introduce methods for decision making when dealing with multiple and competing objectives
- Provide practical examples along the way, not just hand-wave and talk in the hypothetical

Agenda

- Motivation
- Quality Function Deployment
- Multi-Attribute Decision Making
- Integrated Modeling & Simulation through Surrogate Modeling
- Robust Design and Quality
- Top-down Design
- Collaborative Decision Making



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Motivation and Overview

A need drives us to solve a specific problem

Motivation: Solving Complex Problems

A modern power system designer must be able to consider renewable as well as fossil sources of energy

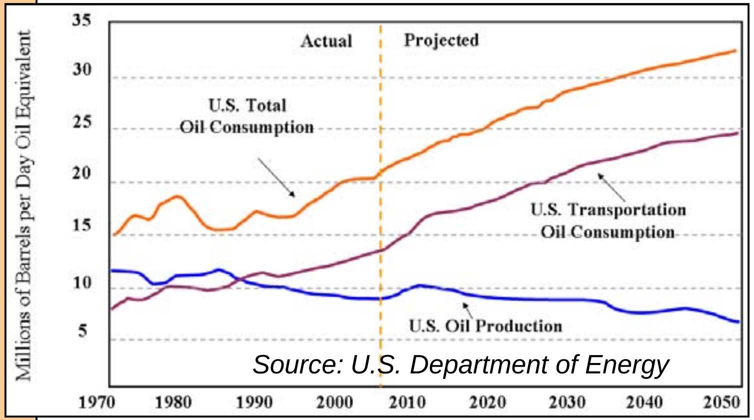
- The cost of fossil fuels is volatile and rising
- Concerns about CO_2 motivate a move away from fossil fuels, and future carbon restrictions will be the likely policy extension of that concern

Renewable sources of energy add uncertainty

- Sources like sun, wind, and waves are stochastic and variable by nature

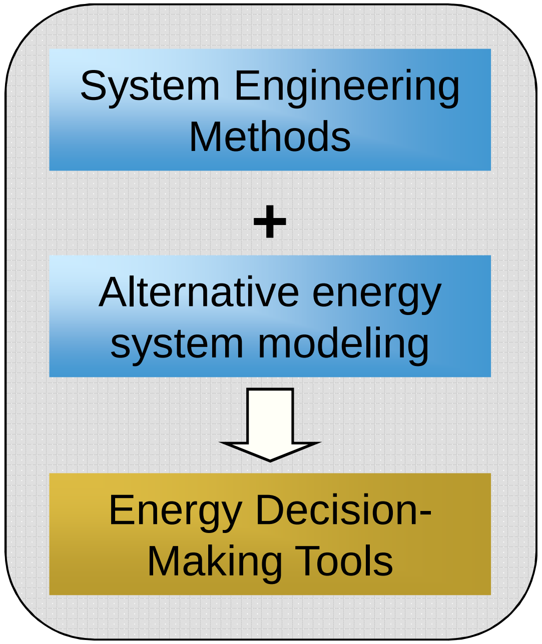
Other uncertainties must be considered as well

- Market uncertainties
- Policy changes
- ...



There is a need for energy related decision-making tools based on practical systems engineering methods

- Designer must make complex trade-offs
- Need ability to consider uncertainty
- Must consider non-technical as well as technical factors



Hybrid Energy Systems Design Considerations

Design Parameters

Systems Modeling

- Hybrid power systems
  - Integrate multiple power sources and storage devices to provide best system solution
- Energy storage and conversion
  - Control algorithms that decide when to charge/discharge batteries

Multiple Objectives

- **Power quality**
- **Efficiency**
- **Emissions**
- **Cost**
- **Availability**
- **Prioritization of multiple load demands**

Baseline: State of the Art

Methods for evaluating hybrid power systems

- Statistical approach
- Frequency-based methods
- Simplified linear programs
- Time series simulations
  - Most accurate
  - Run-time is too long for real-time usage

Methods for Optimizing hybrid power systems

- Optimize a single performance parameter
- Optimize an economic parameter with performance constraints
- Multi-objective optimization

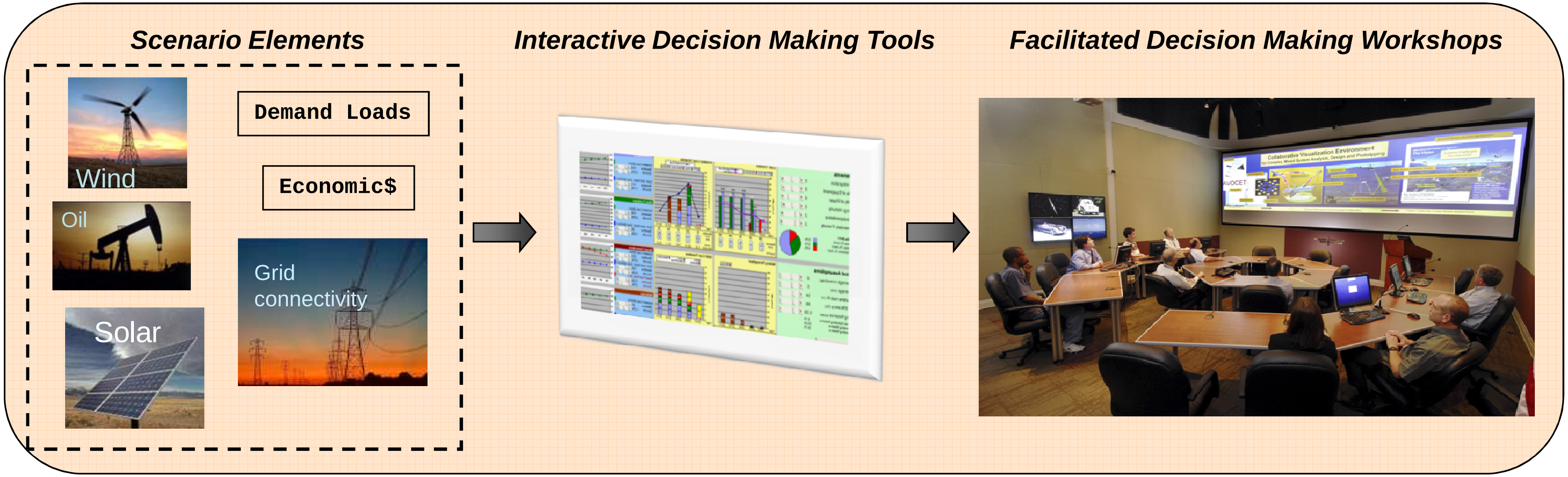
Enabling real-time design exercises by engineers and decision-makers

- Fast-running surrogates of time-series simulations
- Multi-objective optimization

Novelty of Approach

Moving beyond notion of individual component design

- Utilizes our expertise in the field of ***systems-of-systems*** research
  - Each system independently managed and operated
  - Capability of the integrated whole to produce results greater than sum of the individual components
- Research conducted on ***capability-focused*** and inverse design to identify hybrid energy solutions that meet *dynamic* requirements
- Decision-makers afforded novel real-time, panoramic view of trade-offs and parametric sensitivities via ***advanced visualization features***

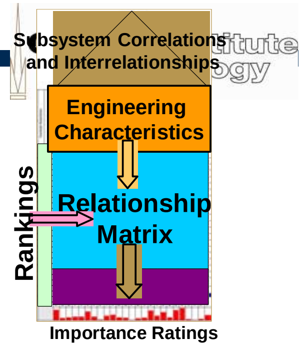


Methods Practiced

Quality Function Deployment

– Relates the what the customer wants with what the engineer can provide

– Captures "qualitative" desires and functional mappings



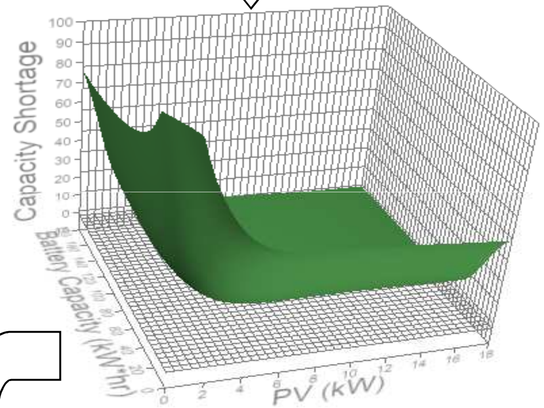
Multi-Attribute Decision Making

– Methods for handling multiple and conflicting objectives

Surrogate Modeling

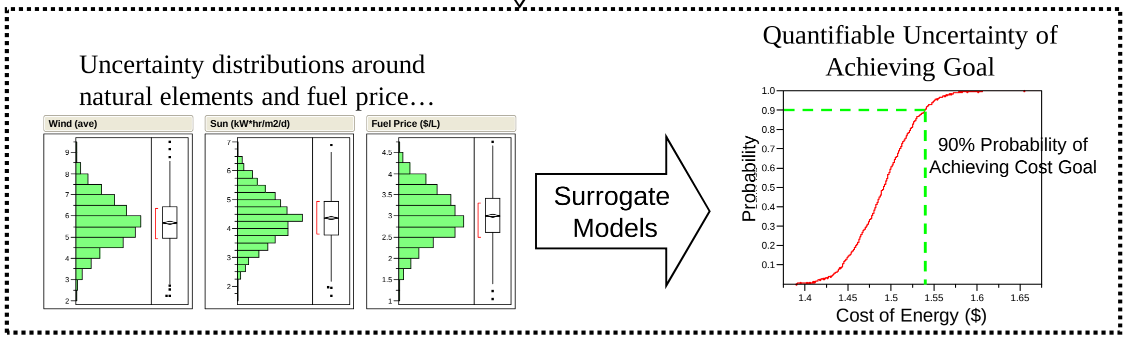
– Enables rapid modeling & simulation which are used for on-the-fly tradeoffs

– Yield results that may not otherwise have been discovered because of computationally intensive limitations



Robust Design

– Methodology for creating a design that is least sensitive to uncontrollable uncertainties (i.e. fuel price fluctuation, atmospheric conditions)



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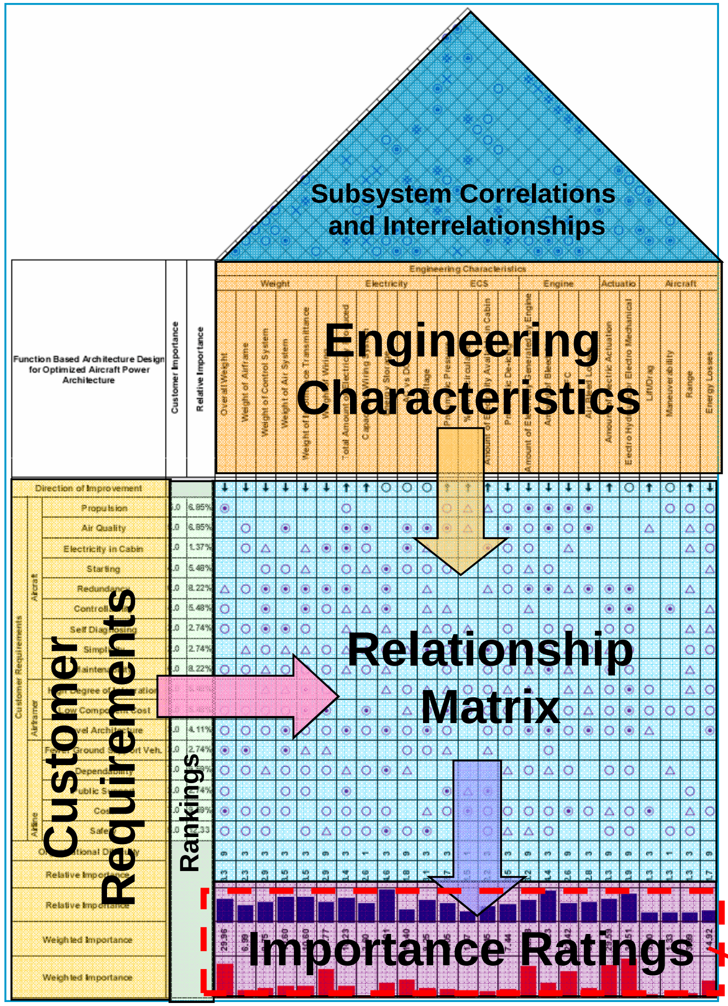
Quality Function Deployment

Properly direct engineering analysis by capturing the voice of the customer

Quality Function Deployment (QFD)

- A formal technique for capturing the user's requirements (voice of the customer) and mapping them into product and process parameters
- Consist of techniques for creating and completing a series of matrices showing the association between specific features of a product and statements representing the voice of the customer
- Uses teamwork and creative brainstorming as well as market research to identify customer demands and design parameters

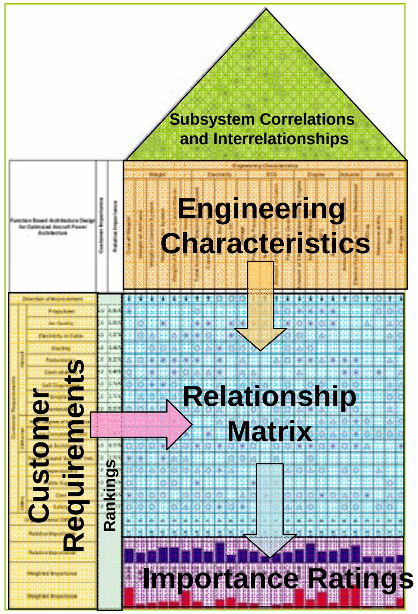
Quality Function Deployment (QFD)



- The QFD is used to relate the “voice of the customer” to the “voice of the engineer”
  – Voice of the Customer: relative weightings and hierarchy of requirements
  – Voice of the Engineer: measurable engineering characteristics are identified to meet the desired function for each requirement
- A qualitative mapping is used to measure the impact of each measurable engineering characteristic on each customer requirement

Ranking or weighting customer requirements, used with the qualitative mappings, yields the importance ratings of each engineering characteristic

Quality Function Deployment (QFD)



- Basic example shows how to map impacts of energy systems modeling attributes to customer requirements
  - Impacts measured qualitatively
    - » Low = 1
    - » Medium = 3
    - » High = 9
  - Direction of improvement
    - » Positive = Green
    - » Negative = Red
- Goal is to determine importance of each engineering attribute as a function of requirements weightings

Weighted Score

```
= 5*0
+ 5*0
+ 8*(-9)
+ 5*0
+ 2*(-9)
+ 2*0
= 90
```

		Quantitative M&S Metrics						
Requirements	*Customer Weightings*	Capacity Shortage	Renewable Fraction	Diesel Fuel Used (L)	Production wind	Production Solar	Production generator	Battery Throughput
Ease of Integration	5	0	0	-1	-9	-3	-1	-5
Reliability of Equipment	5	0	0	-1	-3	-1	-5	-5
Availability of Power	8	-9	0	0	1	2	9	9
Technology Maturity	5	0	0	0	3	2	9	2
Energy Independence	2	-9	9	-9	9	9	-9	5
Environmentally Friendly	2	0	9	-9	9	9	-9	2
Weighted Score		-90	36	-46	1	42	51	46

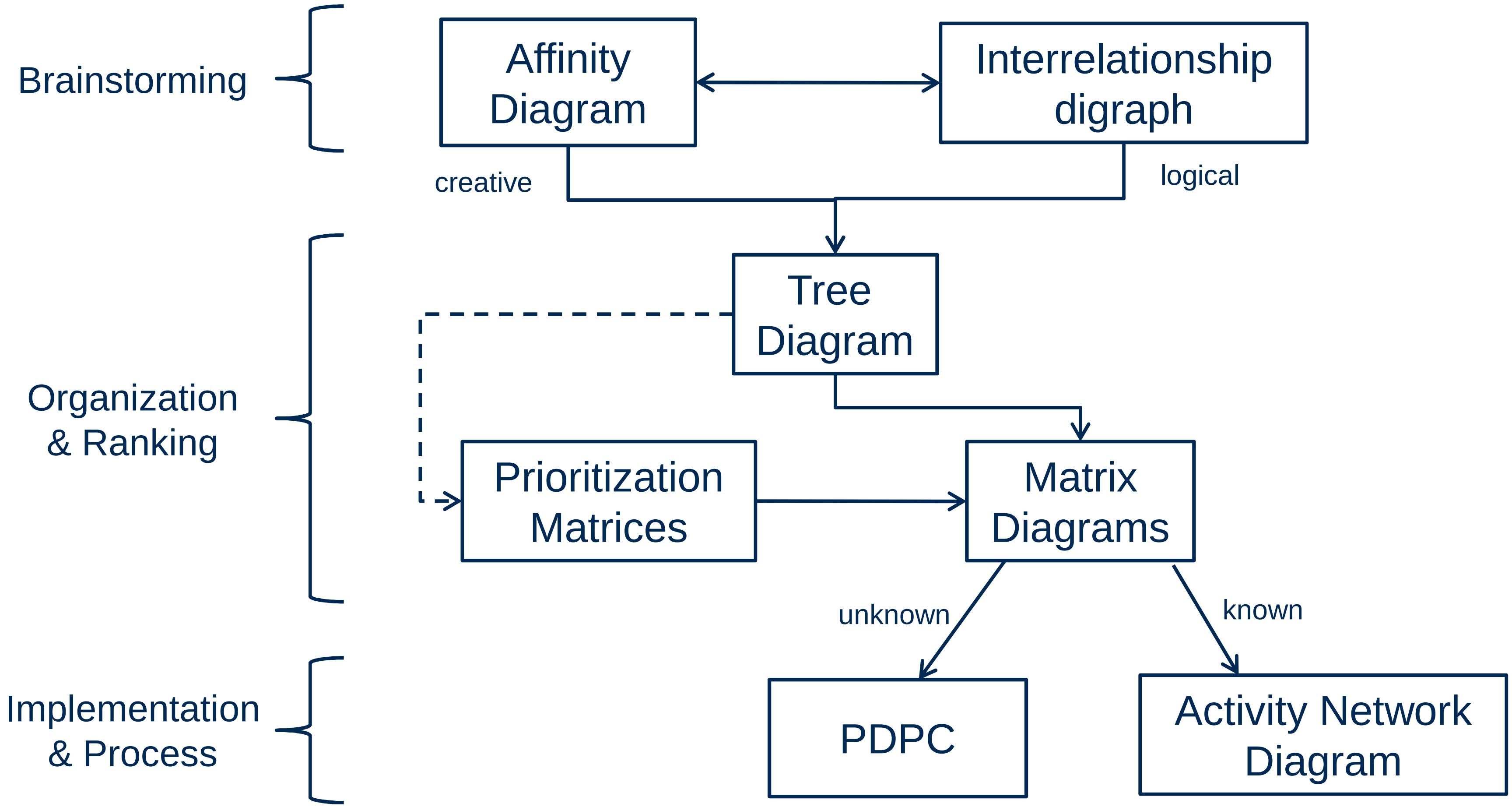
7 Management and Planning Tools

- These tools are brainstorming and communication methods for groups that require little training.
- Most of the tools are process-based, so assumptions about product attributes are avoided.
- The formality of a specified process and format allow new teams to work together, instead of arguing about a seat-of-the-pants approach to problem solving.
- Planning and evaluation expertise can be integrated with technical, logistical and operational expertise.

1. Affinity Diagram
2. Interrelationship digraph
3. Tree Diagram
4. Prioritization Matrices
5. Matrix Diagram
6. Process Decision Program Chart (PDPC)
7. Activity Network Diagram

Source: The Memory Jogger Plus+, Brassard, 1996

7 Management and Planning Tools



Source: The Memory Jogger Plus+, Brassard, 1996

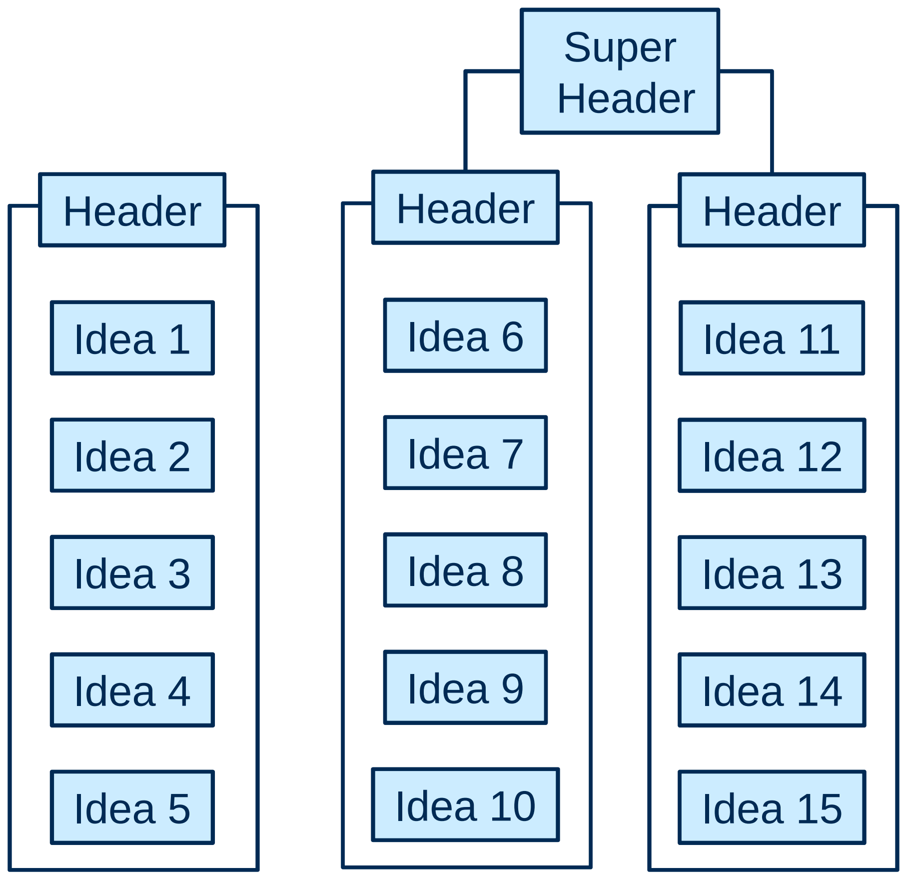
Affinity Diagram

- Primary goal of the Affinity Diagram:
  1. Gathers large amounts of data (ideas, opinions, issues, etc.)
  2. Organizes this data into groupings based on the natural relationships between each item (i.e. their *affinity* for one another)
  3. Defines groups of items
- Creating an Affinity Diagram is primarily a creative process

Source: The Memory Jogger Plus+, Brassard, 1996

Affinity Diagram

1. Phrase the issue under discussion
2. Generate ideas
3. Group similar ideas
4. Create groups headers
5. Draw the finished affinity diagram



Source: The Memory Jogger Plus+, Brassard, 1996

Affinity Diagram

- Generally, Affinity Diagram is always useful
- "Cleanest" use of Affinity Diagram is when
  - Facts or Ideas are in chaos
  - When Issues seem too large/complex to grasp
  - Breakthrough in traditional concepts is needed
  - Support for a solution is essential for successful implementation
- Not recommended when the problem is simple or requires a very quick solution

Source: The Memory Jogger Plus+, Brassard, 1996

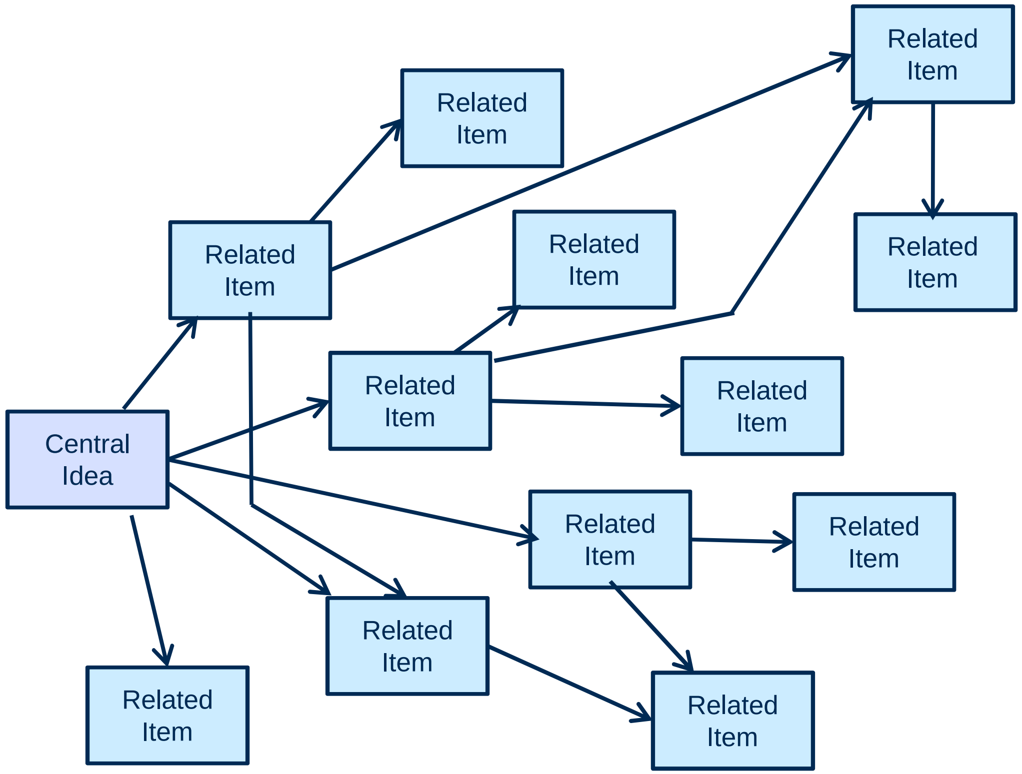
Interrelationship Digraph

- Primary goals of the Interrelationship Digraph:
  1. Takes a central idea, issue or problem and maps out the logical or sequential links among related items
  2. Shows that every idea can be logically linked with more than one other idea at a time
  3. Allows for “multi-directional” rather than “linear” thinking
- The Interrelationship Digraph shows cause-and-effect relationships
- Helps a group analyze the natural links between different aspects of a complex situation

Source: The Memory Jogger Plus+, Brassard, 1996

Interrelationship Digraph

1. Determine the central issue/problem
2. Layout all of the associated ideas/issues
3. Draw the relationship arrows
   – Which issues are caused or influenced by the current issue?
4. Review and iterate as necessary
5. Select key items for further planning



Source: The Memory Jogger Plus+, Brassard, 1996

Interrelationship Digraph

- Interrelationship Digraph is useful for both specific operational issues as well as general organizational issues
- Best use of Interrelationship Digraph:
  - An issue is sufficiently complex that the interrelationships between and among ideas is difficult to determine
  - The correct sequence of actions is critical
  - There is a feeling the central problem is only a symptom
  - There is sufficient time to complete the required review iteration

Source: The Memory Jogger Plus+, Brassard, 1996

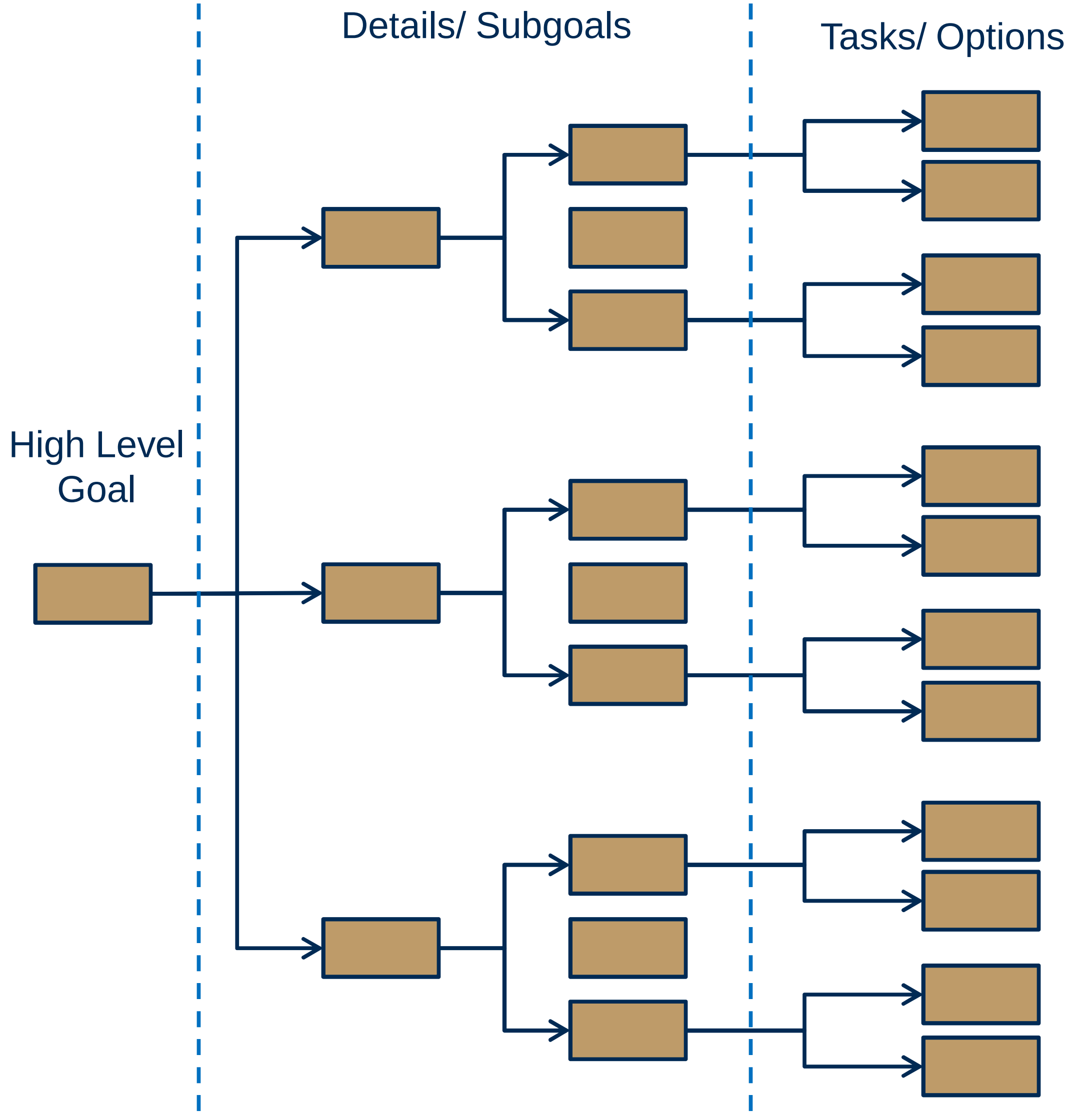
Tree Diagram

- Primary goals of the Tree Diagram:
  1. Systematically maps out in increasing detail the full range of path and tasks that need to be done to achieve a goal and associated subgoals
  2. Describes the methods by which every purpose is to be achieved
  3. Links the "Mother and apple pie" objective to the details of implementation
- The Tree Diagram takes the key issues identified in the Affinity and Interrelationship diagrams and maps them down to the lowest practical level of detail

Source: The Memory Jogger Plus+, Brassard, 1996

Tree Diagram

1. Choose the high level goal
2. Generate the major tree headings
3. Break each major heading to greater detail
   – What needs to happen/be addressed to resolve/achieve the problem/ goal statement?
4. Review for logical flow and completeness



Source: The Memory Jogger Plus+, Brassard, 1996

Tree Diagram

- Key questions answered:
  - What sequence of events needs to be completed in order to fully address the key issue/problem/goal?
  - What are all the component parts of the key problem that need to be addressed?
  - Does the implementation logic hang together?
  - How complex (or simple) will the solution implementation be?
  - What are the assignable tasks/options that can be spun off from the key issue?

Source: The Memory Jogger Plus+, Brassard, 1996

Tree Diagram

- When to use the Tree Diagram?
  - When a specific task or goal has become the focus but is not a simple assignable job.
  - When it is known (or suspected) that implementation will be complex.
  - When there are strong consequences for missing key tasks (e.g. safety or legal compliance issues).
  - When a task has been considered a simple one yet has run into repeated roadblocks in implementation.

Source: The Memory Jogger Plus+, Brassard, 1996

Prioritization Matrices

- Primary goals of Prioritization Matrices:
  – Used to prioritize tasks, issues, product/service characteristics, etc. based on known criteria.
  – Uses a combination of Tree and Matrix Diagram techniques to populate options to prioritize.
  – In general, this tool is used for decision making.
- Prioritization Matrices are designed to rationally narrow down the focus of any team before detailed implementation can begin.

Source: The Memory Jogger Plus+, Brassard, 1996

Prioritization Matrices

- Three primary applications of the Prioritization Matrices:
  1. The Full Analytical Criteria Method
  2. The Consensus Criteria Method
  3. The Combination I.D./Matrix Method
- Full Analytical Criterion Method steps:
  1. Prioritize and assign weights to the list of criteria
  2. Prioritize the list of options based upon each criteria
  3. Prioritize and select the best option across all the criteria

Source: The Memory Jogger Plus+, Brassard, 1996

Prioritization Matrices

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Step 1: Ranking the Criteria

	Low Cost to Imple-ment	No Custom-ized Tech-nology	Quick to Imple-ment	Easily Accept-ed by Users	Minimal Impact on Other Depts.	Total Across Rows as % of Grand Total ( )
Low Cost to Implement		5	1/10	1/10	1/5	5.4 (.08)
No Customized Technology	1/5		1/5	1/10	1/5	.7 (.02)
Quick to Implement	10	5		1/10	1/5	15.3 (.21)
Easily Accepted by Users	10	10	10		1/5	30.2 (.40)
Minimal Impact on Other Depts.	5	5	5	5		20 (.28)
Column Total	25.2	25	15.3	7.3	.8	Total Across Columns 73.6 Grand Total

Step 2: Ranking Options by Criteria

Quick To Implement	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	Total Across Col. (% Grand Total)
(A) Error Prevention Training		1/5	1/5	5	10	1/5	10	1/5	1/10	1/5	1/5	1/5	1/5	1/10	5	5	1/10	36.9 (.04)
(B) Sequential Inspection Training	5		5	10	10	1/5	10	1/5	1/5	1/5	1/5	1/5	1/10	1/10	10	5	1/5	56.6 (.07)
(C) Problem Solving Training	5	1/5		5	10	1/5	10	1/5	1/10	1/5	1/5	1/5	1/5	1/10	5	5	1/10	41.7 (.05)
(D) Optical Scanning System	1/5	1/10	1/5		1	1/10	5	1/5	1/10	1/5	1/5	1/10	1/10	1/10	1	1/5	1/10	8.9 (.01)
(O) Shorten 11-Digit Product Code	1/5	1/10	1/5	1	1	1/5	5	1/5	1/10	1/5	1/5	1/10	1/5	1/10		1	1/10	9.9 (.01)
(P) More Obvious Difference Among Prod. Grp. Codes	1/5	1/5	1/5	5	5	1/5	10	1/5	1/5	1/5	1/5	1/5	1/5	1/10	1		1/10	23.2 (.03)
(Q) Train Clerical Sales & Customer Service Pers.	10	5	10	10	10	5	10	5	1	5	5	1	5	1	10	10		103.0 (.12)
Column Totals:	70.8	56	66	102.2	117.2	14.2	130	34.5	10.6	37.6	28.7	10	23.6	3.9	88.2	71.5	4.9	869.9

Step 3: Ranking Options by All Criteria

Options / Evaluation Criteria	Quick to Implement	Easily Accepted By Users	Minimal Impact on Other Depts.	Total Across Rows as % of Grand Total
(A) Error Prevention Training	.04 X .21 = .008	.03 X .42 = .013	.03 X .28 = .008	.029 (.03)
(B) Sequential Inspection Training	.07 X .21 = .015	.04 X .42 = .017	.02 X .28 = .006	.038 (.04)
(C) Problem Solving Training	.05 X .21 = .011	.04 X .42 = .017	.03 X .28 = .008	.036 (.04)
(O) Shorten 11-Digit Product Code	.01 X .21 = .002	.12 X .42 = .050	.03 X .28 = .008	.060 (.07)
(P) More Obvious Differences Among Prod. Group Codes	.03 X .21 = .006	.10 X .42 = .042	.13 X .28 = .036	.084 (.09)
(Q) Train Clerical Sales and Customer Service Personnel	.12 X .21 = .025	.03 X .42 = .013	.04 X .28 = .011	.049 (.05)
Column Total	.211	.421	.279	Grand Total .911

Source: The Memory Jogger Plus+, Brassard, 1996

Prioritization Matrices

- When to use Prioritization Matrices?
  - When key issues have been identified and the options generated must be narrowed down.
  - When the criteria for a "good" solution are agreed upon but there is disagreement over their relative importance.
  - When there are limited resources for implementation.
  - When the options generated have strong interrelationships.
  - When generating lots of options all of which needed to be done and sequencing is important.

Source: The Memory Jogger Plus+, Brassard, 1996

Matrix Diagram

- Primary goals of the Matrix Diagram:
  - Organizes large amounts of information such as characteristics, functions and or tasks into sets of items to be compared.
  - Graphically shows the logical connections between any two items
  - Can also show the strength and direction of influence between two items.
- Matrix Diagrams are the most useful of the methods for decision making
- Matrix Diagrams essentially form the core of QFD applications

Source: The Memory Jogger Plus+, Brassard, 1996

Matrix Diagram

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1. Determine the key factors affecting successful implementation
2. Select the appropriate matrix format
3. Define the relationship symbols
4. Score the Matrix

◎ Primary Responsibility
○ Secondary Responsibility
△ Communications/Needs to Know

+Slightly More Emphasis

	Bob	Mike	Lee	Larry	Anna	Jetty	Dona	Brd.Dir.	Other
Administration									
Payroll	◎		△					○	
Benefits	○	△	◎	△	△	△	△	○	
Office Systems	○	○	◎			◎	△		
Computer Programs	○	△	◎			○	○		
Courses									
Update Mailing List			○			◎	◎		
Select Courses to be Offered	◎	◎	◎			△	△		
Approve Course Content	◎	◎	○			△			
Prepare Brochures	○	○	○		◎	△			
Prepare Mailing			△			◎	○		
Hotel Arrangements	△	△	◎			△+	△		
Order Materials	△	△	◎			○	△		
Register People			△		△	◎	○		
Copy Materials					△	◎	○		
Prepare Packets	△	△	△			◎	○		
Room Set-up	◎	◎	◎						
Post Receipts			◎						
Prepare Bills	△		◎				○		
New Course Development									
Market Research	○	◎	△			△			
Implementing Deming	◎	◎	△	○		△	○		
TQC	◎	○	△						
Fundraising									
Annual Reports	○	○	◎		◎	○	△	△	
Corporate Donations	◎	○	○	◎	○				
Committees									
Program Planning	◎	○	△			△			
Statistical Resources	○	◎	△	△	△	△			
TQC	◎	○	△	△	△	△			

Source: The Memory Jogger Plus+, Brassard, 1996

Matrix Diagram

- When to use the Matrix Diagram:
  - When high level goal as evolved into a definable set of tasks that must be ranked
  - When the “focused activities” must ranked against other things that your organization is already doing
  - When your organization is trying to prioritized present activities against a new set of goals and objectives
  - When there is a need to get a cumulative score that allows you to compare items based on a set of common metrics

Source: The Memory Jogger Plus+, Brassard, 1996

Process Decision Program Chart (PDPC)

- Primary goals of the PDPC Chart:
  - Used to map out conceivable events and contingencies which can occur in any implementation plan
  - Helps to identify feasible countermeasures in response to know or foreseeable problems
  - Used to plan each possible chain of events that needs to occur when a problem or goal is an unfamiliar one
- Creating PDPC Charts is essentially an exercise in Contingency Planning
  - What could be done as a countermeasure if ‘A’ happened? If ‘B’ happened? and so on.

Source: The Memory Jogger Plus+, Brassard, 1996

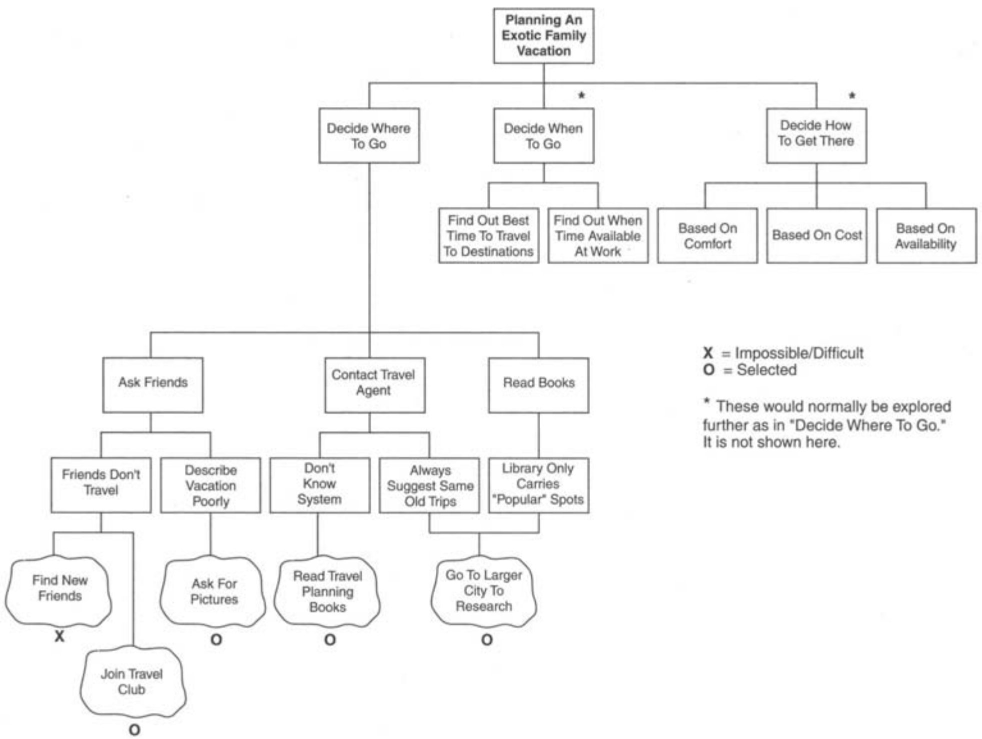
Process Decision Program Chart (PDPC)

- PDPC Chart creation steps:
  1. Assemble the right team
  2. Determine the basic flow of proposed activities
  3. Choose the most workable format for the chart
     - » Graphical versus Outline
  4. Construct the PDPC using the chosen format

Source: The Memory Jogger Plus+, Brassard, 1996

Process Decision Program Chart (PDPC)

Graphical Format



Outline Format

Implementation Steps

1.0 Decide where to go
1.1 Ask friends
1.2 Contact travel agent
1.3 Read books
2.0 Decide when to go
2.1 Find out best time to travel to destination
2.2 Find out when time is available at work
3.0 Decide how to get there
3.1 Decide based on comfort
3.2 Decide based on cost
3.3 Decide based on availability

"What if" Problems

1.1.1 Friends don't travel
1.1.2 Describe vacation poorly

Possible Countermeasures

X 1.1.1.1 Find new friends
O 1.1.1.2 Join travel club
1.1.2.1 Ask for pictures
1.2.1 Don't know system
1.2.2 Always suggest same old trips
O 1.2.1.1 Read travel planning books
1.2.2.1 Go to larger city to research
1.3.1 Library carries only "popular spots"
O 1.3.1.1 Go to larger city to research

X = Impossible/difficult
O = Selected

Source: The Memory Jogger Plus+, Brassard, 1996

Process Decision Program Chart (PDPC)

- When to use Process Decision Program Chart:
  - Whenever uncertainty exits in a proposed implementation plan
  - When the task at hand is new or unique
  - When the implementation plan has sufficient complexity such that potential deviations are not trivial or self-explanatory.
  - When the cost of failure is high.
  - When the efficiency of the implementation plan is critical.

Source: The Memory Jogger Plus+, Brassard, 1996

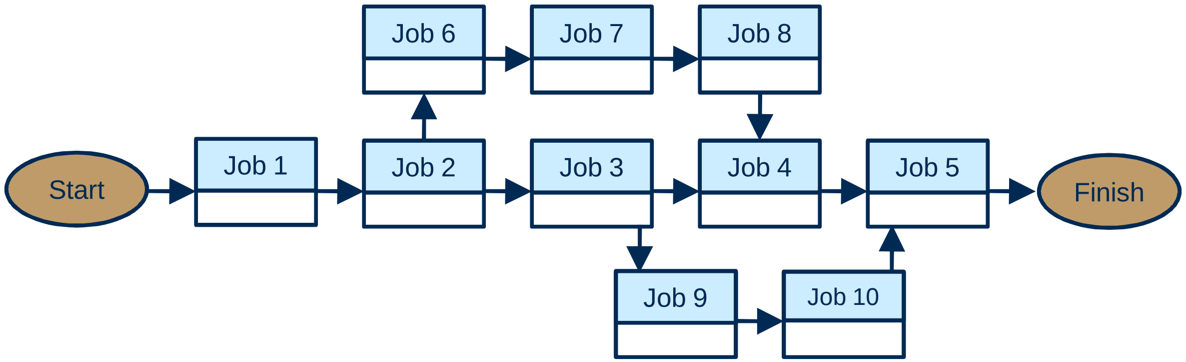
Activity Network Diagram

- Primary goals of the Activity Diagram:
  - Used to plan the most appropriate schedule for completion of complex tasks and related sub-tasks
  - Projects the likely completion time of the tasks
  - Can be used to monitor sub-tasks for adherence to the necessary schedule.
  - Used when the task at hand is familiar with sub-tasks of a known duration
- Activity Network Diagram is essentially the same as a PERT chart or CPM (Critical Path Method) chart

Source: The Memory Jogger Plus+, Brassard, 1996

Activity Network Diagram

1. Brainstorm and all the tasks needed to complete the project
2. Sequence all of the identified activities
3. Give each subtask a duration
4. Calculate the shortest possible schedule using the Critical Path Method
5. Calculate earliest and latest starting and finishing for each task
6. Locate jobs with slack time and calculate total slack time



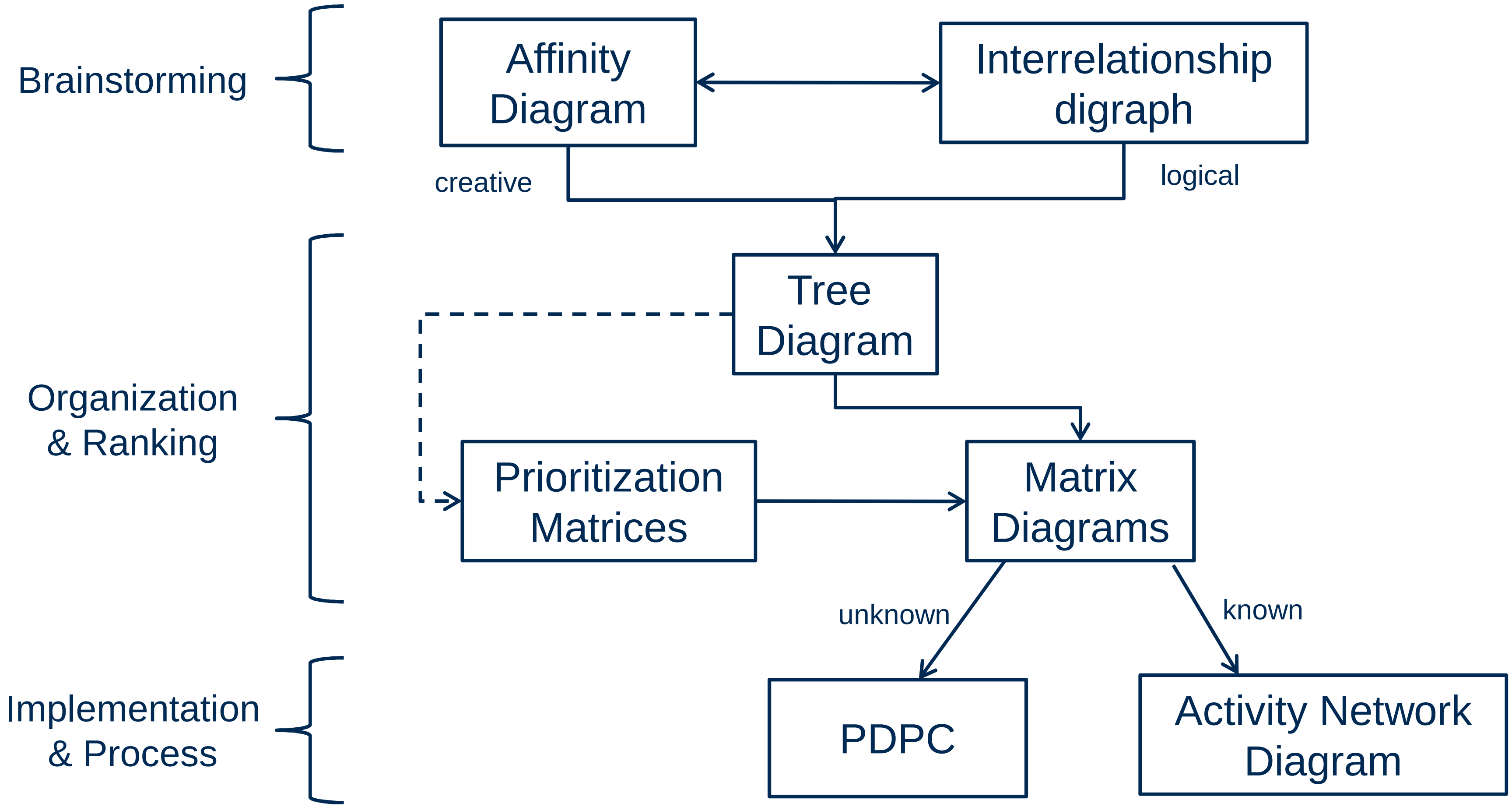
Source: The Memory Jogger Plus+, Brassard, 1996

Activity Network Diagram

- When to use the Activity Network Diagram:
  - When the task/project to be completed is a complex one.
  - When the sub-tasks are familiar with known durations even if they may have been combined in different sequences in the past.
  - When there are simultaneous implementation paths that must be coordinated.
  - When there is little margin for error in the actual versus estimated time to completion.

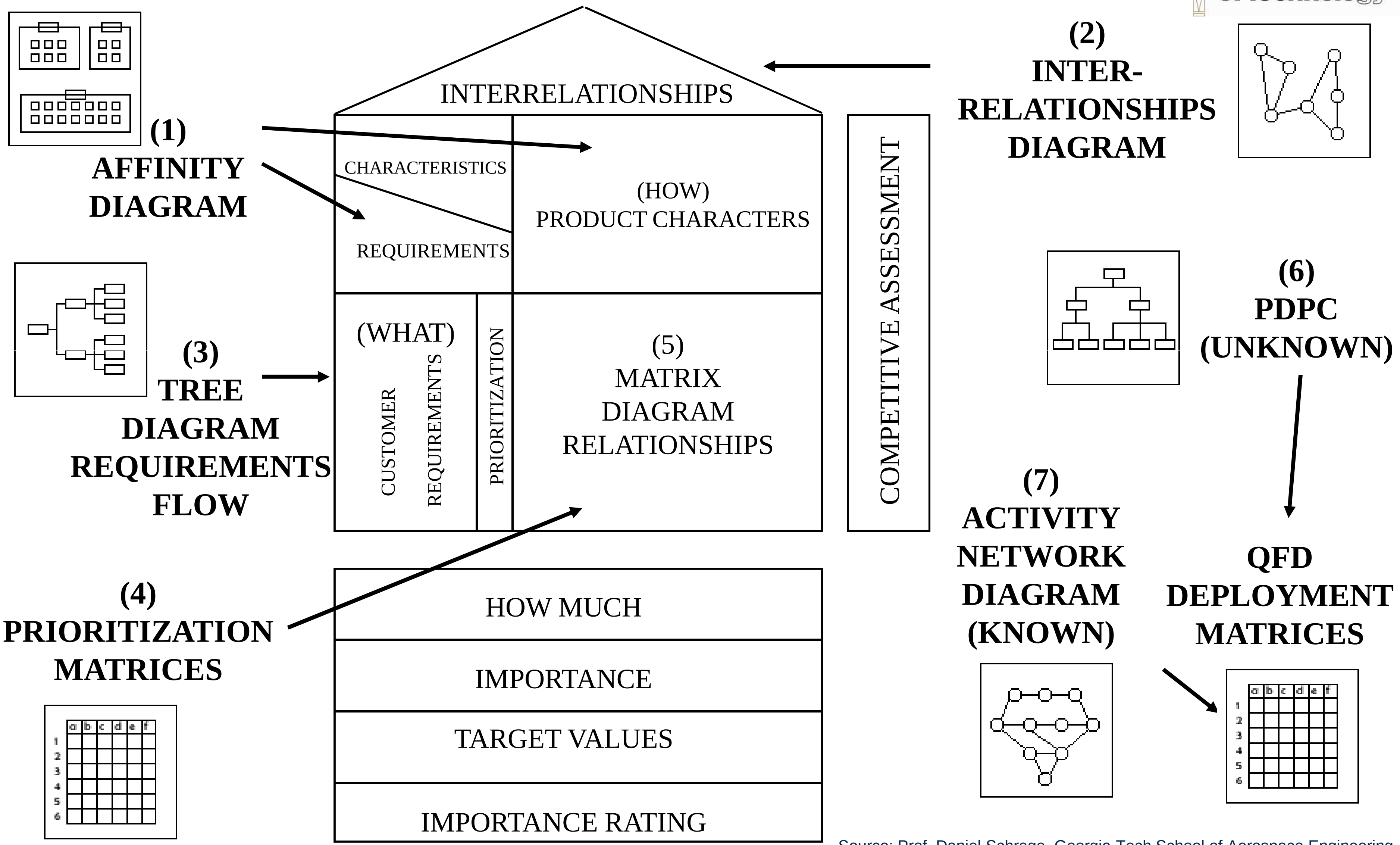
Source: The Memory Jogger Plus+, Brassard, 1996

7 Management and Planning Tools



Source: The Memory Jogger Plus+, Brassard, 1996

How the Seven Management and Planning Tools Relate to Quality Function Deployment



Source: Prof. Daniel Schrage, Georgia Tech School of Aerospace Engineering

Enabling Collaborative Decision Making
through Applied Systems Engineering Tools, Methods, and Processes

Multi-Attribute Decision Making

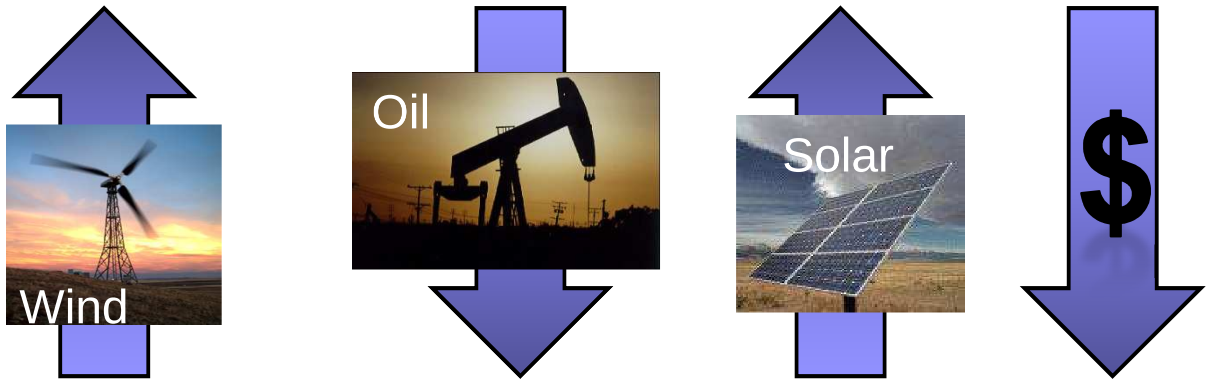
Methods for decision making when dealing with multiple and competing objectives

Multi-Attribute Decision Making

Q: How do we design a system that both provides reliable power and minimizes fossil fuel dependency?

A: That depends on the importance of each requirement – this drives which requirements can be sacrificed for others

Multi-Attribute Decision Making (MADM) methods exist for handling multiple and conflicting objectives



Multi-Attribute Decision Making

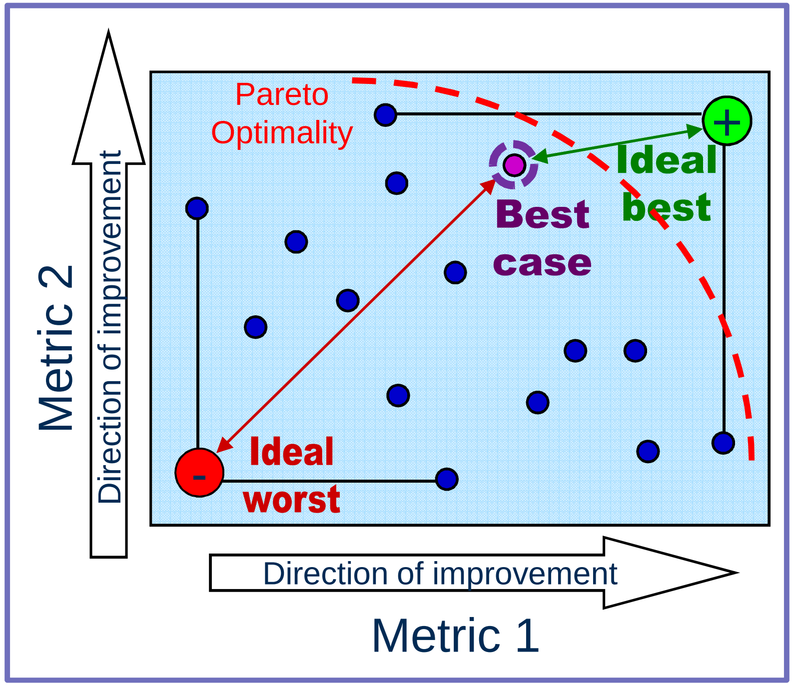
- Most *optimization* techniques for design are poorly suited to handle multiple objectives

- The design of complex systems *requires* holistic solutions that are valid in multiple dimensions and for multiple criteria
  - ➢ Requirements can impact multiple design variables
  - ➢ Measures of Effectiveness may be conflicting

- Starting in the 1950's and continuing all the way to the 1970's, U.S. Department of Defense invested heavily in the development of mathematical techniques for decision making in the presence of many attributes

Multi-Attribute Decision Making

- We do not necessarily want a design which is optimized for a single metric
- Want solutions that are good in multiple dimensions; *Pareto* optimality
- One method is the Technique for Ordered Preference by Similarity to the Ideal Solution (TOPSIS)
  - Select from a range of alternative solutions
  - Uses a weighted series of criteria to identify the best and worst of each criteria and combines them into the theoretical best and worst points
  - Actual ranking is performed based on maximizing the normalized distance from the theoretical worst and minimizing the distance from the theoretical best



Technique for Ordered Preference by Similarity to the Ideal Solution (TOPSIS)

- Step 1: Create decision matrix by mapping alternatives to evaluation criteria/attributes
- Step 2: Non-dimensionalize the attribute value by dividing it by the norm of the total outcome vector (sum of squares of a criterion) of the criterion at hand
- Step 3: Establish relative importance of the criteria by assigning weighted values
- Step 4: Determine if the attributes are a “Benefit” or a “Cost”
- Step 5: Create positive and negative ideals
- Step 6: Separation of each alternative from ideal is measured by the n-dimensional Euclidean distance
- Step 7: Relative closeness to the ideal solution

TOPSIS Methodology

- Step 1: Create decision matrix by mapping alternatives to evaluation criteria/attributes

Quantitative Metrics	Hybrid Energy System Portfolios Analyzed			
	Portfolio Mix 1	Portfolio Mix 2	Portfolio Mix 3	Portfolio Mix 4
Capacity Shortage	1%	5%	22%	46%
Renewable Fraction	0.37	0.66	0.78	0.41
Diesel Fuel Used (L)	205	67	10	0
Production wind	2051	3541	984	111
Production Solar	564	234	0	3978
Production generator	6521	0	187	621
Battery Throughput	967	1231	1621	0

  – Quantify qualitative criteria using an interval scale (very high-9, average-5, very low-1)

TOPSIS Methodology (cont.)

Georgia Institute of Technology

- Step 2: Nondimensionalize the attribute value by dividing it by the norm of the total outcome vector (sum of squares of a criterion) of the criterion at hand

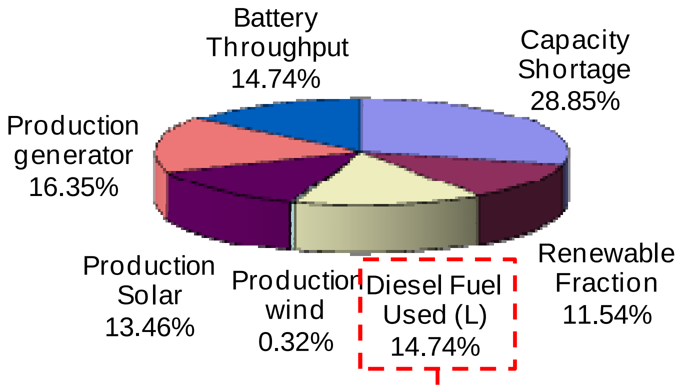
Quantitative Metrics	Hybrid Energy System Portfolios Analyzed			
	Portfolio Mix 1	Portfolio Mix 2	Portfolio Mix 3	Portfolio Mix 4
Capacity Shortage	0.0195	0.0976	0.4293	0.8977
Renewable Fraction	0.3186	0.5682	0.6716	0.3530
Diesel Fuel Used (L)	0.9495	0.3103	0.0463	0.0000
Production wind	0.4871	0.8411	0.2337	0.0264
Production Solar	0.1401	0.0581	0.0000	0.9884
Production generator	0.9951	0.0000	0.0285	0.0948
Battery Throughput	0.4291	0.5463	0.7193	0.0000

$$\frac{1\%}{\sqrt{(1\%)^2+(5\%)^2+(22\%)^2+(46\%)^2}} = 0.0195$$

Adapted from course material developed by Dr. Michelle Kirby, Georgia Tech School of Aerospace Engineering

TOPSIS Methodology (cont.)

- Step 3: Establish relative importance of the criteria by assigning weighte



0.9495*0.1474=0.1400

Quantitative Metrics	Hybrid Energy System Portfolios Analyzed			
	Portfolio Mix 1	Portfolio Mix 2	Portfolio Mix 3	Portfolio Mix 4
Capacity Shortage	0.0056	0.0281	0.1238	0.2589
Renewable Fraction	0.0368	0.0656	0.0775	0.0407
Diesel Fuel Used (L)	0.1400	0.0458	0.0068	0.0000
Production wind	0.0016	0.0027	0.0007	0.0001
Production Solar	0.0189	0.0078	0.0000	0.1331
Production generator	0.1627	0.0000	0.0047	0.0155
Battery Throughput	0.0633	0.0805	0.1061	0.0000

TOPSIS Methodology (cont.)

- Step 4: Determine if the attributes are a "Benefit" or a "Cost"
  - Maximize "Benefits" and minimize "Costs"

Quantitative Metrics	*Direction of Improvement*
Capacity Shortage	Cost
Renewable Fraction	Benefit
Diesel Fuel Used (L)	Cost
Production wind	Benefit
Production Solar	Benefit
Production generator	Cost
Battery Throughput	Benefit

TOPSIS Methodology (cont.)

- Step 5: Create positive and negative ideals
  - Create positive ideal solution: maximum value of the "Benefit" criterion and minimum value of the "Cost" criterion
  - Create negative ideal solution: minimum value of the "Benefit" criterion and maximum value of the "Cost" criterion

	Positive Ideal	Negative Idea
Capacity Shortage	0.0056	0.2589
Renewable Fraction	0.0775	0.0368
Diesel Fuel Used (L)	0.0000	0.1400
Production wind	0.0027	0.0001
Production Solar	0.1331	0.0000
Production generator	0.0000	0.1627
Battery Throughput	0.1061	0.0000

TOPSIS Methodology (cont.)

- Step 6: Separation of each alternative from ideal is measured by the n-dimensional Euclidean distance

$$S_i^{*/-} = \sqrt{\Sigma(\text{Alternative Value - Pos/Neg Ideal Value})^2}$$

$$S_1^* = \sqrt{(0.2589-0.0056)^2 + (0.0407-0.0775)^2 + \ldots} = 0.2775$$

	Portfolio Mix 1	Portfolio Mix 2	Portfolio Mix 3	Portfolio Mix 4
Separation from Positive Ideal	0.2502	0.1381	0.1782	0.2775
Separation from Negative Ideal	0.2618	0.3098	0.2718	0.2428

TOPSIS Methodology (cont.)

- Step 7: Relative closeness to the ideal solution

$$C_i = \frac{S_i-}{(S_i*+S_i-)}$$

Example: Alternative 1 $C_1 = \frac{0.2618}{(0.2618+0.2502)} = 0.5113$

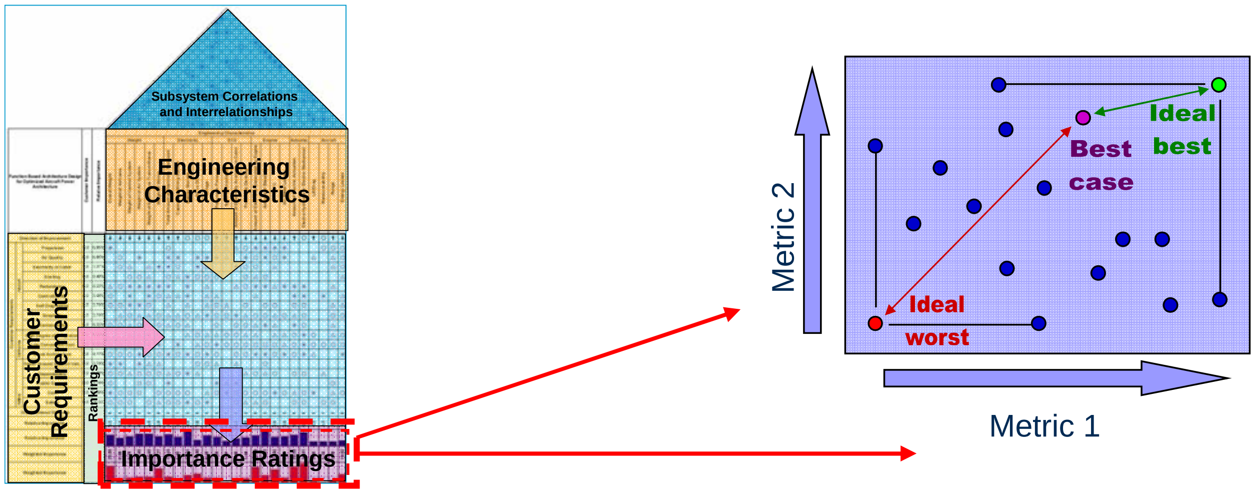
…finally, rank alternatives based on closeness to ideal solution: Best - 1.00, Worst - 0.00

Best Alternative

	Portfolio Mix 1	Portfolio Mix 2	Portfolio Mix 3	Portfolio Mix 4
TOPSIS Score	0.5113	0.6917	0.6040	0.4667

Summary of TOPSIS Decision Making Technique

- Advantages:
  - Easy to implement - Simple equations and processes
  - Can be explained visually – Allows customers and team members to quickly understand the process
  - Quick to perform – Allows frequent changes to inputs or weightings
  - Shows robustness of options – If one options is consistently at the top, more likely to be better overall
- Disadvantage:
  - Like most MADM techniques, the importance weighting of each dimension must be user specified
  - “Ideal” solutions therefore depend on subjective weightings
  - **Overcome disadvantage by obtaining metric weightings from the QFD process**



Adapted from course material developed by Dr. Michelle Kirby, Georgia Tech School of Aerospace Engineering

Enabling Collaborative Decision Making through Applied Systems Engineering Tools, Methods, and Processes

Modeling and Simulation

Informing decision making through integration with complex engineering analysis

Modeling and Simulation

How would you answer this question:

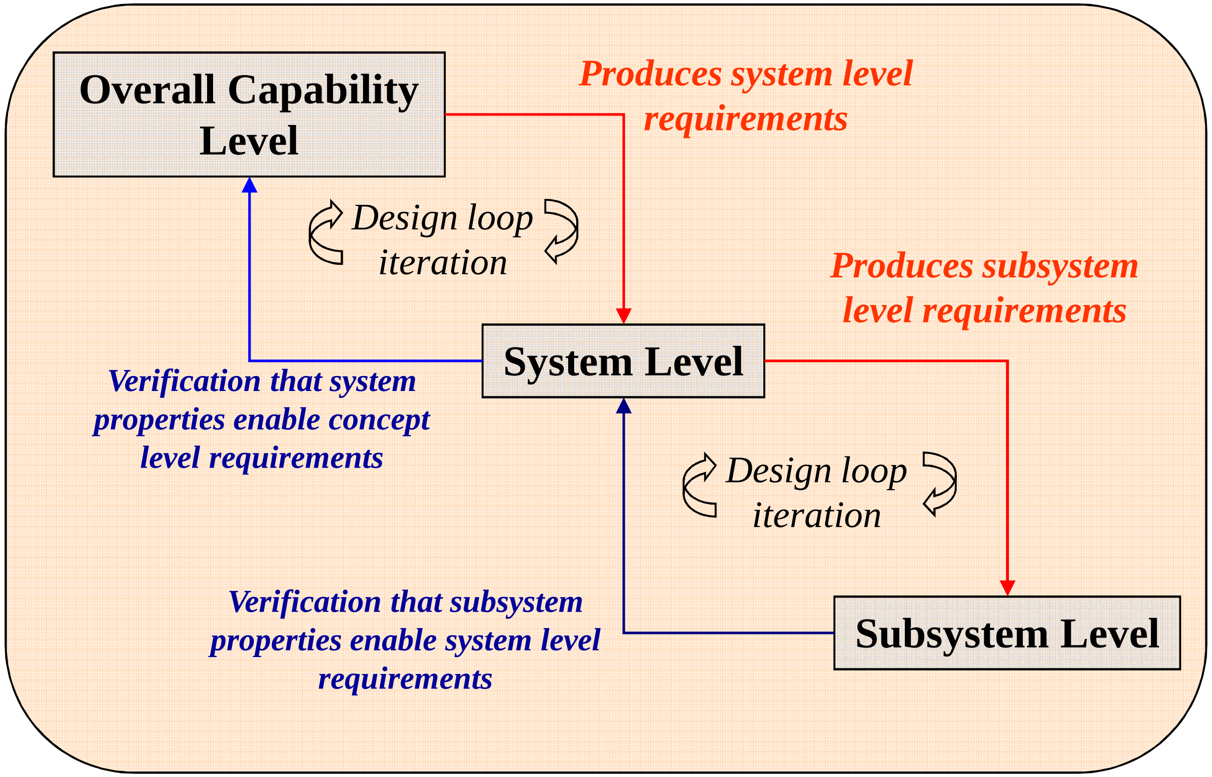
If available wind drops by 5%, how will that affect the power produced from my wind turbine over the course of a day? a week? a month? a year? How will that affect my ability to meet load demand over those same periods of time?

…or this question:

How many wind turbines would I need to add to my energy systems portfolio if I can only obtain half the photovoltaic systems I originally thought I needed? And of course, I want to do this without adding any more reliance on fossil fuel sources.

Systems Engineering Applied to Complex Systems

- Can break the systems engineering process into a hierarchy of decision making levels
  - ***Capability****: produces an overall capability description to meet requirements at highest level
  - ***System***: produces system description, i.e. performance requirement
  - ***Subsystem***: produces subsystem performance description
- "Top-down, comprehensive, iterative, and recursive"
  - Transforms needs and requirements into a set of system product and process descriptions at the next lower level
  - Requirements are decided upon and flowed from the top-down



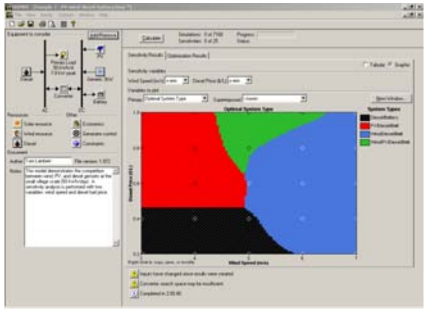
Source: Baumann, J., "Systems Engineering," Session 1-2. Presented at the 2nd AIAA Tactical Interceptor Technology Symposium, Huntsville, AL, 20-21 January, 2005.

Modeling and Simulation

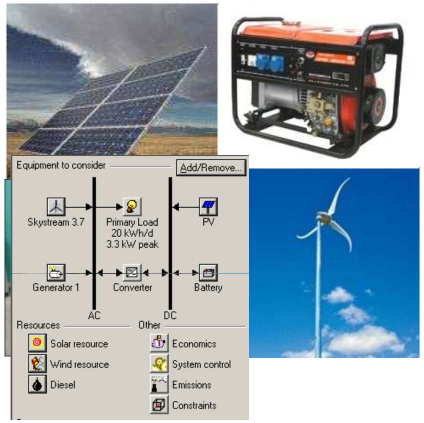
- To answer those questions, we can guess, or make assumptions based on historical data
- Modeling and simulation is the preferred method, but in most cases it can not be used to answer every hypothetical question
- This section will show how we set up a M&S environment such that we capture the elements we want represented, or abstracted at a "higher" level to support decision making

Process Roadmap: Integrating Modeling & Simulation within a Decision Making Environment

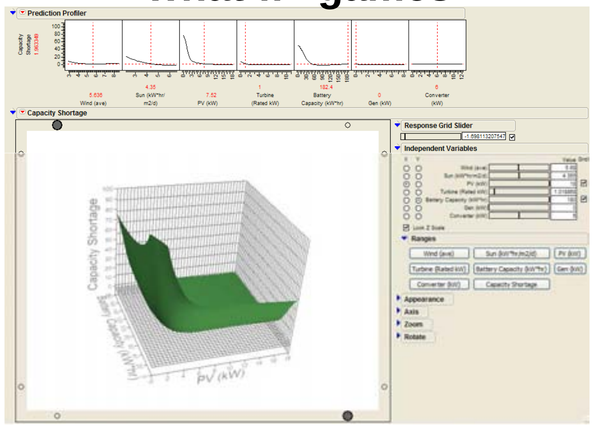
Identify Hybrid RE Modeling & Simulation



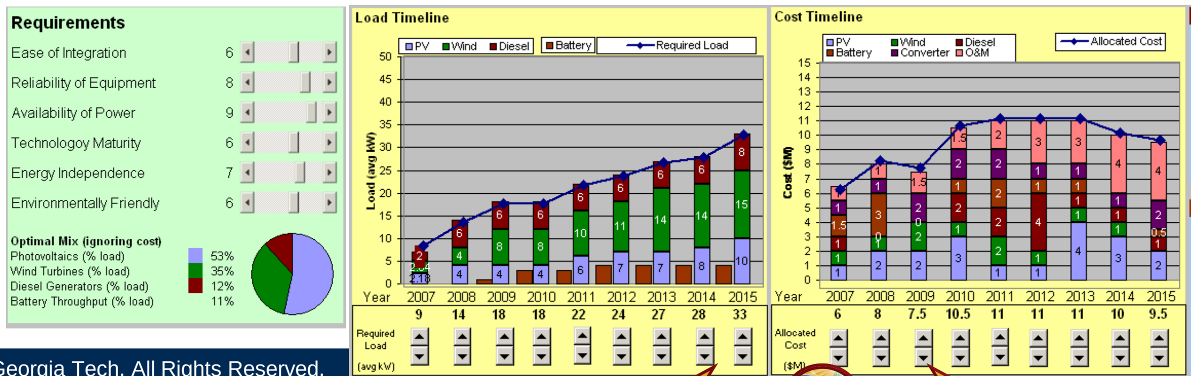
Design-of-Experiment run for Specific Scenario



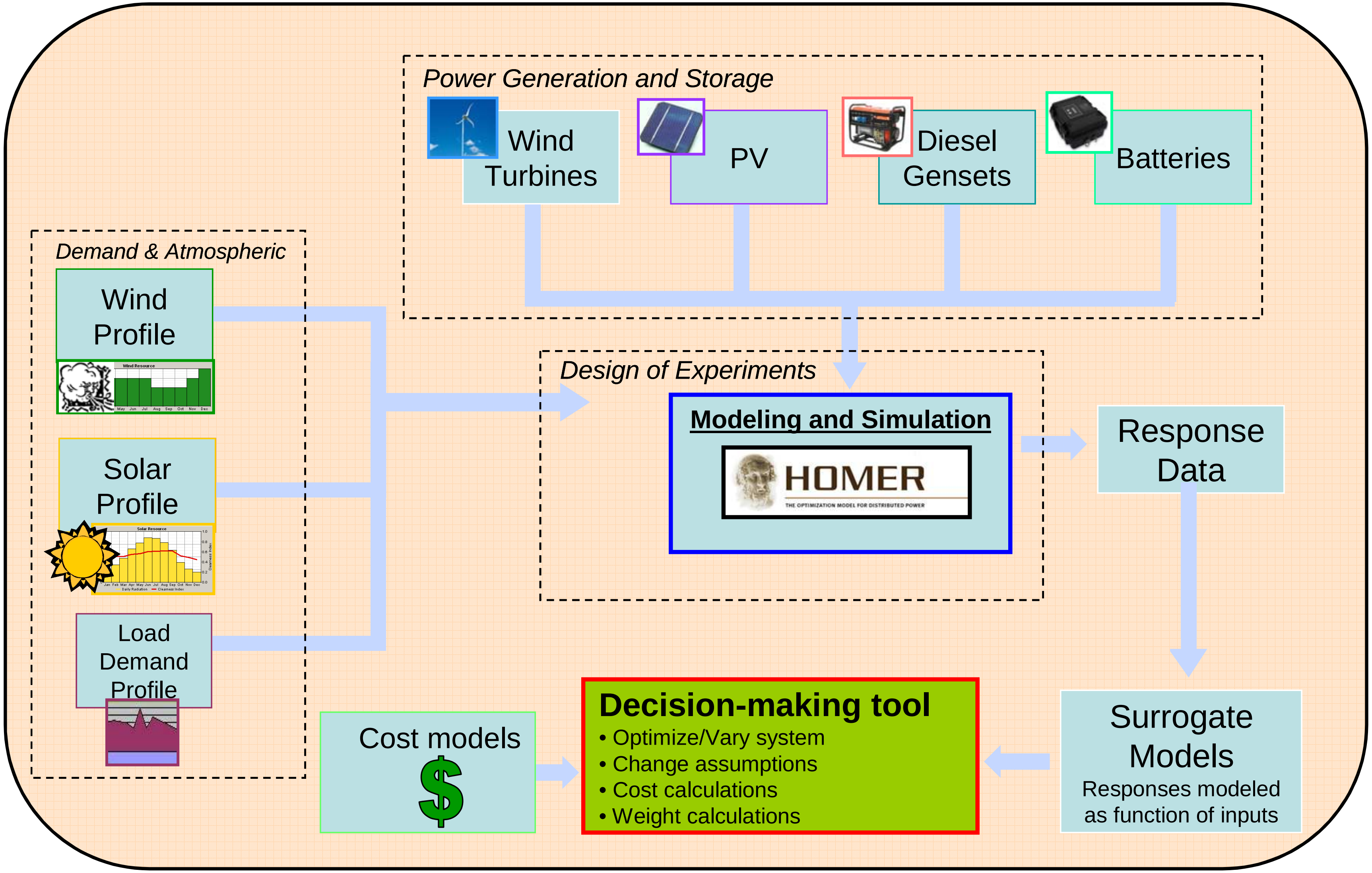
Create Surrogate Models, identify key tradeoffs from "what-if" games



Use quality engineering methods to address socio-economic issues



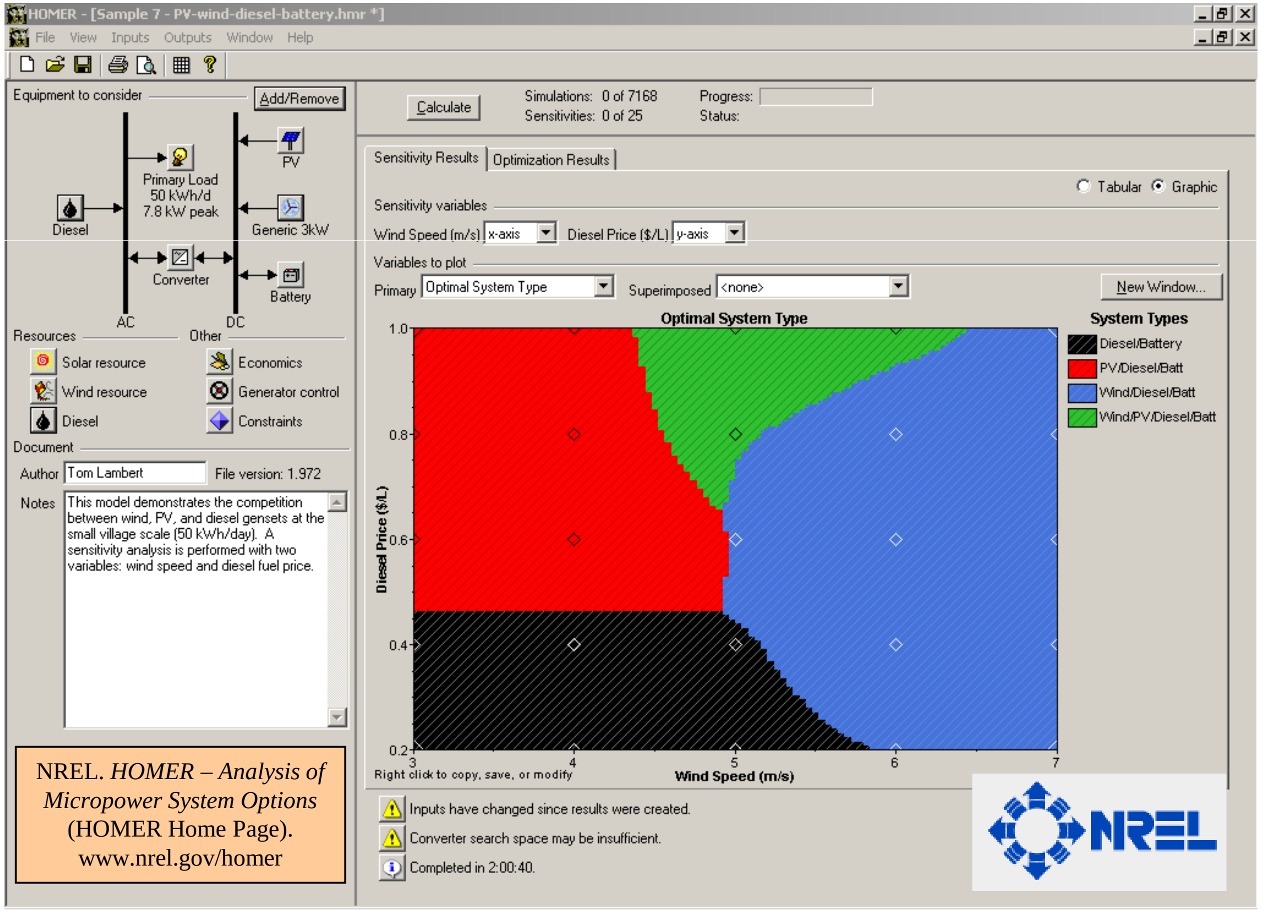
Modeling and Simulation



Modeling and Simulation: HOMER

- A design tool for grid-connected or off-grid power systems developed by and available free through the U.S. Department of Energy's National Renewable Energy Laboratory (NREL)

- Given an array of energy sources (diesel generators, wind turbines, solar, grid, etc) and a load profile, HOMER determines…
  - the lowest-cost energy solution
  - sensitivities to changes in costs and resources



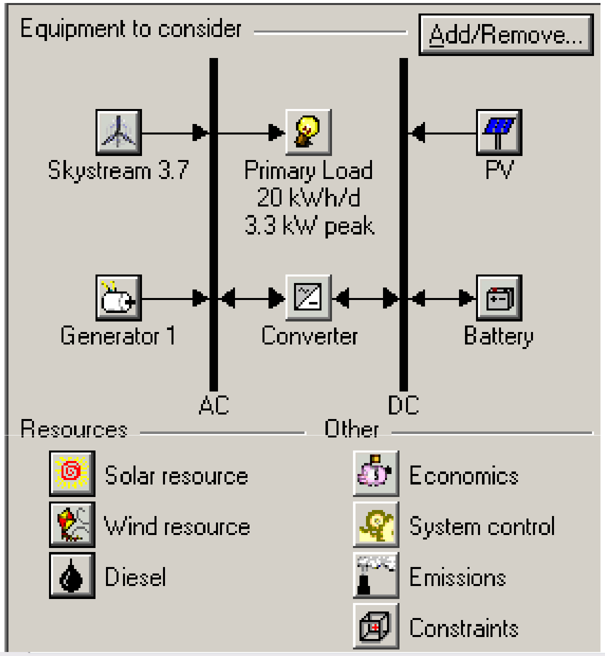
NREL. *HOMER – Analysis of Micropower System Options* (HOMER Home Page). www.nrel.gov/homer

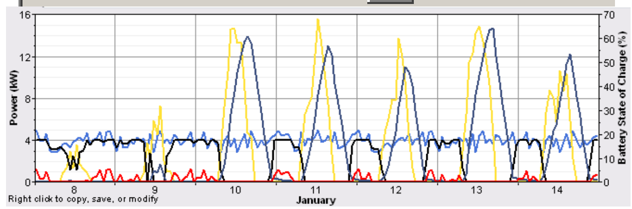
Parametric Models Using HOMER

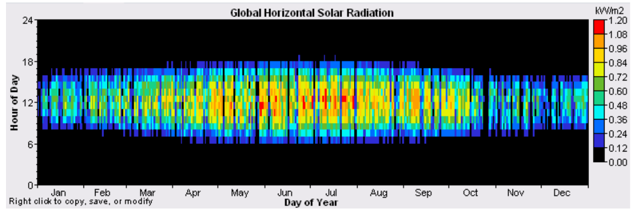
- HOMER used to simulate 12 month scenario analyzed at 1 hour intervals
- Notional scenario created, using a sample desired load profile and representative wind and solar radiation data

Mission: provide best “mix” of energy solutions given a five-year budget profile that meets rural electrification needs

- Create a parametric space of various economic, power load, and pollutant metrics

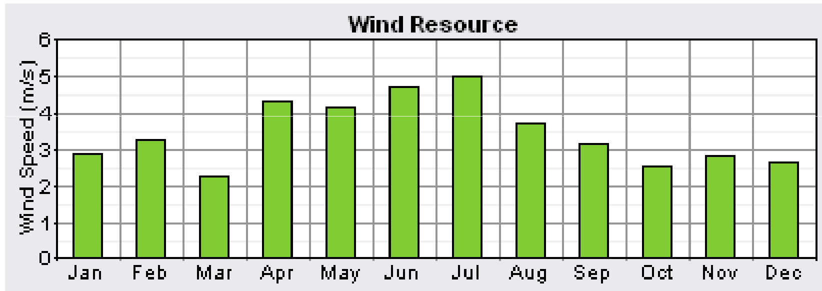


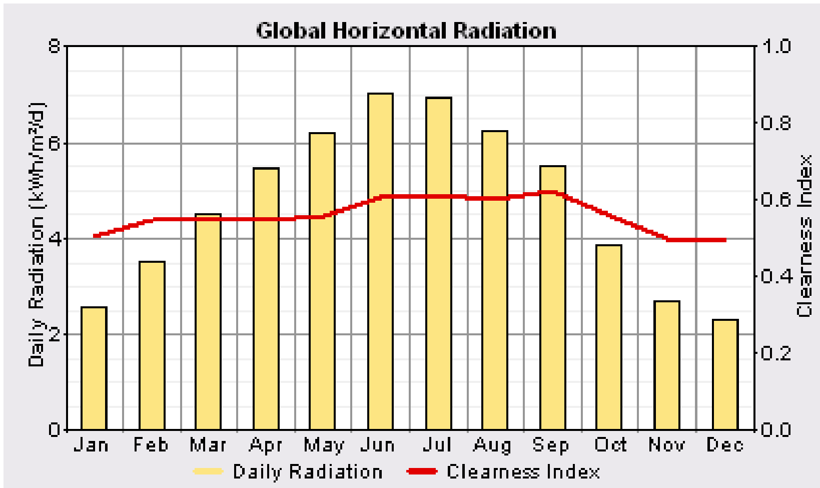




Environmental Conditions

- Wind data was taken from the NOAA
  - Hourly data from the nearest weather station with complete or nearly complete data
  - If the data had significant gaps, it was replaced by synthetic data (built-in HOMER feature)
  - Average speed of the data set was varied to allow for local adjustment
- Solar data was taken from NASA
  - HOMER can automatically import monthly average data from NASA's Surface Solar Energy Data Set
  - HOMER generates synthetic hourly radiation

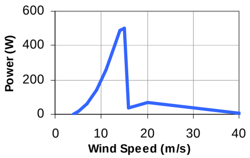




Parametric Models Using HOMER

A photovoltaic (PV) array, with price data based on commercial prices

Wind Turbine: Southwest Windpower Skystream 3.7, entered manually, with approximate price data taken from the manufacturer's datasheet



A 2 kW diesel generator, with a price based on U.S. online distributor prices

Batteries taken from the internal HOMER database and using cost data from an NREL sample case

– (Surrette 4KS25P's)

2kW converter, with cost taken from an NREL sample case

Power Generation & Storage Models

Wind Turbine

Wind Turbines are modeled using a generic power curve

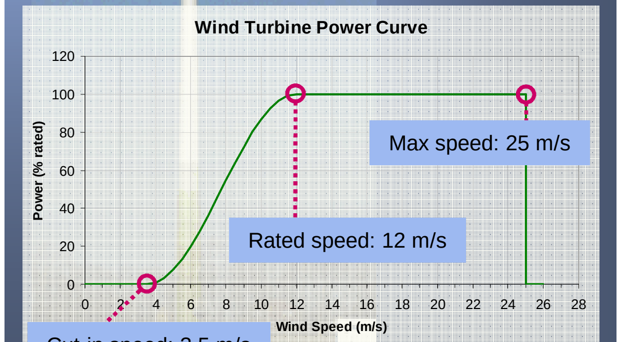
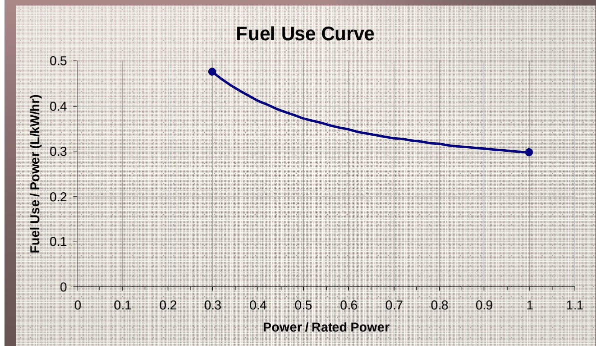


Image Source: Enercon GmBH

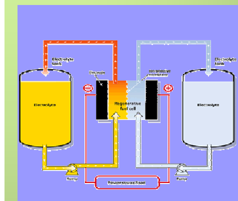
Diesel Generator

Source: tg-marketing.tripod.com

Diesel generators are modeled with a steady-state power/fuel use curve



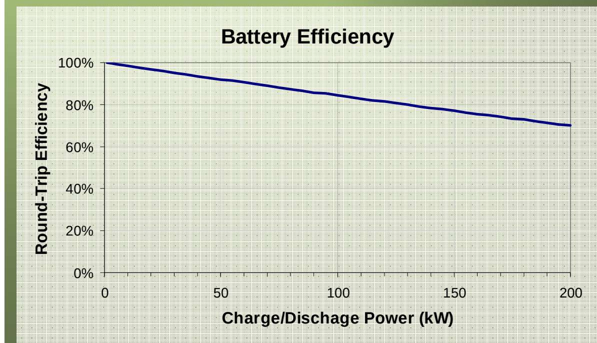
Battery



Source: VRB Power Systems

In a flow battery, capacity and power are independent

Efficiency modeled as a function of charge/discharge rate

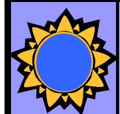


Components are individually modeled

Modeling and Simulation: Inputs and Responses

Inputs

- Sizing of four components
- Two environmental noise variables

	Variable	units	Min	Max
	PV	kW rated	0	18
	Wind Turbines	kW peak	0	18
	Generator	kW rated	0	8
	Batteries	kW*hr cap	0	50
	Mean Solar Insolation	Scaling	0.5	1.5
	Mean Wind Speed	Scaling	0.5	1.5

Responses

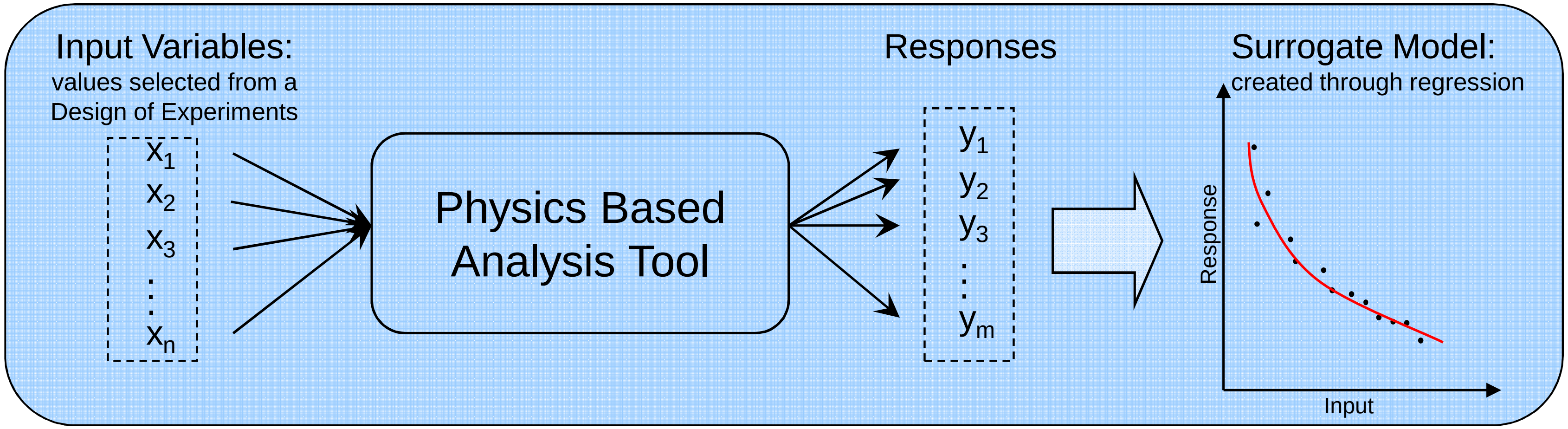
- System performance parameters
- Aggregated by month

	Response	units
	PV Production	kW*hr
	Turbine Production	kW*hr
	Generator Production	kW*hr
	Fuel Used	Liters
	Batt. Throughput	kW*hr
	Batt. Mean State	% SoC
	Unmet Load	kW*hr

Surrogate Models

Surrogate models enable rapid manipulation of any modeling and simulation tools, based on Response Surface Methodology

- Equation based regressions of complex codes
- Negligible loss in accuracy of original tools
- Can be executed in fractions of a second instead of hours or days
- On-the-fly tradeoffs yield results that otherwise may not have been discovered
- Enables decision making across a systems-of-systems hierarchy



Bringing Modeling & Simulation Forward in the Decision Making Process

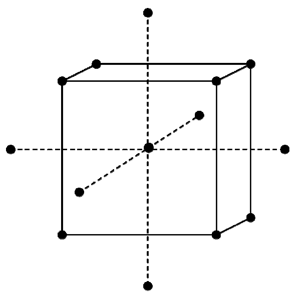
Design of Experiments

- Very complex system models requiring many time consuming computer codes to run drives the need for a structured method for data sampling with the minimum number of simulation runs

> A Design of Experiments (DoE) is a statistical approach to experimental design used to draw meaningful conclusions from data

- A common DoE for creating second order polynomial RSE's with minimum amount of simulation executions is the Central Composite Design (CCD)
  - Combines a two-level fractional factorial with center points (point at which all of the factor values are zero, or midrange) and axial points (points at which all but one factor are zero, and one point is at an outer axial value)

CCD



$$R = b_0 + \sum_{i=1}^{n} b_i x_i + \sum_{i=1}^{n} b_{ii} x_{ii}^2 + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} b_{ij} x_i x_j$$

n = number of factors

b_0 = intercept regression coefficient

b_i = regression coefficients for linear terms

b_{ii} = regression coefficients for pure quadratic terms

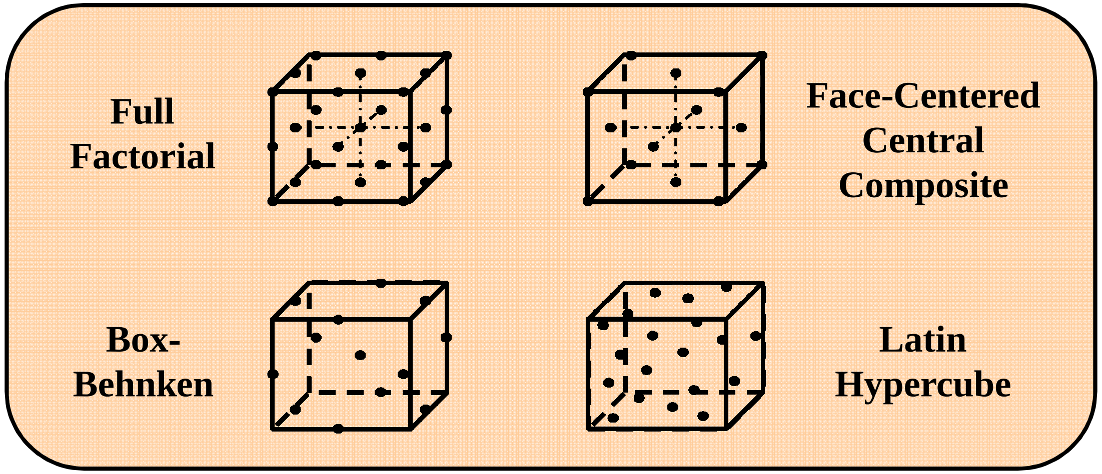
b_{ij} = regression coefficients for cross product terms

x_i, x_j = design variables or factors

Design of Experiments

- The data set used to create the surrogate should
  - Have equal weighting throughout the design space (uncorrelated)
  - Maximize the design range for the number of points considered

- Problems with the structure of the data could cause
  - Skewed functional representation of the data (fits only some regions well)
  - Unexplored regions within the design range, requiring extrapolation

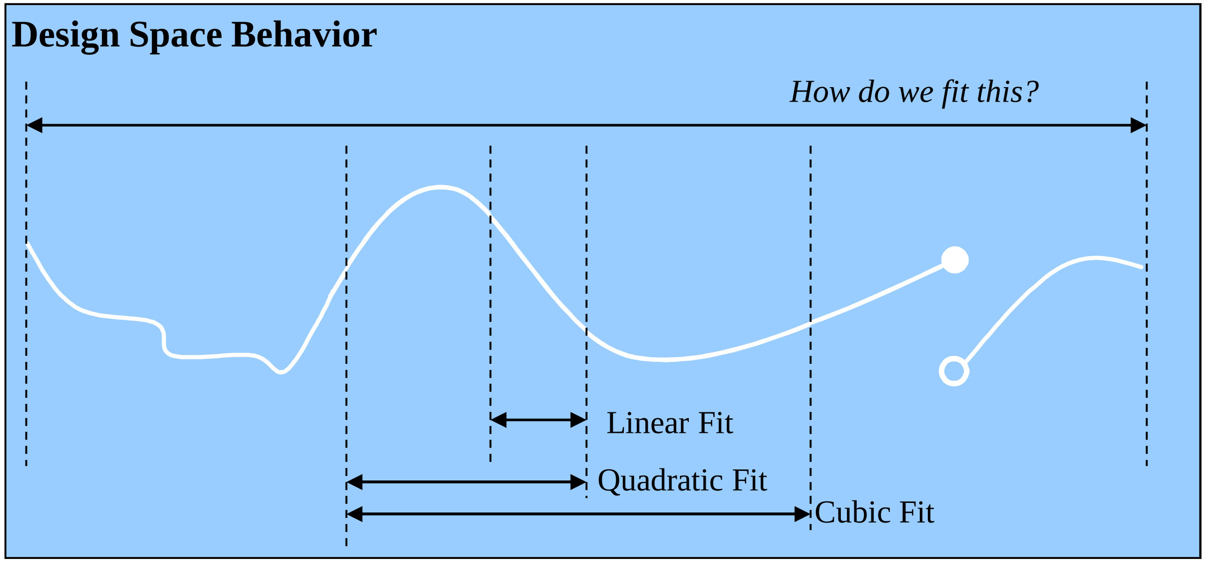


As the number of variables increases, statistical software packages are required to manage the growing complexity

Regression of Complex Design Spaces

- Any regression model must make assumptions as to the behavior of a measured response and accept a certain amount of error
  - i.e. Response "Y" roughly varies linearly with variables X_1 and X_2
  - Polynomial based Response Surface methods are proven

- How does one create regressions in which a behavior assumption is not possible?



Regression Functional Form

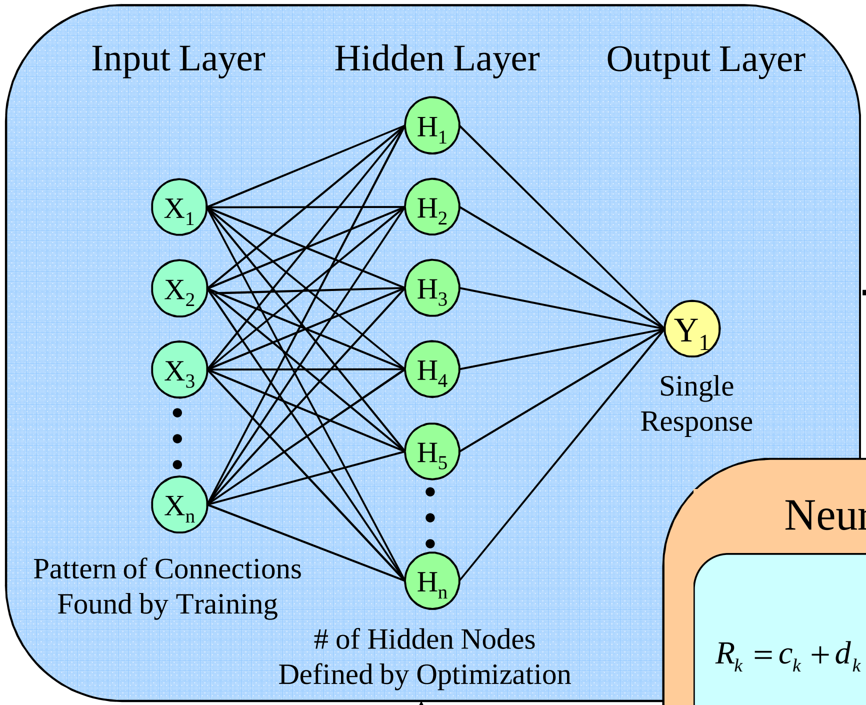
Equation Form	Solve for:
~~$Y = mx+b$~~	~~m, b~~
~~$Y = ax^2+bx+c$~~	~~a, b, c~~
~~$Y = ax^3 + bx^2 + cx + d$~~	~~a, b, c, d~~

Neural Network

Neural Networks are emerging as a useful way of creating highly nonlinear regression models

The Neural Network Surrogate Model

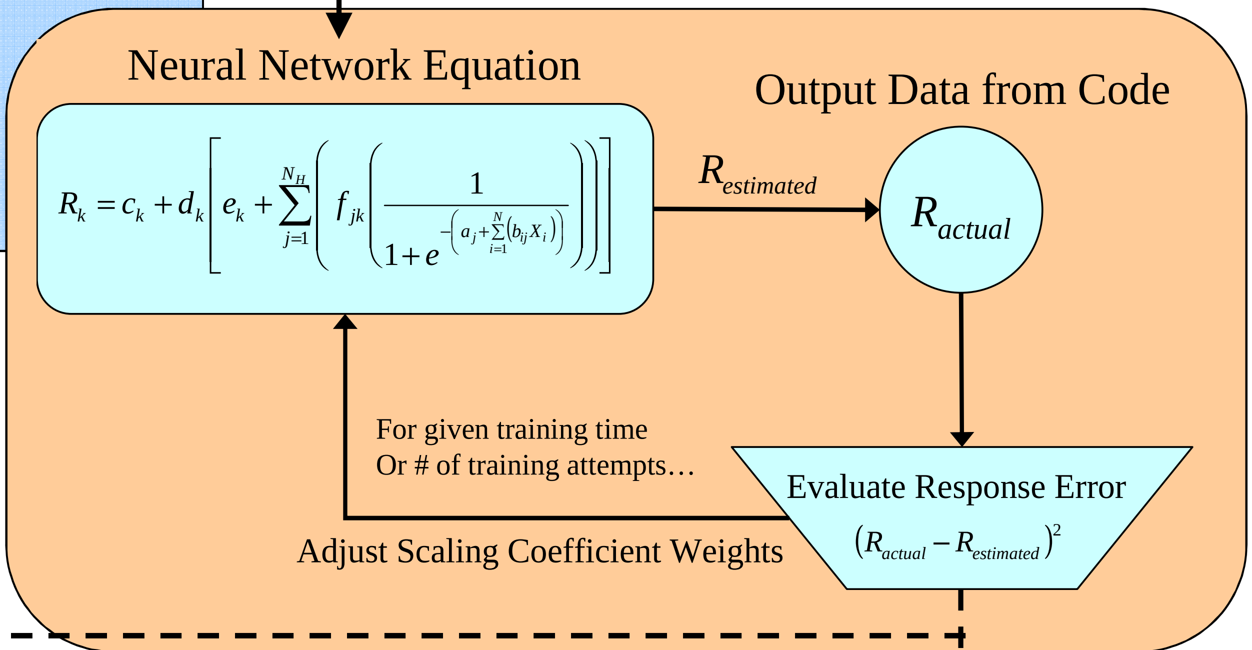
Neural Network Structure



A *Neural Network* is a "computational architecture" based on the design of the interconnections of neurons in our brains"

– The elements of Neural Networks were inspired by biological nervous systems, in which the connections between elements determines the network function

– It is a set of nonlinear equations that predict output variables from a set of given input variables using layers of linear regressions and *S*-shaped logistic functions



$$R_k = c_k + d_k\left[e_k + \sum_{j=1}^{N_H}\left(f_{jk}\left(\frac{1}{1+e^{-\left(a_j+\sum_{i=1}^{N}(b_{ij}X_i)\right)}}\right)\right)\right]$$

$$\left(R_{actual} - R_{estimated}\right)^2$$

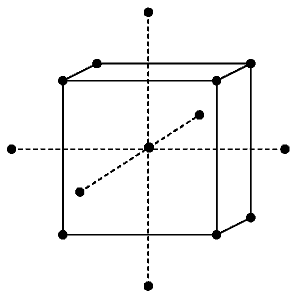
The Neural Network Surrogate Model

- Unlike the approach used to define the cases needed to run to capture the design space using polynomial RSE's, there is no formal approach for defining the DoE to obtain Neural Network regressions
  - Space-filling design needed to define the multimodal space
  - Latin Hypercube Sample method is configured to uniformly spread design points to the maximum distance possible from each other (within variable limits), with a constraint that involves maintaining the even spacing between factor levels and minimizing the correlation in the design (source: The SAS Institute, JMP Software)

A DoE that accurately represents a complex design space requires representing the corners of the space with a CCD and an LHS to fill the space in between

=

Central Composite Design (CCD)



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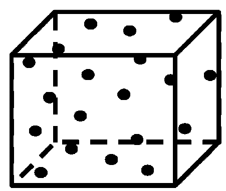
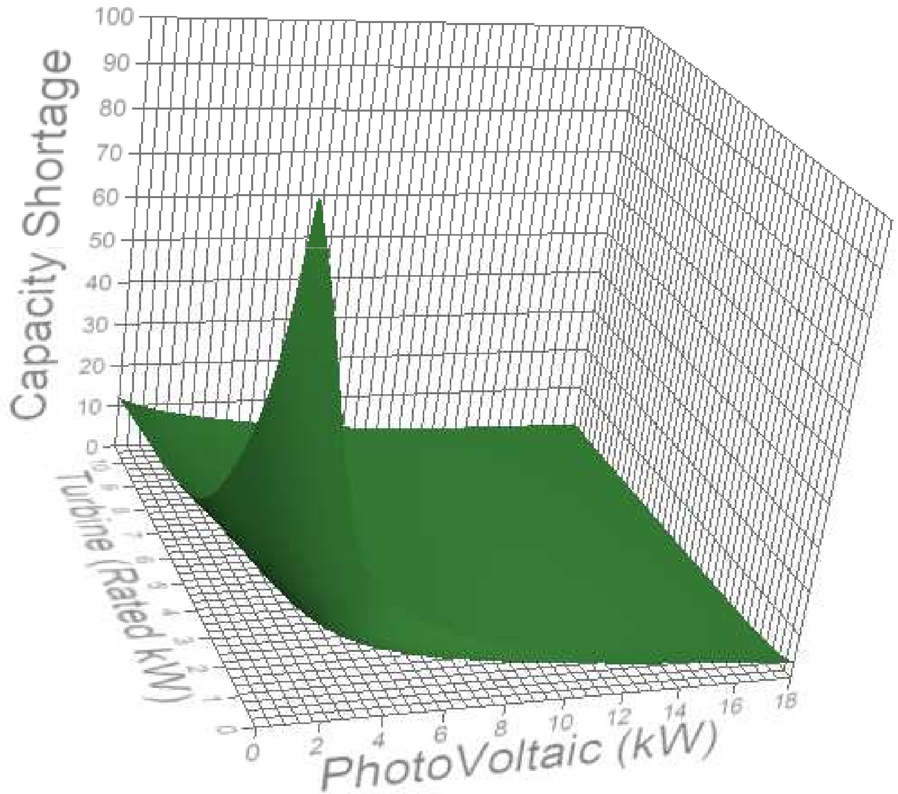
Latin Hypercube Sample (LHS)



Parametric Hybrid Energy Systems Models

Using Neural Network Surrogate Models



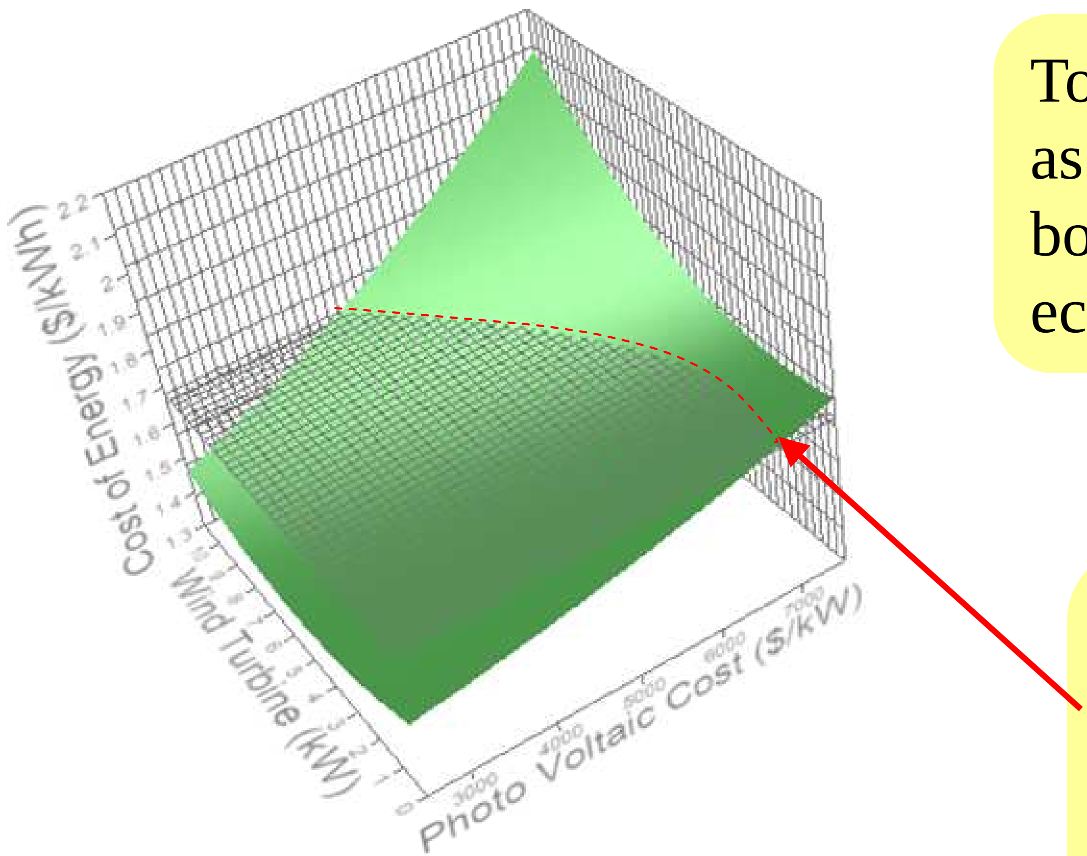
User Input

Wind (avg)	3.4
Sun (kW*hr/m2/d)	2.6
PhotoVoltaic (kW)	-
Wind Turbine (rated kW)	-
Battery Capacity (kW)	50
Generator (kW)	1.1

Power requirements available as dynamic tradeoff across each of the energy source capabilities

Parametric Hybrid Energy Systems Models

Using Neural Network Surrogate Models

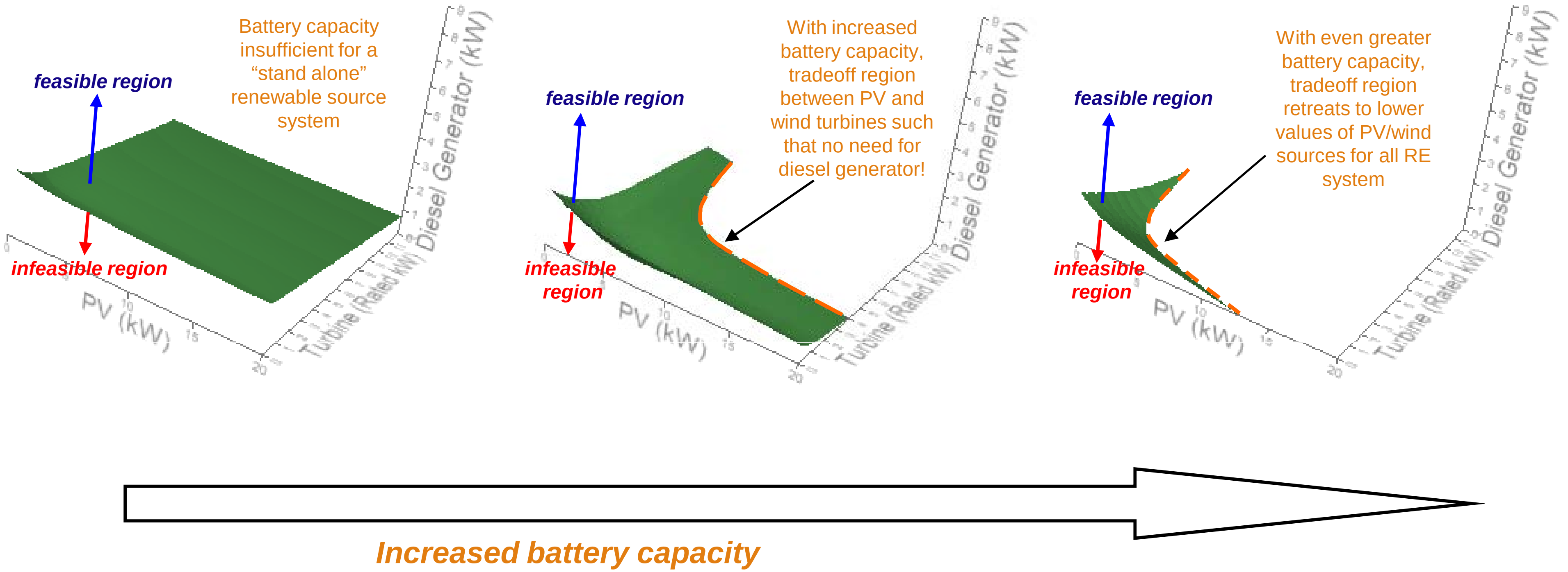


Total cost of energy available as dynamic tradeoff between both power output and economic factors

Shows how cost of one type of source limits load requirements of individual energy system performance

Parametric Hybrid Energy Systems Models

Using Neural Network Surrogate Models



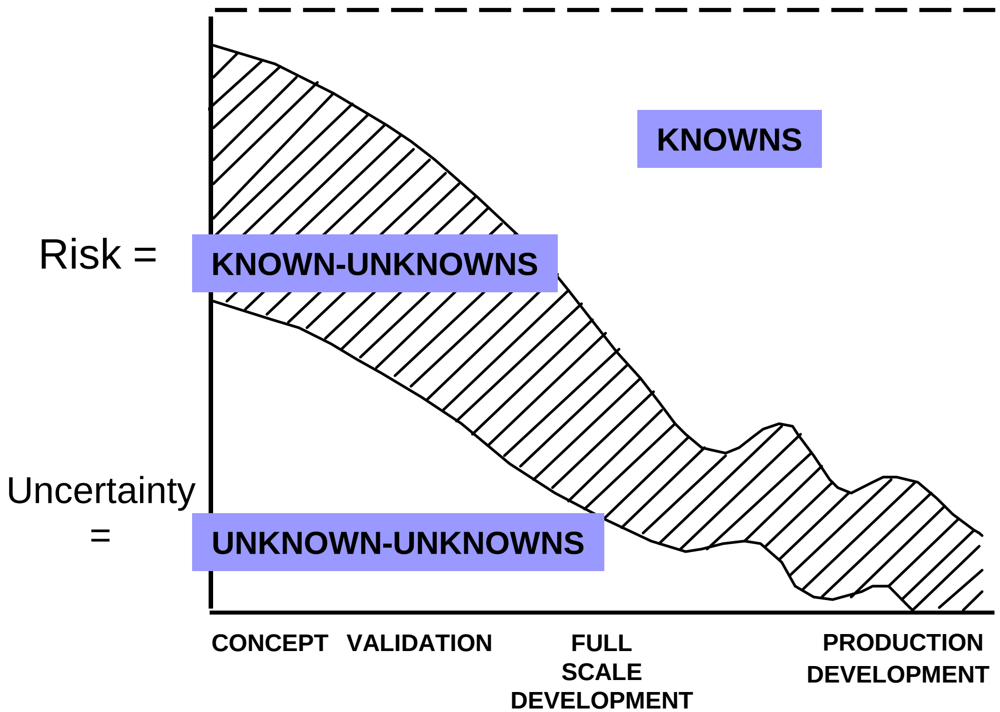
Dynamically increasing battery storage capacity shows power availability with decreased reliance on diesel generation

Enabling Collaborative Decision Making through Applied Systems Engineering Tools, Methods, and Processes

Robust Design Simulation

Informing decision making through integration with complex engineering analysis

Risk & Uncertainty are Greatest Early On

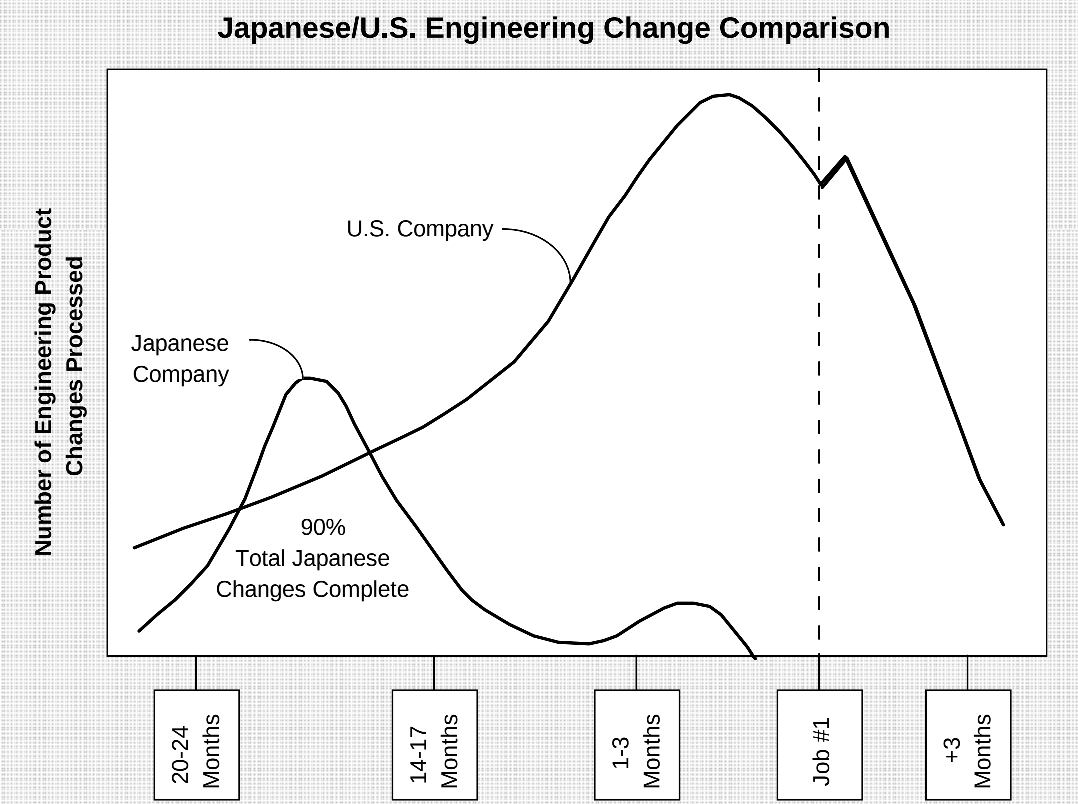


As we know,
There are ***known knowns***.
There are things we know we know.
We also know
There are ***known unknowns***.
That is to say
We know there are some things
We do not know.
But there are also ***unknown unknowns***,
The ones we don't know
We don't know.

—Donald Rumsfeld
Feb. 12, 2002
Department of Defense news briefing

Managing Life Cycle Uncertainty

The need for ***quality***—the ability to meet requirements consistently—demands that systems-level analyses be moved forward into earlier stages of the design timeline



Japanese Auto Industry Made Changes Earlier Than U.S. Auto Industry
(MIT Lean Study)

Early Decisions Impact *Quality*

I. Decisions made in the design process cost very little in terms of the overall product cost but have a major effect on the cost of the product

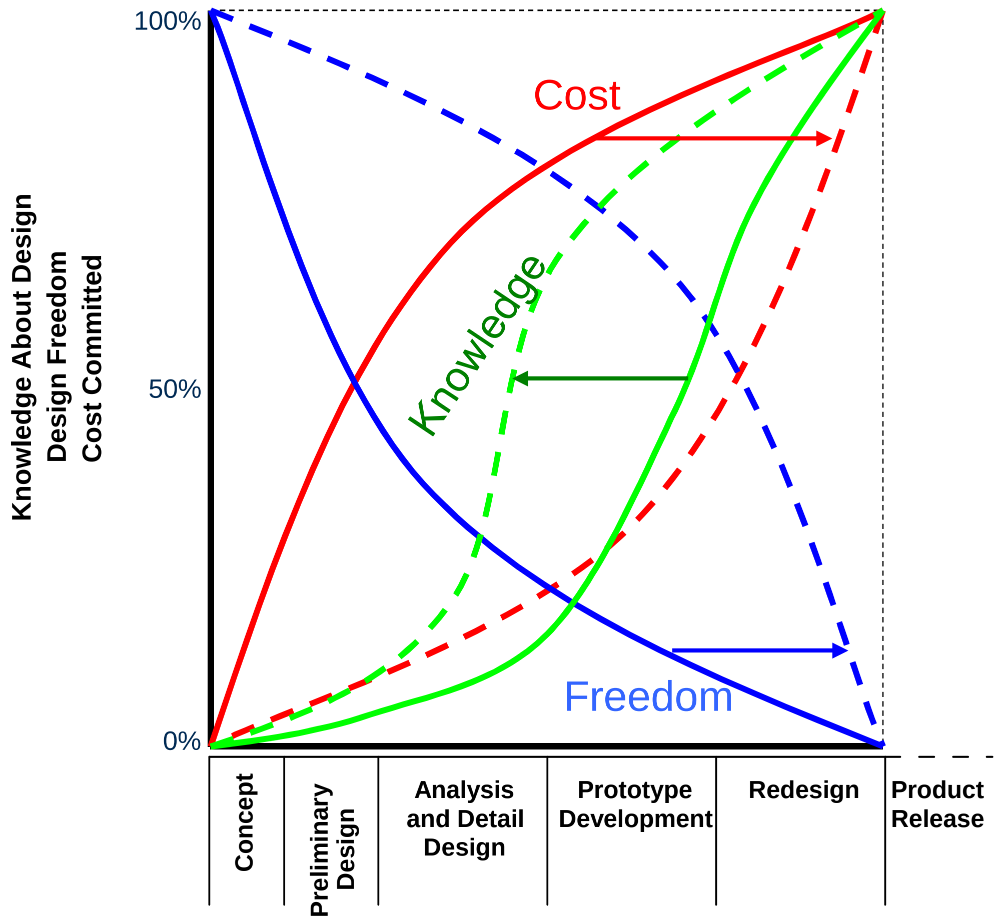
II. Quality cannot be built into a product unless it is designed into it

III. The design process should be conducted so as to develop quality cost-competitive products in the shortest time possible

True quality must be *designed* into the product such that it will not have to be redesigned after it goes into the market

Source: Dieter, G. E., Engineering Design: A Materials and Processing Approach. McGraw Hill, 2000.

Design Process Paradigm Shift



- A ***paradigm shift*** is underway that attempts to change the way complex systems are being designed
- Emphasis has shifted from ***point design for performance*** to ***design for affordability***, where affordability is defined as the ratio of system effectiveness to system cost +profit
- System ***Cost - Performance Tradeoffs*** must be accommodated early
- ***Downstream knowledge*** must be brought back to the early phases of design for ***system level tradeoffs***
- The design Freedom curve must be *kept open* until ***knowledgeable tradeoffs*** can be made – requires a probabilistic family solution approach

Graphic Source: Research Opportunities in Engineering Design, NSF Strategic Planning Workshop Final Report, 1996

Integrated Product/Process Development

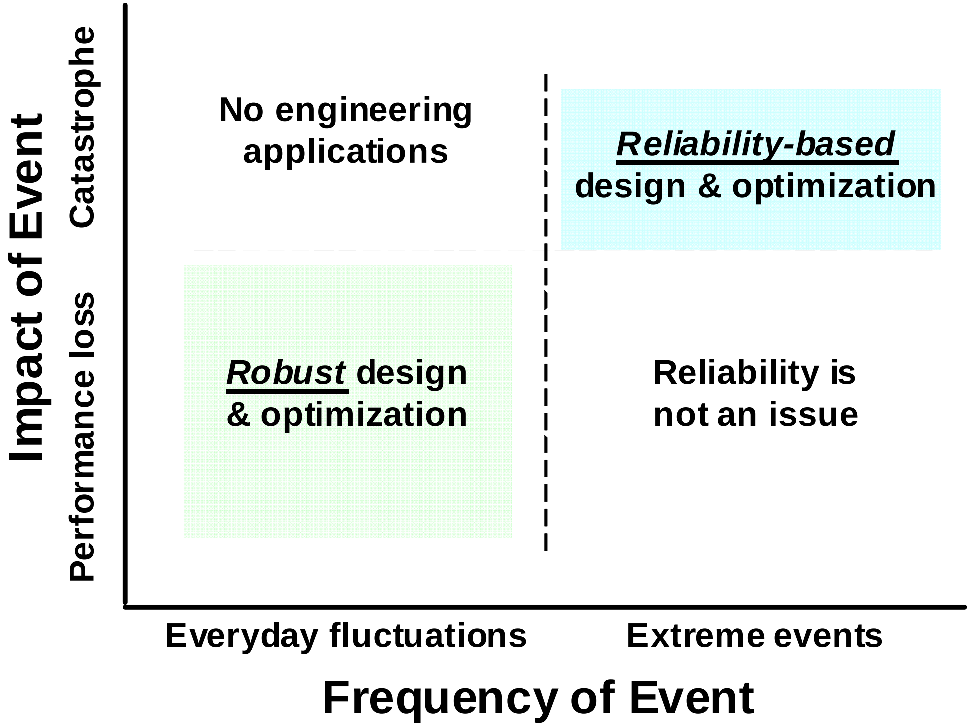
- ***Integrated Product/Process Development (IPPD)*** means applying Concurrent Engineering at the front end of a system's life cycle where design freedom can be leveraged and product/process design tradeoffs conducted in parallel at the system, component, and part levels

- Implementation of IPPD drives the need to ***move from a deterministic point design approach to a probabilistic family design approach*** to keep the design space open and from committing life cycle cost before the system life cycle design trade-offs can be made

Source: Prof. Daniel Schrage, Georgia Tech School of Aerospace Engineering

Uncertainty Based Design Domains

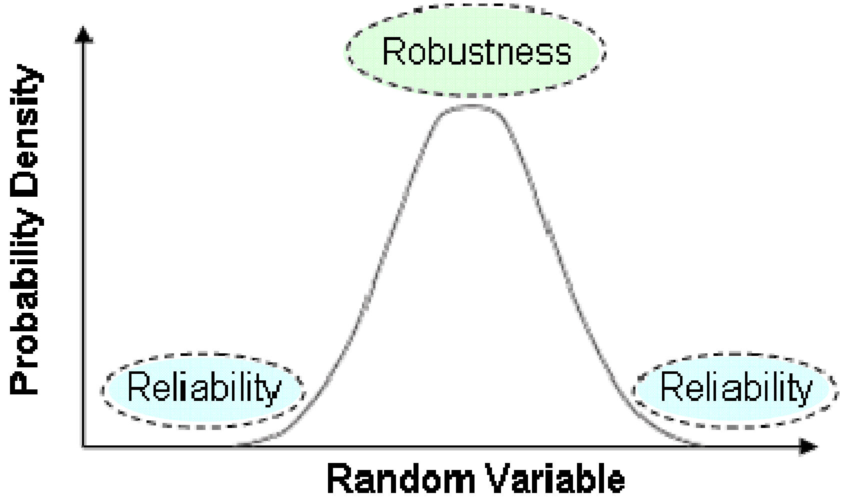
- *Uncertainty-based designs* are design problems that have a nondeterministic formulation
- Do not confuse the *frequency* of an event with the resulting *impact* or severity of that event



Graphic modified from: Zang, T. A., et al., "Needs and Opportunities for Uncertainty-Based Multidisciplinary Design Methods for Aerospace Vehicles," Tech. Rep. TM-2002-211462, NASA Langley Research Center, Hampton, VA, 2002.

Reliability vs. Robust Design

- A *robust design* problem seeks a design relatively insensitive to small changes in uncertain quantities
- A *reliability-based design* seeks one in which the probability of failure is less than a predetermined acceptable value



Graphic modified from: Zang, T. A., et al., “Needs and Opportunities for Uncertainty-Based Multidisciplinary Design Methods for Aerospace Vehicles,” Tech. Rep. TM-2002-211462, NASA Langley Research Center, Hampton, VA, 2002.

IPPD Through Robust Design Simulation

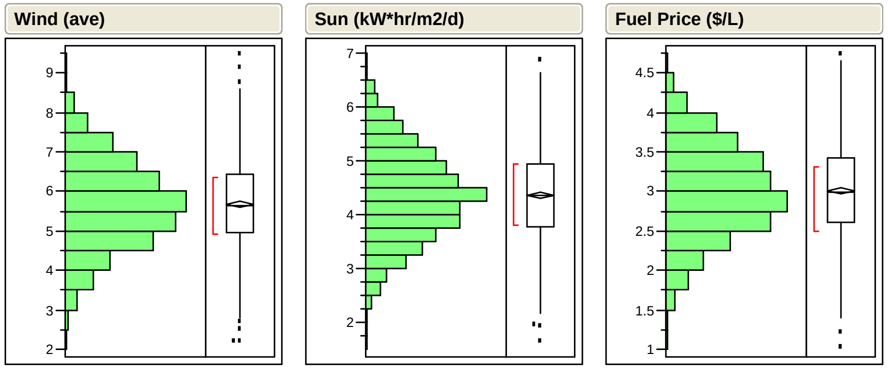
- ***Robust Design Simulation (RDS)*** provides the necessary simulation and modeling environment for executing IPPD at the ***System level***

- Continuation of RDS along the system life cycle implies the creation of a ***Virtual Stochastic Life Cycle Design Environment***

Source: Prof. Daniel Schrage, Georgia Tech School of Aerospace Engineering

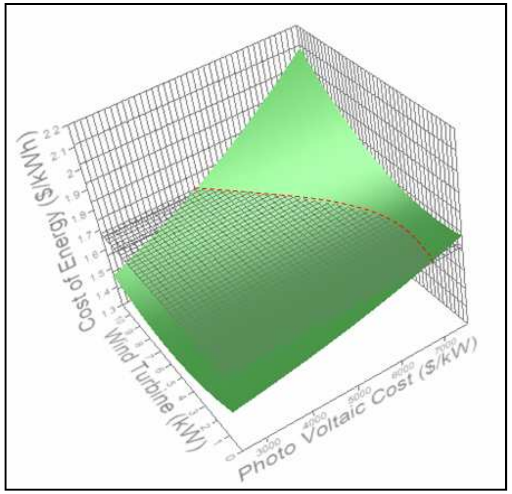
Managing Risk from Renewable Energy Sources

Uncertainty distributions around natural elements and fuel price…



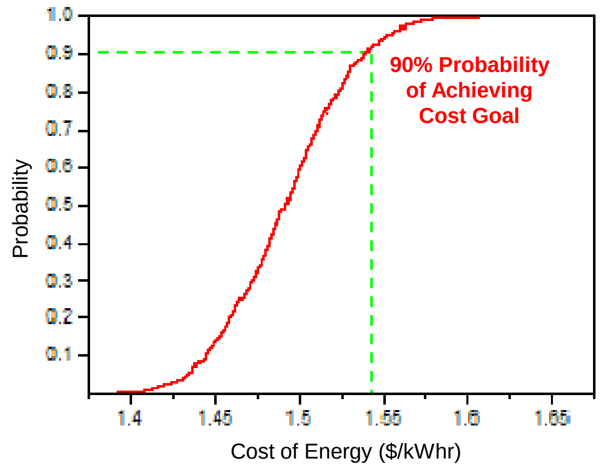
Enabling the answer to the question:
"How do changes in available sun and wind sources, as well as uncertain fuel prices ultimately affect total Cost of Energy?"

…call upon surrogate models thousands of times in a matter of seconds…



…which gives a distribution of any measure of merit

Quantifiable Uncertainty of Achieving Any Goal



Enabling Collaborative Decision Making
through Applied Systems Engineering
Tools, Methods, and Processes

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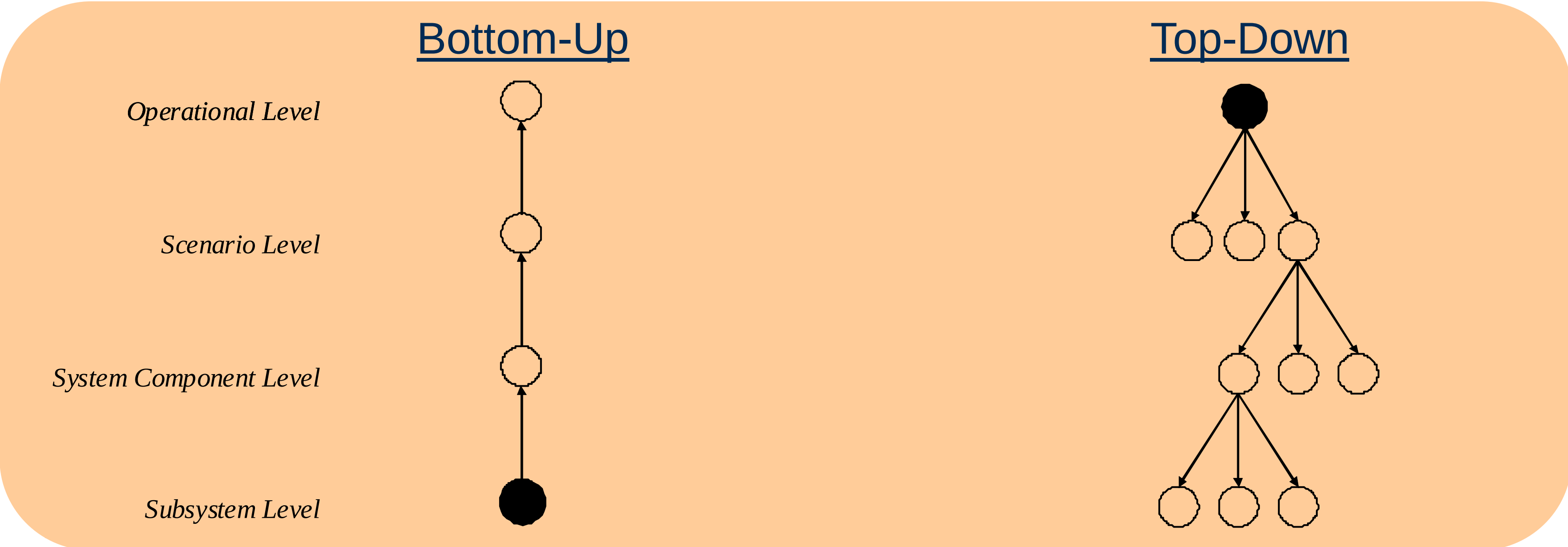
Top-Down Design

Inverse design enabled through filtered Monte Carlo

Bottom-up Single Design Point vs. Top-down Multiple Design Points

- For bottom-up design, selections are made at the lowest level, which define the capability at the next highest level
  - Results in one design point flowing up the hierarchy
  - An optimizer could be used to search the design space at each level (one level at a time) for options that do not violate constraints, and minimize/maximize a response

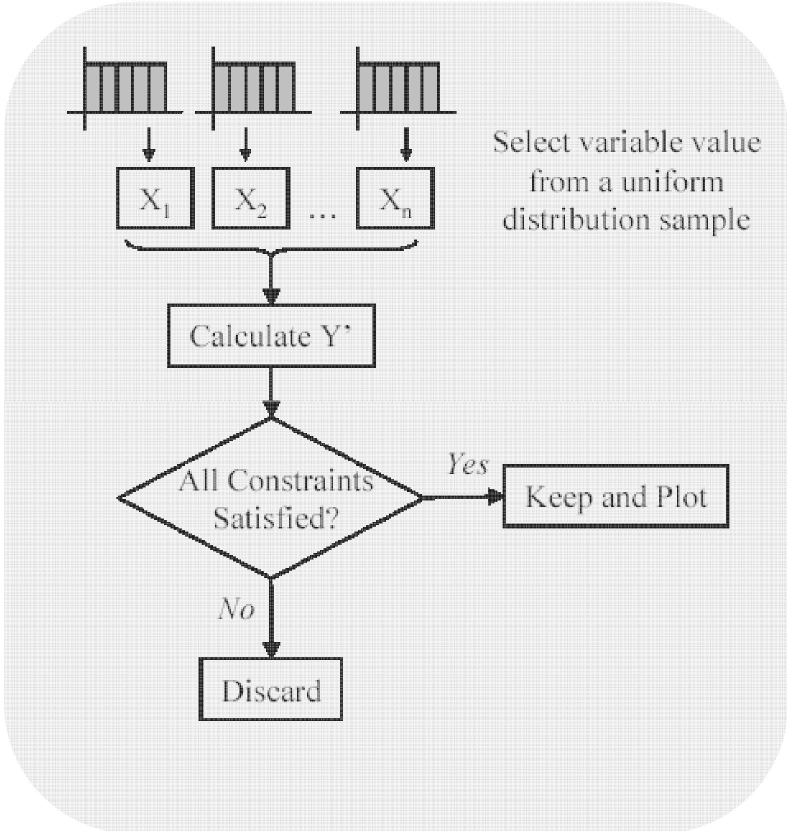
- The top-down design approach will yield multiple combinations of variable values that meet constraints at higher levels
  - Monte Carlo simulation employing rapid surrogate models to fill the design space
  - Multivariate scatter plot can be used to visualize the design space between any combination of variable/variable, variable/response, response/response



Enabling Top-Down Design: The Filtered Monte Carlo Method

- Design space is populated with response values obtained by running a simulation many times with randomly selected values from bounded distributions on input variables

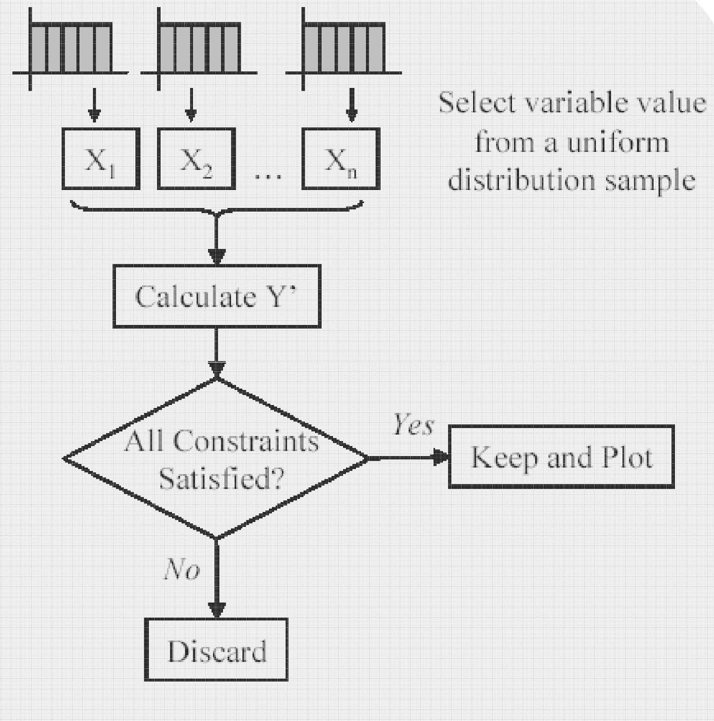
- If the output for a particular Monte Carlo simulation trial *violates* the constraints defined a priori, it is *discarded*



Source: Kuhne, C., Wiggs, G., Beeson, D., Madelone, J., and Gardner, M., "Using Monte Carlo Simulation for Probabilistic Design," Proceedings of the 2005 Crystal Ball User Conference, 2005.

Enabling Top-Down Design: The Filtered Monte Carlo Method

- The responses that do not violate the constraints are then plotted on a scatter plot versus any of the inputs
  - Gives user the ability to sensitivity of responses to those inputs
  - Khune et al. note the biggest challenge to this approach is with problems with large numbers of inputs and responses (greater than 10)

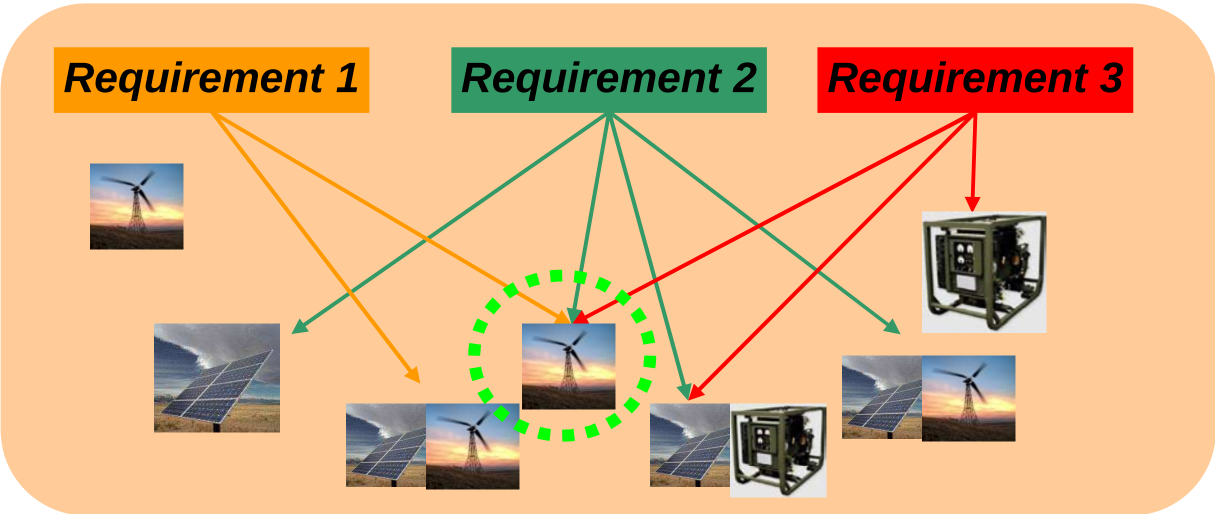


[Kuhne et al.,2005]

Drives the need for improved visualization and data mining tools that would enable the user to explore multiple response/variable design space while conducting input variation sensitivity

Requirements Analysis through Inverse Design

- Up to this point, the ability to *rapidly generate point solutions* has been addressed
  – Using surrogate models, we can generate point solutions very quickly
- We can use probabilistic techniques to generate *thousands* of point solutions across the entire design space
  – Monte Carlo simulation used to generate “clouds” of solutions at the capability level
  – System solutions are non-unique
- **Inverse Design:** Generate data using *bottom-up* tools but analyze with a *top-down* view…any response can be treated as an independent variable



Enabling Collaborative Decision Making through Applied Systems Engineering Tools, Methods, and Processes

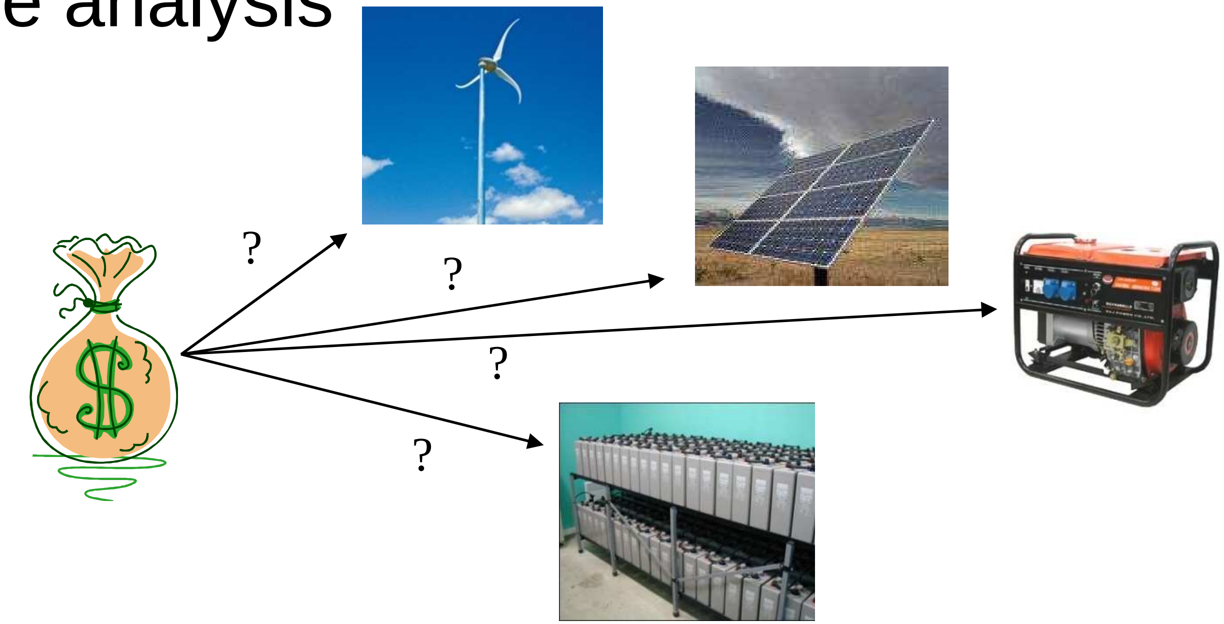
Collaborative Decision Making

Tying it all together with an energy systems example

Portfolio Management of Hybrid Renewable Energy Sources

- Similar methods can be applied to provide guidance for *energy systems portfolio investment* over time

- Inclusion of qualitative systems engineering methods to capture socio-economical impacts, which in turn drive quantitative analysis

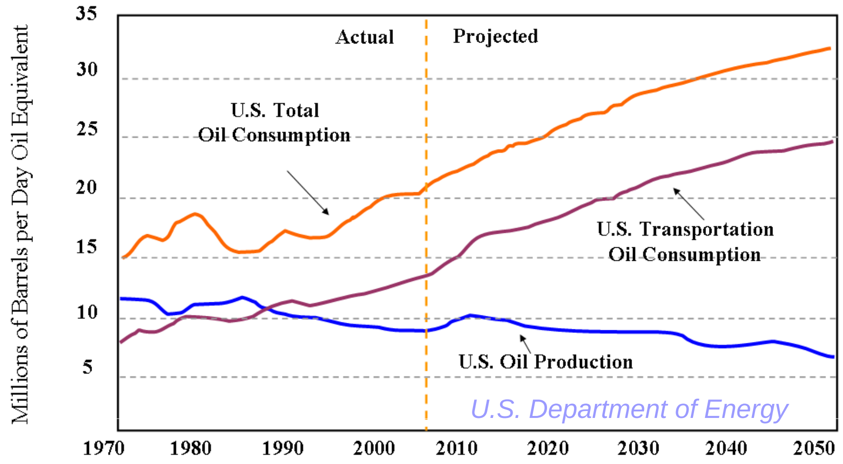


Motivation

The Problem

Cost of doing business in the energy market will increase with rising energy prices and other taxations

- The lead time required to design, fabricate, and site a power source drives people to make far-reaching decisions with incomplete data
- Competitive advantage lies with those that adopt a forward-thinking strategy:
  facing uncertainty brings knowledge forward in the design process



Stakeholders

Developing governments are increasingly in need of such an advisory development tool given that

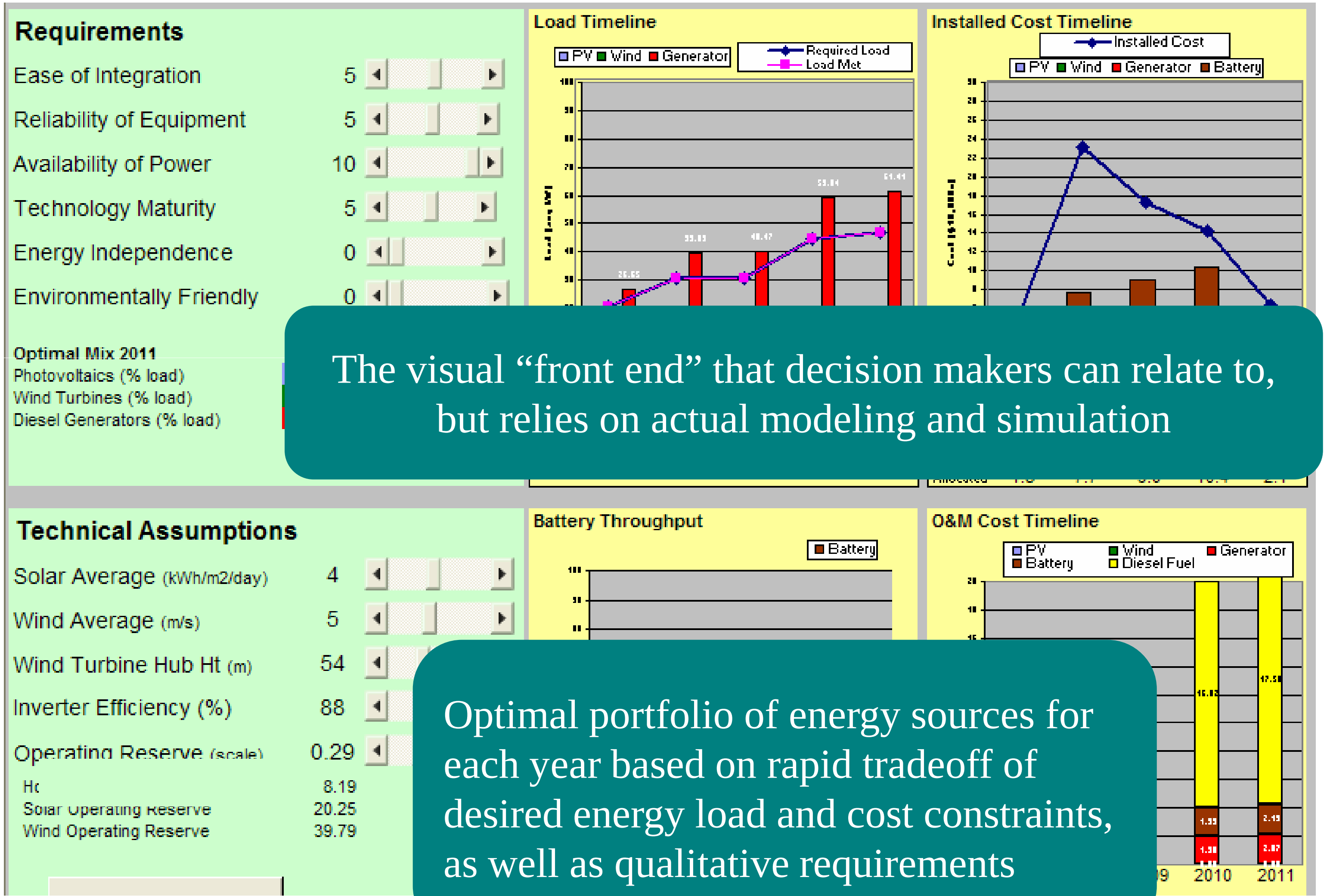
- In a manner similar to the "leapfrogging" of conventional telephone wire systems for mobile/cellular telephones; dispersed, rural societies would more readily accommodate distributed RE rather than centralized fossil-based scenarios
- The ability to approach a ***self-sustainable energy scenario bodes well from a political-economic perspective***

Traditional approaches for energy systems portfolio planning do not consider:

- …complex interactions of ***social, economical, environmental factors in addition to the technical***
- …the non-deterministic nature of energy modeling has defined its current limits

Hybrid renewable energy portfolio management

Integrating socioeconomic factors with modeling & simulation



The visual "front end" that decision makers can relate to, but relies on actual modeling and simulation

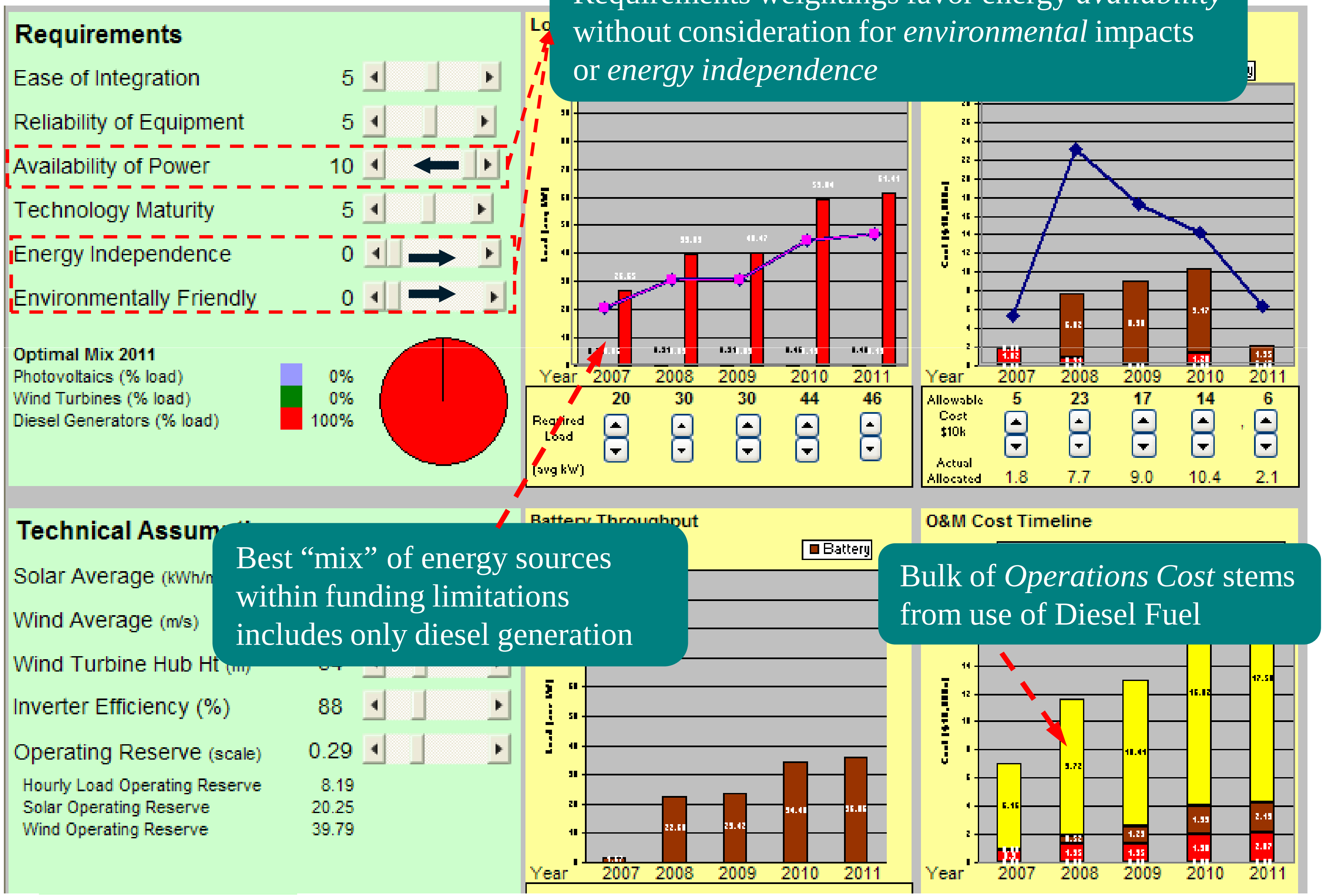
Optimal portfolio of energy sources for each year based on rapid tradeoff of desired energy load and cost constraints, as well as qualitative requirements

Hybrid renewable energy portfolio management

Integrating socioeconomic factors with modeling & simulation

Georgia Institute of Technology

Requirements weightings favor energy *availability* without consideration for *environmental* impacts or *energy independence*



Best "mix" of energy sources within funding limitations includes only diesel generation

Bulk of *Operations Cost* stems from use of Diesel Fuel

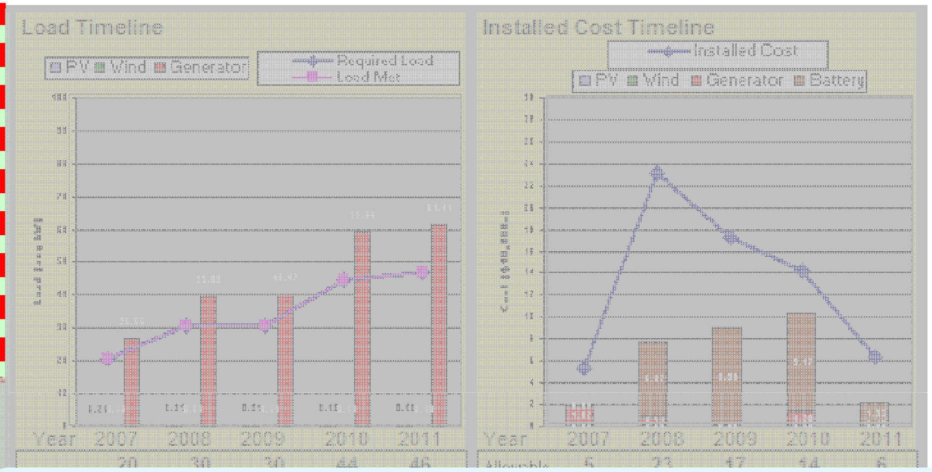
Hybrid renewable energy portfolio management

Integrating socioeconomic factors with modeling & simulation

Georgia Institute of Technology

Requirements

Ease of Integration	5
Reliability of Equipment	5
Availability of Power	10
Technology Maturity	5
Energy Independence	0
Environmentally Friendly	0



Customer Requirements are translated to Engineering metrics through *Quality Function Deployment*

M&S Environment evaluates *thousands* of energy portfolios very quickly through the use of *surrogate models*

Multi-Attribute Decision Making score attributed to each portfolio options

Hybrid Energy System Portfolios Analyzed

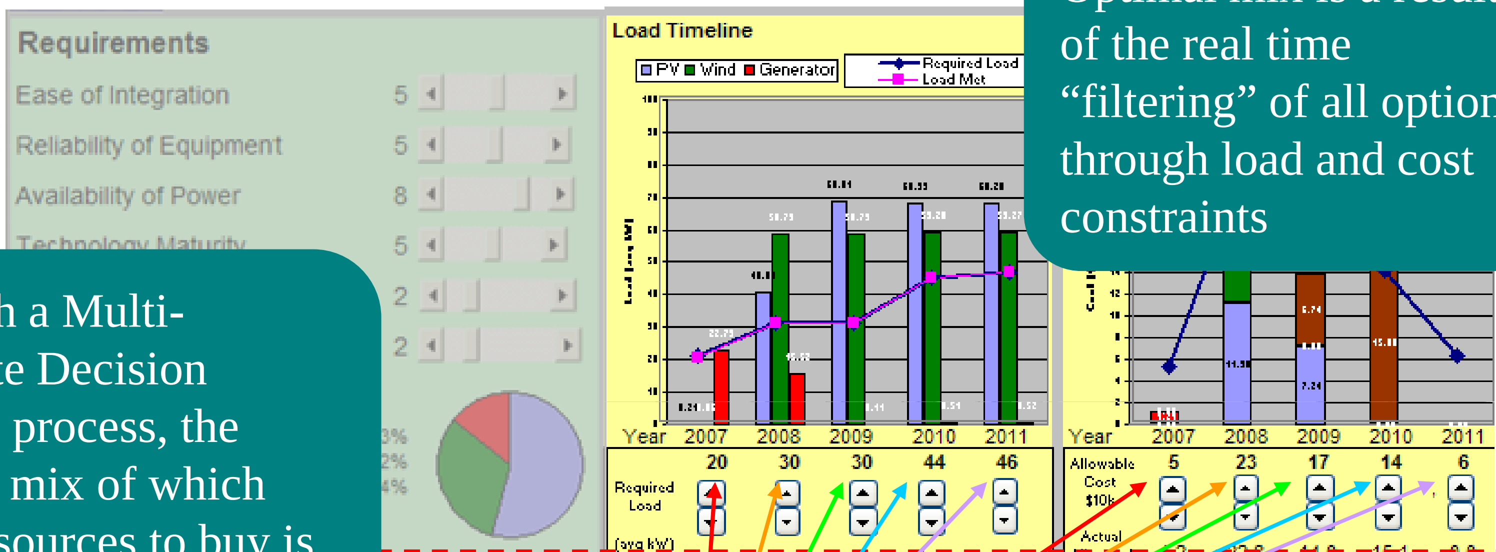
Quantitative M&S Metrics	weighting	Portfolio Mix 1	Portfolio Mix 2	Portfolio Mix 3	Portfolio Mix 4	……	Portfolio Mix n-1	Portfolio Mix n
Capacity Shortage	0.288	1%	5%	22%	46%		0%	3%
Renewable Fraction	0.115	0.37	0.66	0.78	0.41		0.02	0.44
Diesel Fuel Used (L)	0.147	205	67	10	0		74	22
Production wind	0.003	2051	3541	984	111		231	656
Production Solar	0.135	564	234	0	3978		789	123
Production generator	0.163	6521	0	187	621		3654	465
Battery Throughput	0.147	967	1231	1621	0		745	593
TOPSIS Score		0.654	0.674	0.231	0.221		0.324	0.474
Solution Set Rank		2	1	5	6		4	3

Hybrid renewable energy portfolio management

Integrating socioeconomic factors with modeling & simulation

Optimal mix is a result of the real time "filtering" of all options through load and cost constraints

Through a Multi-Attribute Decision Making process, the optimal mix of which energy sources to buy is shown for each year



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Hybrid renewable energy portfolio management

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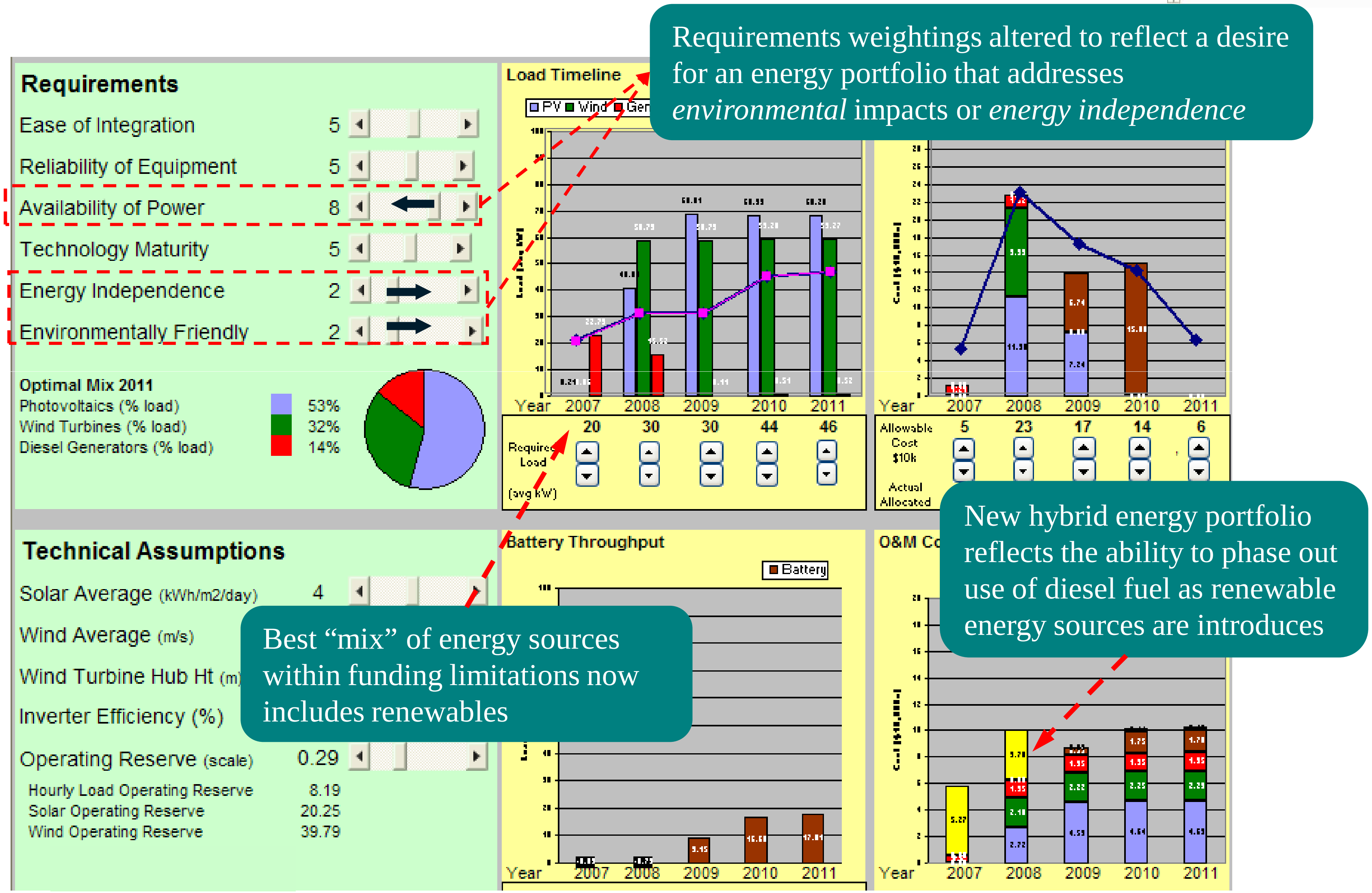

Enabling Collaborative Decision Making through Applied Systems Engineering Tools, Methods, and Processes

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Conclusion and Summary

Summary

- Systems Engineering process introduced that enables ***real-time decision making*** through rapid modeling and simulation

- Elements of QFD, MADM, surrogate modeling, and robust design enable qualitative decision-making based on quantitative tools

- A collection of methods introduced that aid decision makers with ***robust planning and implementation*** of effective renewable energy solutions

Objectives (Revisited)

- ✓ Show how complex, quantitative engineering level analysis is brought into and informs decision making
- ✓ Show how to best capture customer requirements such that engineering analysis is properly directed
- ✓ Introduce methods for decision making when dealing with multiple and competing objectives
- ✓ Provide practical examples along the way, not just hand-wave and talk in the hypothetical

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Thank You

Enabling Collaborative Decision Making
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