Architecting & Designing Air Transportation Systems

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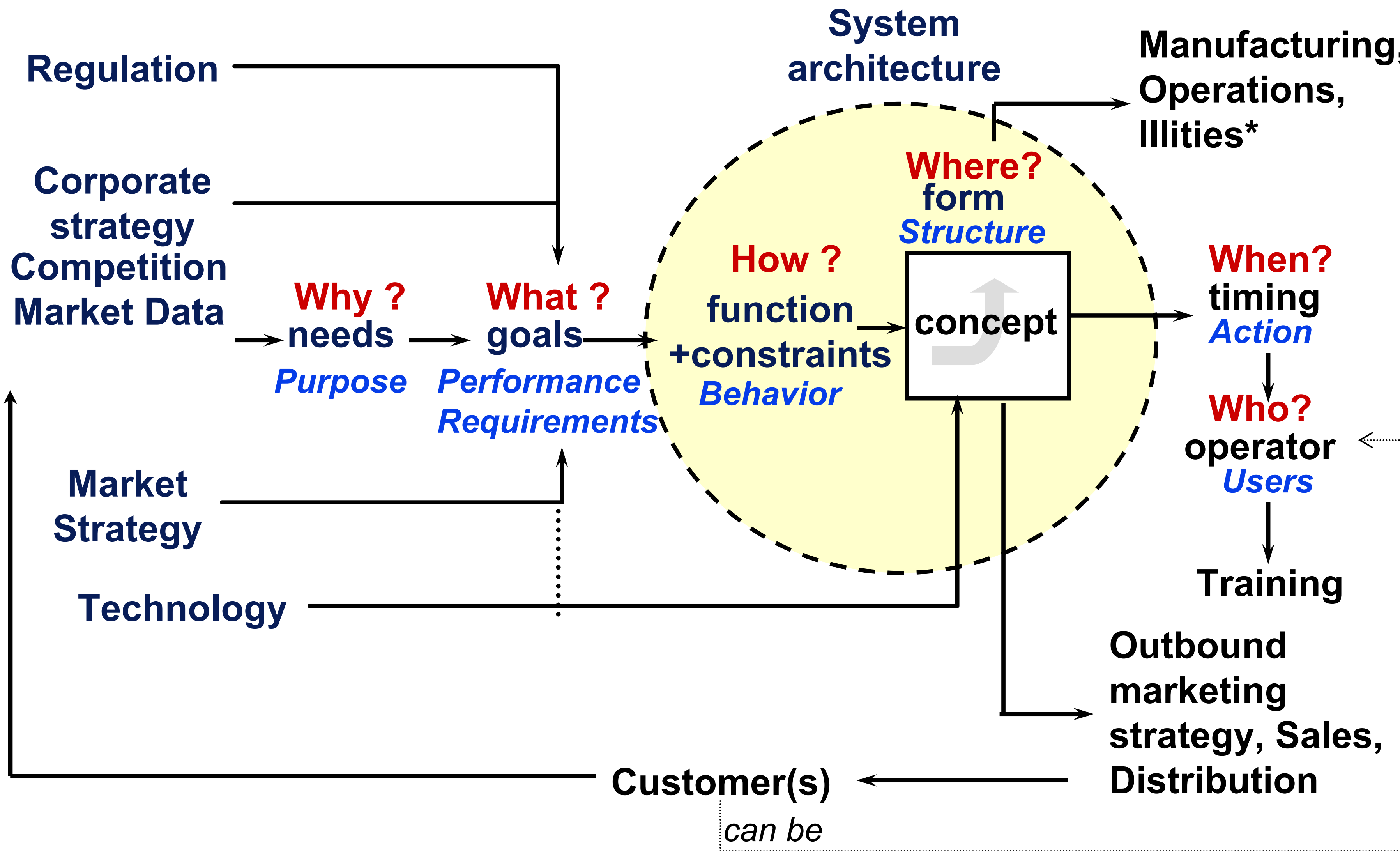
System Architecture Framework

Source: Crawley and de Weck



*Reliability, Servicability, Environmental Impact, Upgradeability, Flexibility,etc…

What is architecture?

- Logical and physical embodiment of a system
- Mechanism that
  - Shapes the functional and physical boundaries of the system
  - Governs the behavior and structure of the system

Why is architecture important?

- The “right” architecture can:
  - Maximize system robustness
  - Maximize system flexibility
  - Minimize system complexity
  - Enable desirable behavior
  - Deter undesirable behavior
- Example(s):
  - An electrical circuit breaker limits the undesirable behavior that would result from a surge in the supply voltage

How do we determine architecture?

- ☐ Synthesis
- ☐ Discovery
- ☐ Chance

Synthesis

- Combining existing systems to satisfy stated needs
- Requires logic and complete (or near complete) knowledge of existing systems
- Example(s):
  - Designing a mechanism to support a person who wants to cross "over" a river or stream

Key question(s) for synthesis?

- What functions do I need to get the job done?
- Is there a way to combine existing systems to do the desired functions without having too many extra functions and too much extra form?
- What rules do I have to apply to do this?

Discovery

- Using knowledge of existing architecture to “discover” new architecture
- Requires knowledge of existing systems and pattern recognition, analysis and abstraction skills
- Example(s):
  - Man learning how to fly
  - Disease and drug pathways

Key question(s) for discovery?

- ☐ Is there some analogous system in another domain?
- ☐ What are the properties of a given architecture that makes it perform so well (or poorly)?
- ☐ Are there similar (or better) ways to perform those functions?

Chance

- Observing “nature” and recognizing “events”
- Requires pattern recognition skills and lots of luck
- Example(s):
  - Discovery of synthetic rubber
  - First “cave woman” to observe that two rocks struck together produces fire

Key question(s) for chance?

- What activity should I be doing to maximize the likelihood of a concept developing?
  - Should I be drinking coffee at Starbucks of tinkering in the lab?

Are they mutually exclusive?

- No!
- Most of the processes we use to determine architecture combine the three approaches
- Example(s):
  - Chance->Discovery->Synthesis
  - Synthesis->Discovery&Chance

How do I know the best architecture?

- Selection process
  - Natural selection
  - Artificial selection
- Goals and metrics

Robustness

- Ability of a system to “perform” under various operating conditions
- Robustness can be measured
  - Range of operating conditions (both internal and external) over which the performance of a system is within an acceptable “distance” of its peak performance
  - Ex: Frequency response of a control system

Flexibility

- Flexibility is the means though which we achieve robustness
- Flexibility can be measured
  - Number of different modes or states in which system can be successfully operated
  - Ease with which the operating mode or state can be changed
- Ex: Humans
- Flexibility leads to complexity

Complexity

- Complexity is the degree to which the set of possible states of a system exceeds the set of desired states
- Complexity can be measured
  - Information required to describe all the components, their interconnections and their interactions
  - Number of homogeneous/dissimilar elements, homogeneous/dissimilar interconnections, and ways components are organized

Complexity

- **Complexity is subjective**
  - **Influenced by user perception and presentation scheme**
  - **Ex: cruise control system in automobiles**
    - Low apparent complexity as presented to drivers: knobs, buttons
    - High apparent complexity if you include physical parts such as electromechanical components or logics such as control laws

Complexity

- Complexity can be decomposed
  - Essential complexity: minimum level of complexity that is essential to deliver system function
  - Gratuitous complexity: additional complexity beyond essential complexity

Architecture and Complexity

- Architecture determines the parts and their interaction (form and function)
- Different architectures have different levels of robustness, flexibility and complexity
  - Ex: cruise control system vs. driver as a control and feedback mechanism
- Characteristics of good architecture
  - Actual complexity is close to essential complexity
  - Enhances system behavior by improving system predictability

Analogy between Entropy and Complexity

- Complexity has a lower limit i.e. actual complexity is always greater or equal to essential complexity
- Complexity is a property to engineered systems as entropy is to thermodynamic systems
- These generalities cannot be expressed qualitatively, but their importance can be demonstrated with specific examples

Analogy between Entropy and Complexity

Thermodynamic domain:

$$(S_{generated})_{1\rightarrow 2} \equiv (S_2 - S_1) - \int_1^2 \left(\frac{\delta Q}{T}\right)_{irrev} > 0$$

- Objective is to minimize entropy generation or irreversibility
- Limited by physical laws and practical considerations on the rate energy at which energy can be extracted
- Flow systems are energy conversion devices to minimize entropy generation

System Engineering domain:

$$C_{gratuitous} \equiv C_{actual} - C_{essential} > 0$$

- Objective is to minimize gratuitous complexity
- Limited by physical laws and practical considerations on the rate at which information can be shared
- Integrated product teams are the equivalent of “flow systems”

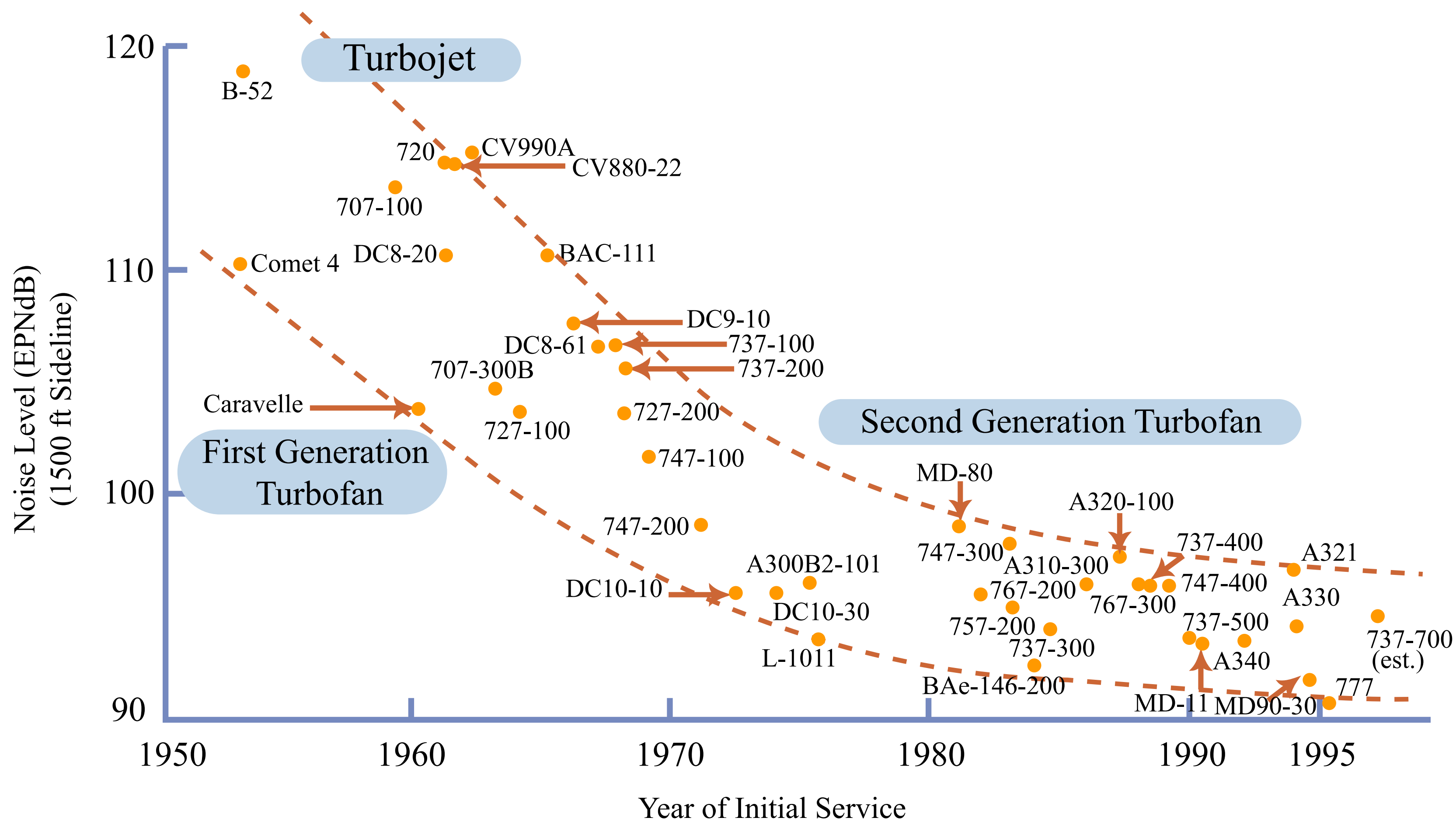
Examples Problem

- How can we reduce the noise impact of aircraft (during approach) on communities near airports without losing capacity?

Motivation

- Noise is an important factor in the siting and operation of airports
  - Negative reaction by community to noise from aircraft
  - Community agreement required for increase in number of operations, airport expansion or airspace changes
  - Lengthy environmental studies required for approval and federal mitigation funding
  - Significant reduction in number of new runways built

Motivation (2)



- Normalized to 100,000 Ib thrust
- Noise level are for airplane/engine configurations at time of initial service

Motivation (4)

- Operational procedures can provide significant additional noise reductions
  - Thrust management strategies redistribute noise impact during departure and reduce impact during approach
  - Lateral deviations direct aircraft away from populated areas during departure and approach
  - Applied only at airports with severe noise restrictions
  - Limited in applications because of flight guidance technology limitations

Motivation (4)

- Advanced flight guidance technologies may be used to improve the applicability and effectiveness of noise abatement procedures
  - GPS will be the base of the future primary navigation system in the United States [FAA, 1996]
  - Flight procedures are being re-examined as part of the transition to satellite navigation
  - Area Navigation (RNAV) using position information from the Global Positioning System (GPS) enables flexible trajectories

Background

- Noise impact determined by 3 components
  - **Source Characteristics**
    - Intensity, frequency content, & directivity
  - **Path Characteristics**
    - Attenuation, diffraction
  - **Receiver Characteristics**
    - Population distribution, time of day

Background (2)

- Components interdependent
  - Thrust & speed determine source characteristics
  - Thrust, aerodynamics, & atmospheric conditions determine aircraft performance
  - Speed & atmospheric conditions determine maximum thrust available
- Provides opportunities for operational modifications that reduce noise impact

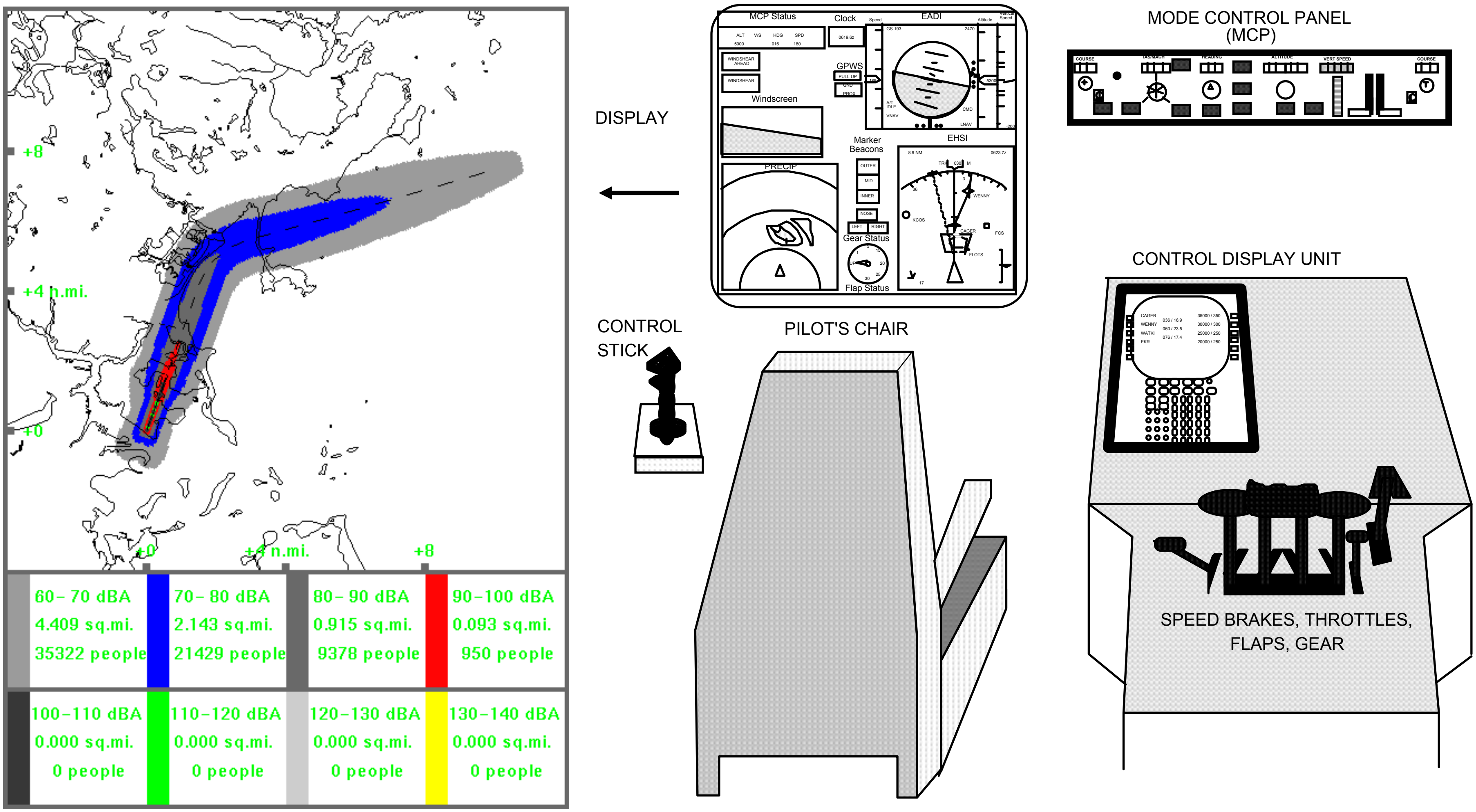
NOISIM

- ☐ Methodology for developing noise abatement procedures
- ☐ Combines Flight Simulator, Noise Model, and Geographic Information System (GIS)
- ☐ Simulates realistic aircraft operation (737-200 & 767-300)
- ☐ Evaluates critical components simultaneously
- ☐ Rapid prototyping and evaluation of noise abatement procedures

Critical Components

- ☐ Aircraft Performance and Trajectory
- ☐ Noise Generated by the Aircraft
- ☐ Population Distribution and Density
- ☐ Flight Safety and Pilot Acceptance
- ☐ Guidance and Navigation Requirements
- ☐ Local Atmospheric Conditions

NOISIM



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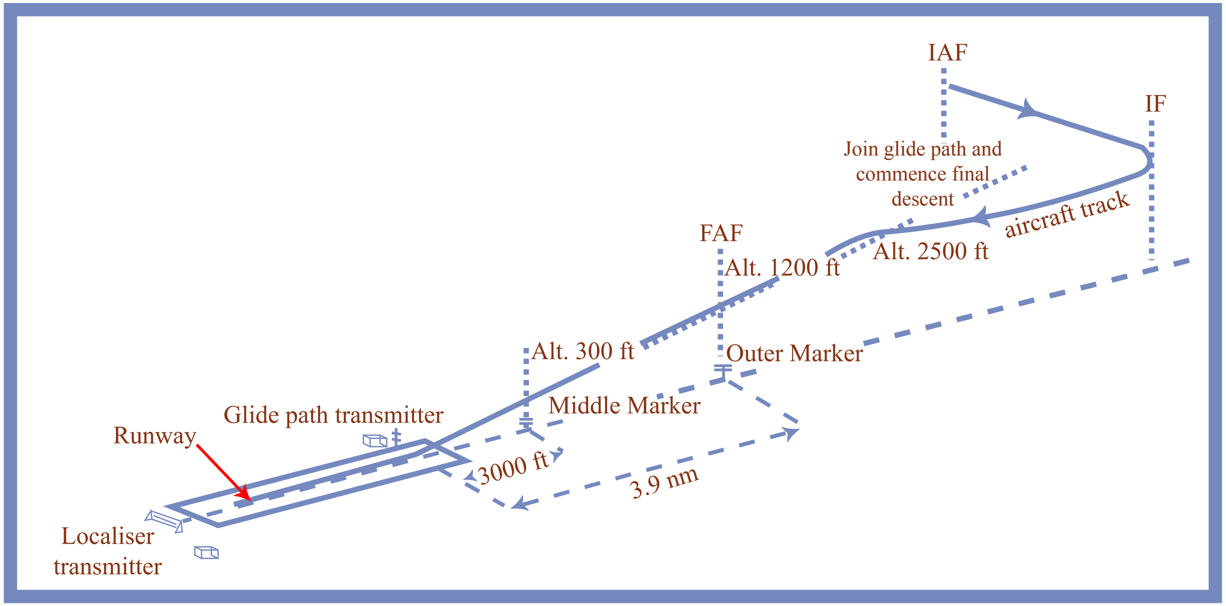
ILS Approach

- Glide Slope intercepted from below
- A/C flies along extended centerline for much of approach (final and intermediate segments)
- Low altitude maneuvering

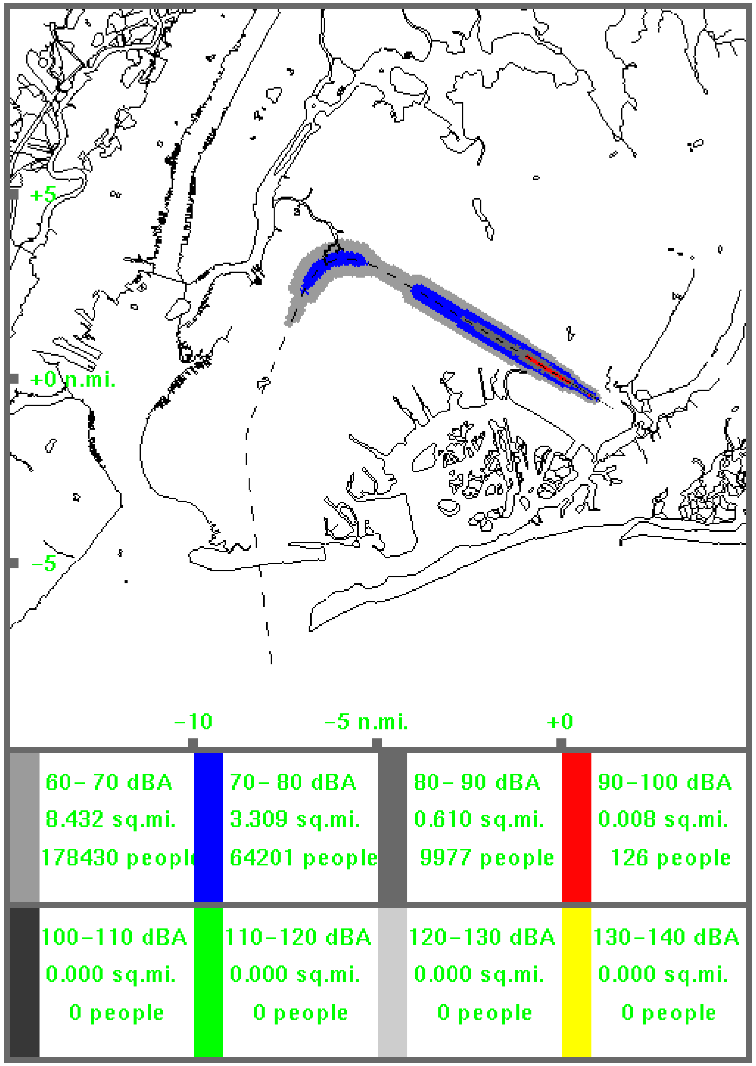


ILS Approach (JFK 13L)

- Approach Chart

(Image removed due to copyright considerations.)

- Noise Impact



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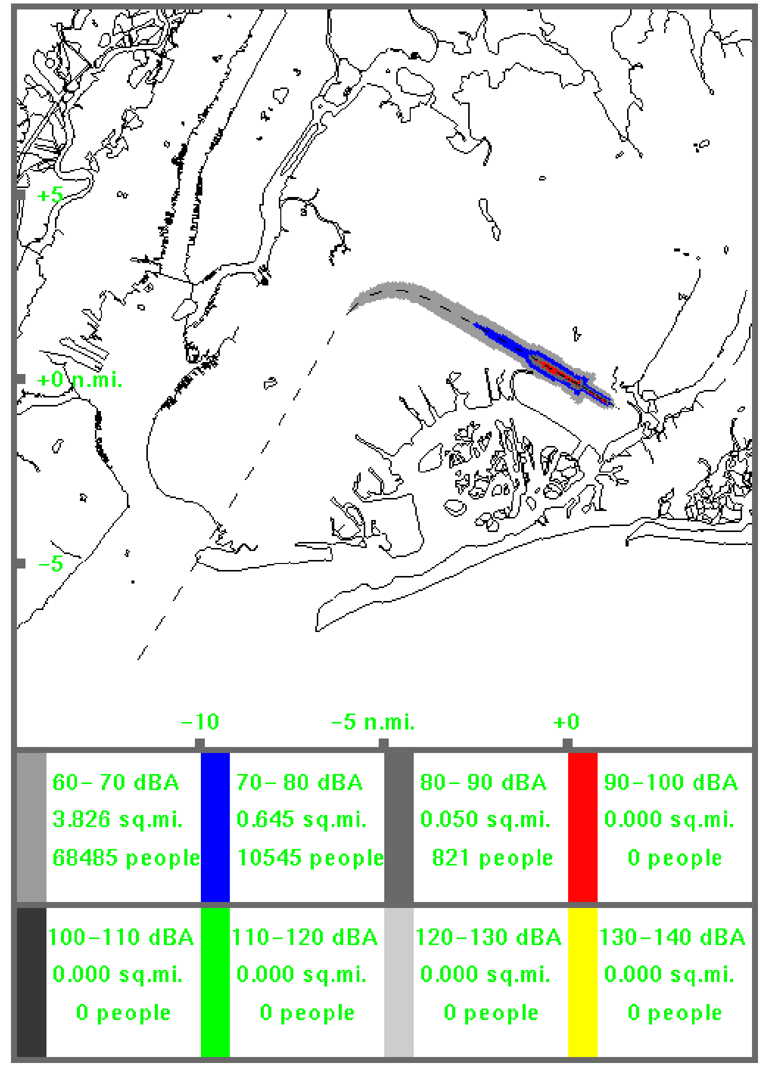
3° Decelerating Approach

- Single segment
- Aircraft intercepts segment at high alt. & speed
- Aircraft decelerates during descent at idle thrust
- Achieves approach speed at 500-1,000 ft AGL
- Does not require additional displays

(Image removed due to copyright considerations.)

3° Decelerating Approach (JFK 13L)

- 3° decelerating approach implemented to reduce noise associated with low altitude vectoring
- Lateral trajectory of decelerating approach similar to ILS approach to avoid traffic of other airports



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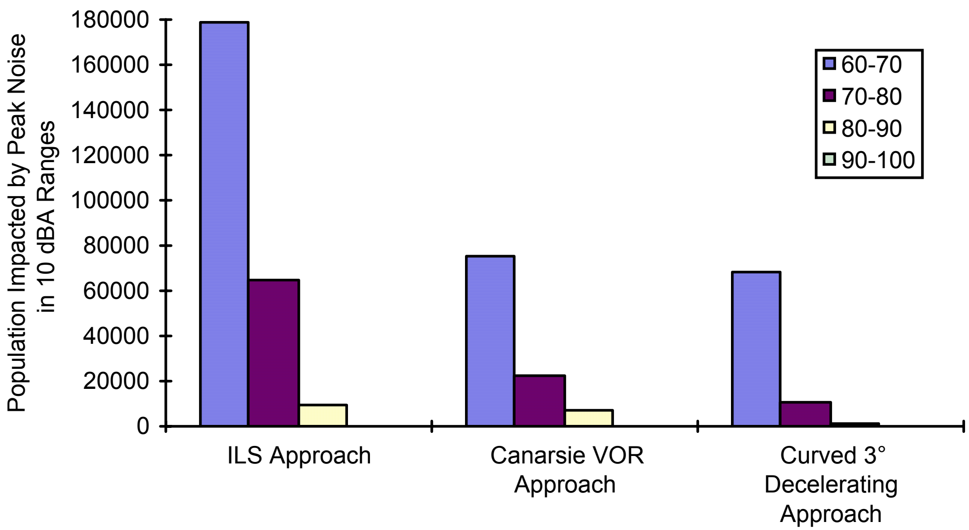
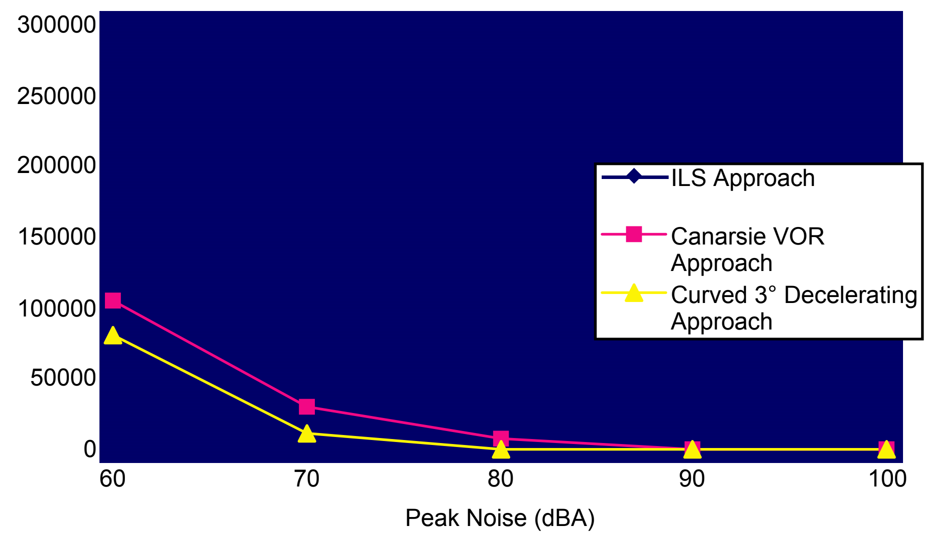
Noise Benefit (JFK 13L)

- 3° decelerating approach has equivalent noise impact to Canarsie approach
- Population impacted by noise greater than 60 dBA reduced from 252,734 (ILS) to 79,851
- 3° decelerating approach can be used in Instrument Meteorological Conditions (IMC)





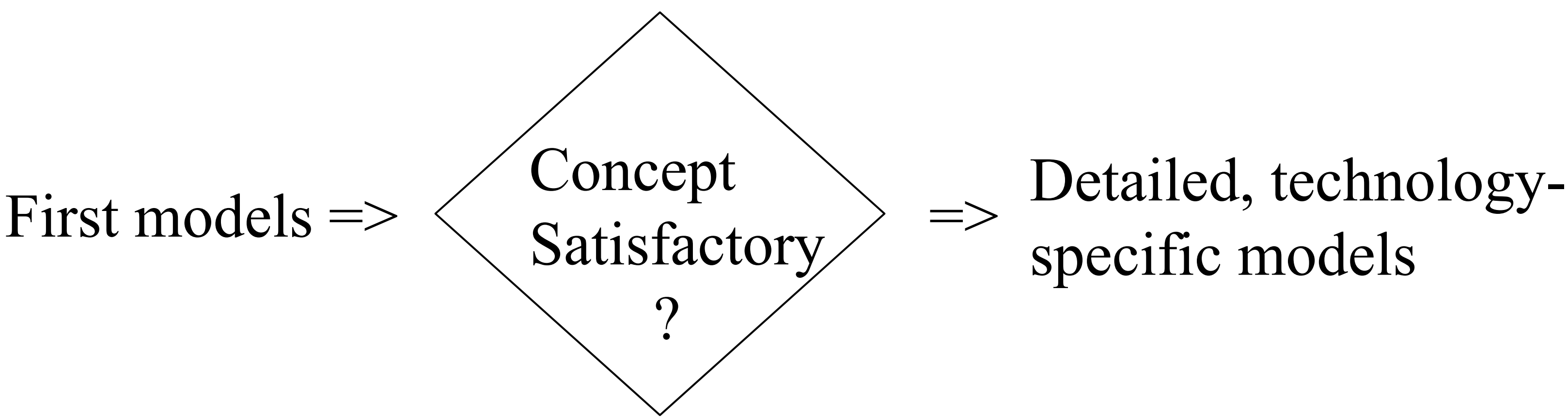
What is the Product of an Architect? (1)

- Building or system?
  - Relationship is indirect: the system is built by the developer!
- Architect connects
  - Problem domain concepts of client AND the solution domain concepts of builders
- System cannot be built unless architect has a mechanism to communicate visions and track construction against it
- Architect provides models of the system!

Source: The Art of Systems Architecting, Maier & Rechtin

What is the Product of an Architect? (2)

- **Individual models are point-in-time representations of a system**
  - **Treat each model as a member of one of several progressions**



Source: The Art of Systems Architecting, Maier & Rechtin

Civil Architecture Analogy

- **Building pleases client aesthetically, functionally, financially**

Model	Purpose
Physical scale model	**Convey look & site placement**
Floor plans	**Ensure building performs desired functions**
External renderings	**Convey look of building**
Budgets, schedules	**Meet client's financial performance objectives**
Construction blueprints	**Communicate design req. and construction criteria to builders**

Source: The Art of Systems Architecting, Maier & Rechtin

Models

- Models
  - Means of communication with clients, builders, and users
  - Language of architect
  - Important for constructing system and describing and diagnosing its operation
  - Can be classified by their roles or content

Source: The Art of Systems Architecting, Maier & Rechtin

Models (2)

- Terminology (IEEE standard):
  - Model: approximation, representation, or idealization of … a real-world system.
  - View: representation of a system from the perspective of related concerns or issues
  - Viewpoint: template, pattern, or specification for constructing a view

Source: The Art of Systems Architecting, Maier & Rechtin

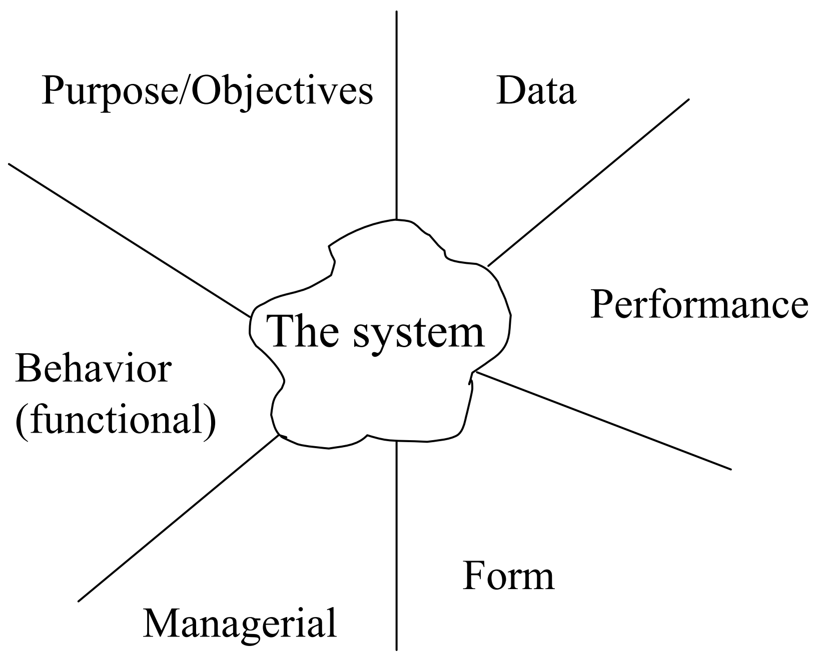
Models (3)

- In other words:
  - A Model is a representation of something
  - A View is a collection of models that share the property that they are relevant to the same concerns for a system stakeholder.
  - A Viewpoint is an abstraction of view across many systems.

Source: The Art of Systems Architecting, Maier & Rechtin

Models (4)

- 6 common views
  - Should be complete and "mostly" independent
  - System can be projected into any view, possible in many ways



View	Description
Purpose/Objective	**What client wants**
Form	**What the system is**
Behavioral or functional	**What the system does**
Performance objectives	**How effectively the system does it**
Data	**The information retained in the system and its interrelationships**
Managerial	**Process by which system is constructed and managed**

Source: The Art of Systems Architecting, Maier & Rechtin

Models (5)

- Integrated modeling method
  - A system of representation that links multiple views
  - Consists of a set of models for a subset of views and a set of rules or additional models to link the core views
  - Most are domain specific

Source: The Art of Systems Architecting, Maier & Rechtin

Integrated Modeling Methodologies

Method	Domain
Hatley/Pirbhai(H/P)	**Computer-based reactive or event-driven systems**
Quantitative quality function deployment (Q^2FD)	**Systems with extensive quantitative performance objectives and understood performance models**
Object modeling technique (OMT)	**Large-scale, date-intensive software systems, especially those implemented in modern object languages**
ADARTS	**Large-scale, real-time software systems**
Manufacturing system analysis (MSA)	**Intelligent manufacturing systems**

Source: The Art of Systems Architecting, Maier & Rechtin

Integrated Modeling Methodologies

- **Quantitative QFD**
  - **Performance objectives are most important to the client**
  - **Performance-centered approach to system specification, decomposition, and synthesis**
  - **Japanese-originated method for visually organizing the decomposition of customer objectives**

Source: The Art of Systems Architecting, Maier & Rechtin

Integrated Modeling Methodologies

- Quantitative QFD-based approach:
  1. Identify a set of performance objectives of interest to the client. Determine appropriate values or ranges for meeting these objectives through competitive analysis.
  2. Identify the set of system-level design parameters that determine the performance for each objective. Determine satisfaction models that relate the parameters and objectives.

Source: The Art of Systems Architecting, Maier & Rechtin

Integrated Modeling Methodologies

- Quantitative QFD-based approach:
  3. Determine the relationships of the parameters and objectives, and the interrelationships among the parameters. Which affect which?
  4. Set one or more values for each parameter. Multiple values may be set, for example, minimum, nominal, and target. Additional slots provide tracking form detailed design activities.

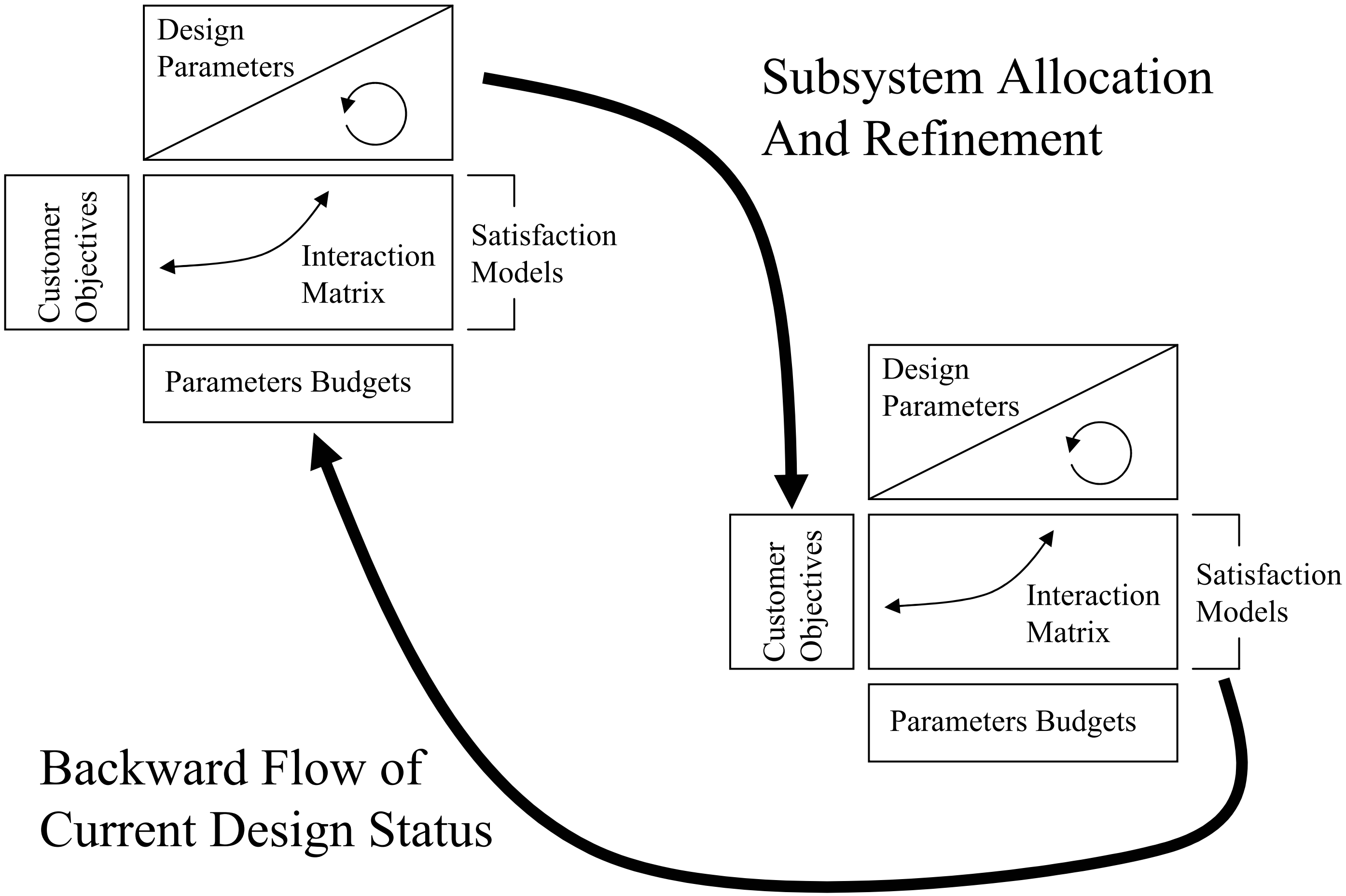
Source: The Art of Systems Architecting, Maier & Rechtin

Integrated Modeling Methodologies

- **Quantitative QFD-based approach:**
  5. Repeat the process iteratively using the system design parameters as objectives. At each stage the parameters at the next level up become the objectives at the next level down.
  6. Continue the process of decomposition on as many level as desired. As detailed designs are developed, their parameter value can flow up the hierarchy to track estimated performance for customer objectives.

Source: The Art of Systems Architecting, Maier & Rechtin

Quantitative QFD



Source: The Art of Systems Architecting, Maier & Rechtin

CDIO

- **Concept View**
  - **Combination of Purpose and Form Views**
  - **Question(s)**
    - What functions does the customer want? (now & in the future)
    - What functions does the customer need? (now & in the future)

CDIO

- **Design View**
  - **Combination of Behavior and Performance Views**
  - **Question(s)**
    - What vehicles and systems do you think will fulfill these wants and needs?
    - How would these vehicles and systems fit together?
    - How well would the system perform?

CDIO

- ☐ **Implementation View**
  - ↓ **Combination of Data and Management Views**
  - ↓ **Question(s)**
    - How would you build the system?
    - What physical resources are required?
    - What financial resources are required?
    - What socio-political resources are required?

CDIO

- **Operations View**
  - **Combination of Management View and the Business Case**
  - **Question(s)**
    - How would you operate the system?
    - What physical resources are required?
    - What financial resources are required?
    - What sociopolitical resources are required?
    - Will all stakeholders profit from this deal?