Strategies for Design Optimization: Lessons from Automotive Systems

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Outline

- Introduction to automated design exploration
- The REAL WORLD – and concessions to it:
  - Costly evaluations → Not your father's GA
  - Typical stepwise design process
    - Design of Experiments
    - EC/hybrid search
    - SHERPA
    - CIA
  - "The Box" and a way to escape it… sometimes
    - COMPOSE
- Example of Component Crashworthiness Optimization

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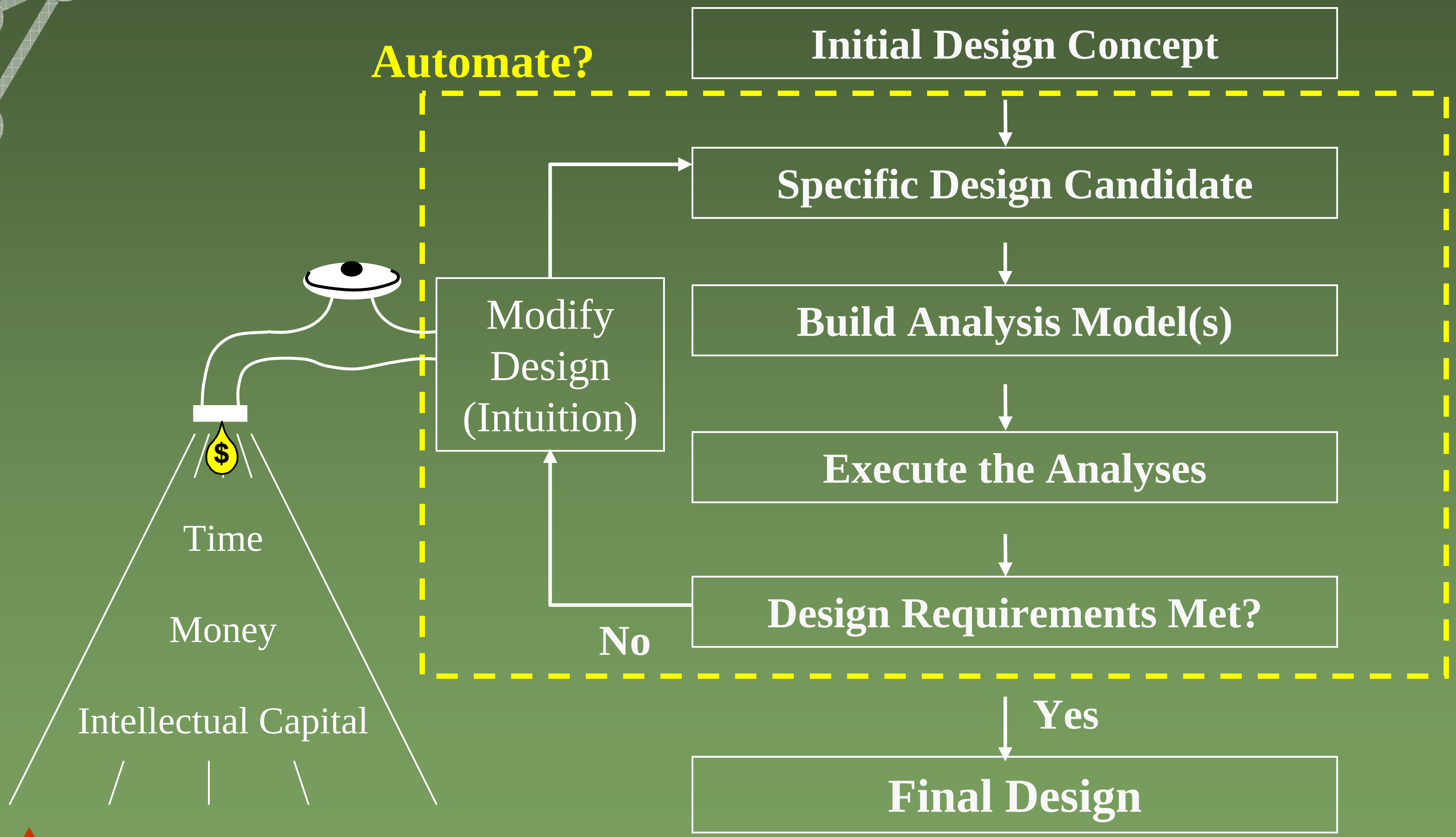
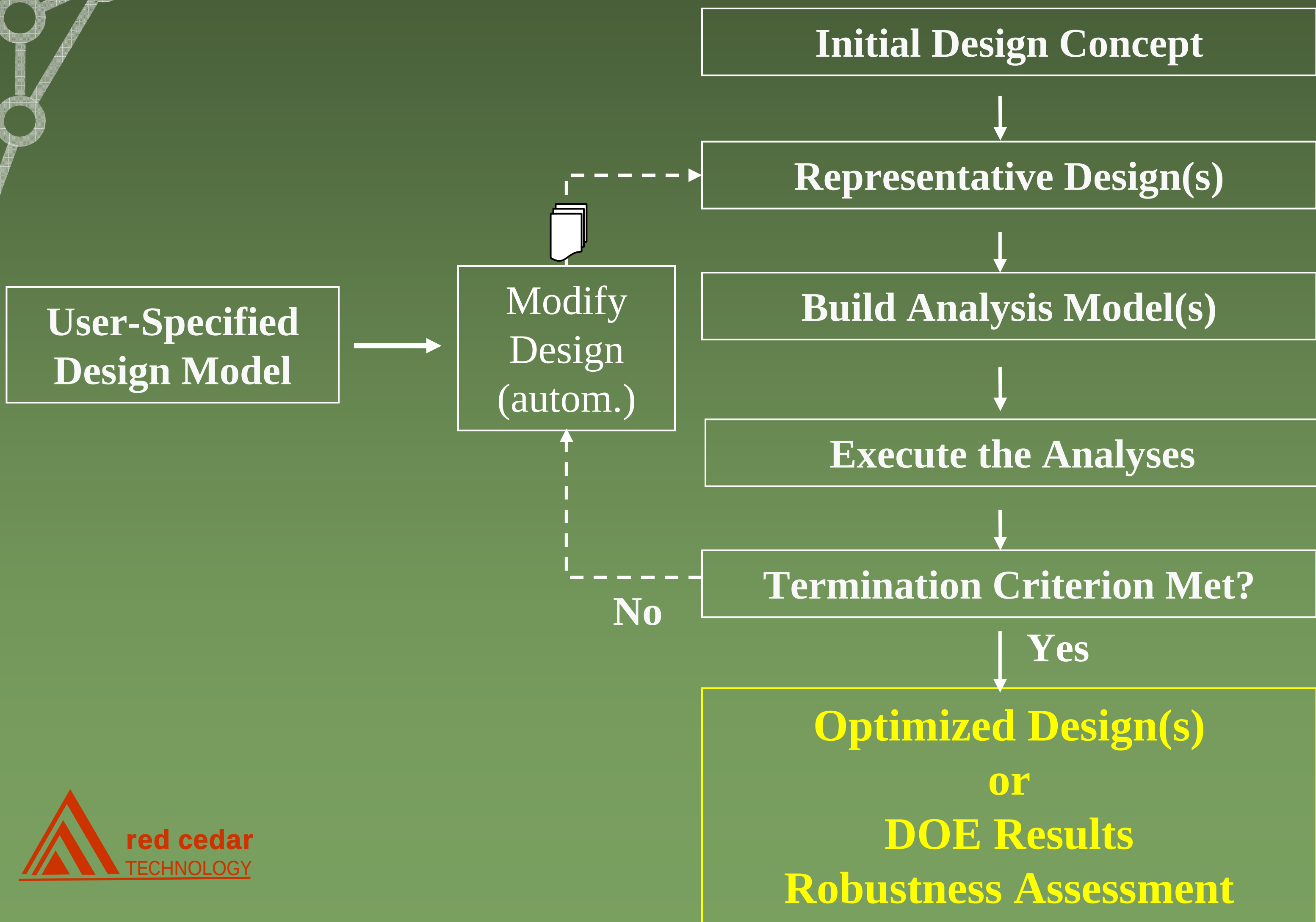
Typical Design Process



Automated Design Process



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Main Benefits

- *Automates* search for design alternatives with improved performance and cost
  - ★ more efficient and thorough search
- *Reduces* design time from weeks to days
  - ★ significant cost reduction
- Accelerates product and process *innovation*
  - ★ increased competitive advantage
- *Integrates* and *leverages* existing investment in CAD/CAE tools and hardware
  - ★ better utilization of capital
- Improves design *robustness*
  - ★ six sigma

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Main Ingredients Needed

- Process Integration
- Design Space Exploration
    - Design of Experiments
    - Design Optimization
    - Reliability and Robustness

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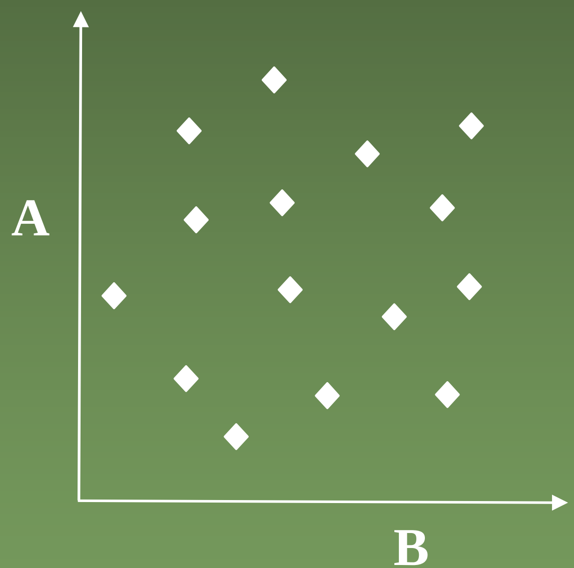
Design of Experiments



Design exploration

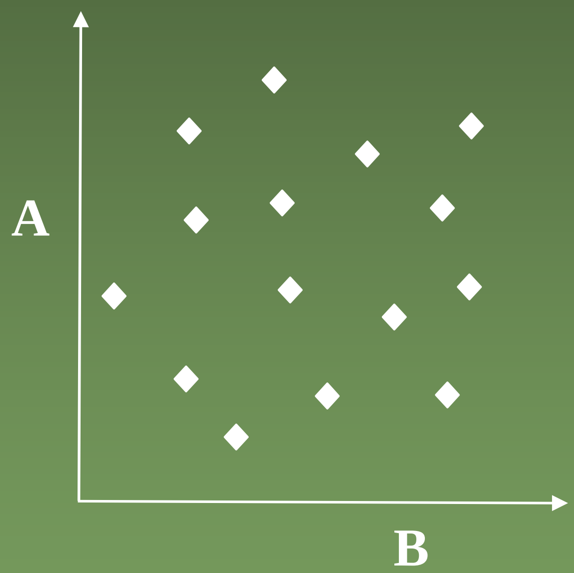
- Design variable screening
- Sensitivity of design performance to changes in parameters
- Suggests design improvements

Local response surface

- Surrogate analysis model
- Reduces number of full evaluations

NOT a direct optimization method

Design of Experiments



Examples of Sampling Methods:

- Full factorial
- Fractional factorial
- Central composite
- Latin hypercube
- Plackett-Burman
- Taguchi orthogonal array
- D-Optimal
- User defined

Post-Processing

- ANOVA
- Pareto charts
- Main and Interaction Effects
- Response Surfaces, …

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Design Optimization Scenarios

- Seek small improvements to an already good design

  Local search, small variable range

- Seek best design or concept within a large design space

  Global search, large variable range

- Seek design that best matches a desired performance

  Minimize difference between actual and desired responses

- Modify an existing design to meet new performance targets

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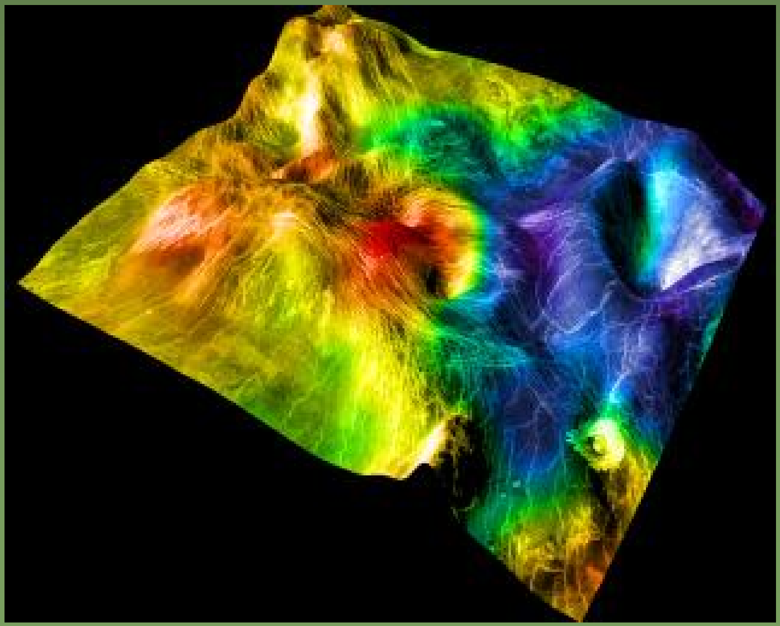
Parameter Optimization

Objective:

Search the performance response surface to find the highest peak or lowest valley within the feasible range



- Local searches may yield only incremental improvement
- Typically don't know the nature of the surface before search begins
- Number of parameters may be large
- Evaluations may be expensive – CANNOT DO MANY
- Shape optimization often involves multi-modal design spaces

Design Approaches

- Perform a DOE, fit a response surface, and search the surface

  Usually valid only in local neighborhood of a given design

- Perform a DOE, select most important variables, and perform optimization over subset of variables

  Lots of preparatory work to perform optimization

- Define engineering and business goals and a meaningful design space, and then search for the design that best meets those goals

  Less overall time spent solving the problem

  Greater potential to find better or innovative designs

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How Can We Make Intractable Problems (more) Tractable?

Examples of tools that can be helpful:

- Response surfaces
- Multiple, Self-Tuning Search Methods
- Parallel/cluster/grid organization
- Multiple representations/agents – problem decomposition
- “Medicine” against convergence other than large populations
- Model decomposition – “COMPOSE”

Range of Application

Number of design parameters

(evaluations)

Time needed to analyze each proposed design

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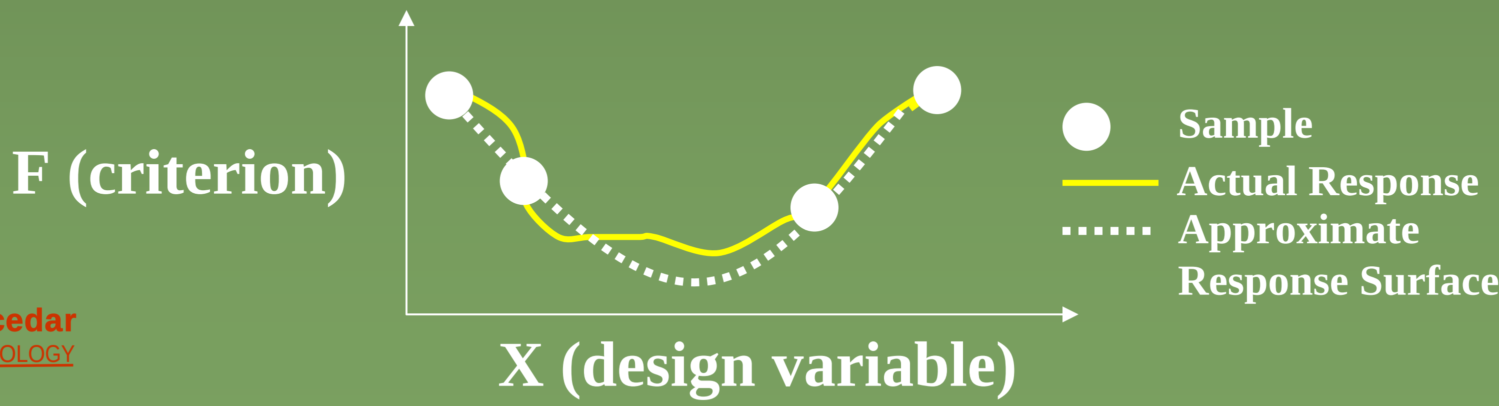
Response Surfaces

- Creates an approximate *model* of the response (a surrogate) as a function of the factors
- Low-order polynomials are often used as surrogate functions
- Typically, response surface models are "least-squares" fit to a sampling of the actual response
- This sampling may be controlled via design of experiments or using points already evaluated and saved



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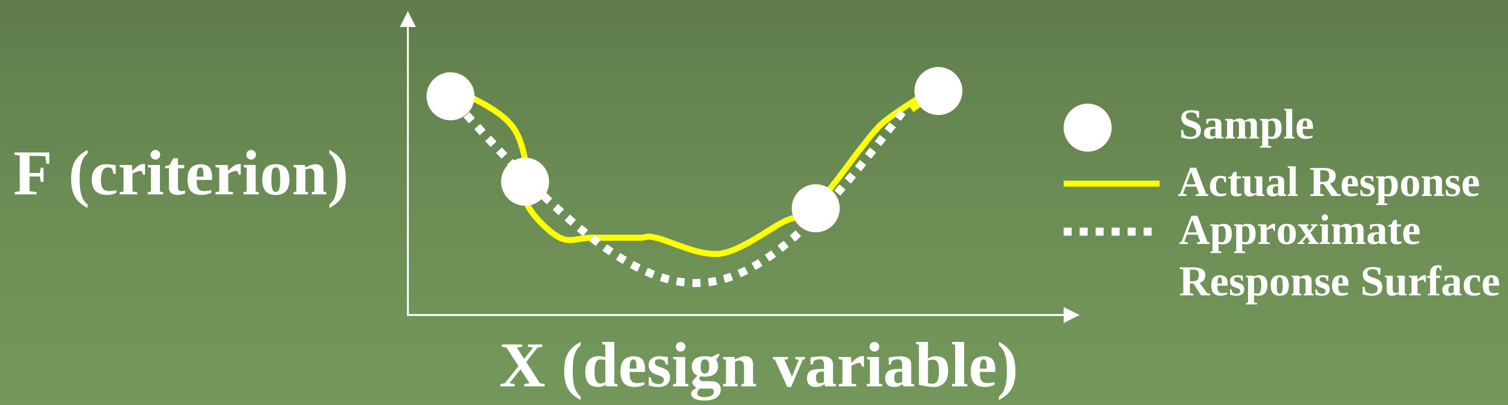
Response Surfaces

- Strengths
  - Eliminate many “full” performance evaluations
  - Potentially define fruitful search directions even if design criteria are not locally differentiable



- Weaknesses
  - Not designed to escape local optima
  - Design variables should be continuous in nature
  - Often works well only in local search

Choosing a Method or a Design Space?

- Design space is a function of:
  - Number, type, and range of design variables
  - Objectives and constraints
- Preferable to define design problem first, and then select search method
  - Which method to choose depends upon the design space
  - But the nature of the design space is not known, unless the problem has been solved before
- Alternative: select search method first, and then make design problem fit that method's capabilities
  - But this limits the problem scope and number of variables, and requires high level of knowledge about the method

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Example of Self-Tuning Search Method: SHERPA

- Hybrid
  - Multiple methods used simultaneously, not sequentially
  - Takes advantage of best attributes of each method
  - Both global and local search techniques are used
- Adaptive
  - Each method adapts itself to the design space
  - Master controller determines which methods get used and how much
  - Tries to learn efficiently about design space and effectively search even very complicated spaces
  - BUT no guarantee of suitability for any particular problem!

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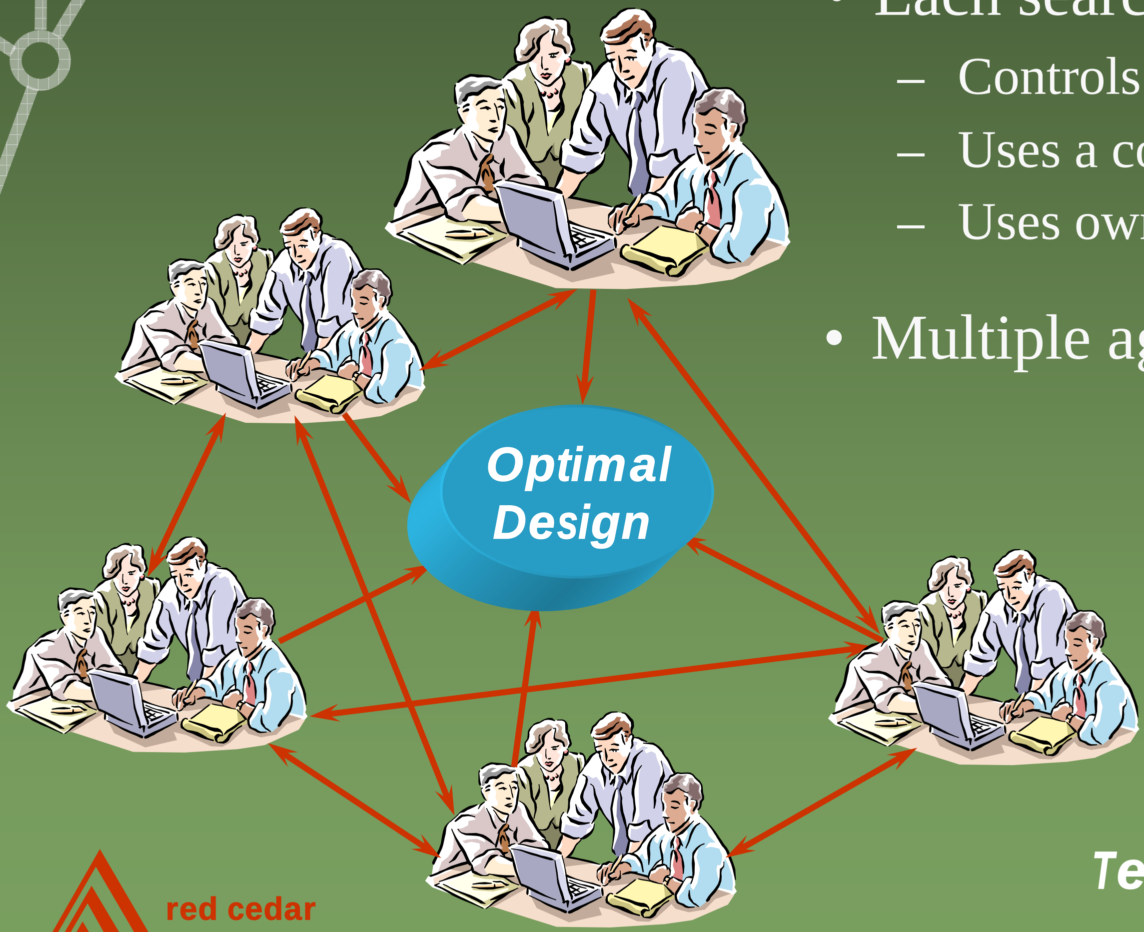
Multi-Agent Search: Cooperative Independent Agents (CIA)



- Each search agent
  - Controls an independent search process
  - Uses a combination of search methods
  - Uses own representation of the problem
- Multiple agents working in parallel
  - Problem decomposition
  - Diverse points of view
  - Shared discovery

Team: Intellectual Diversity

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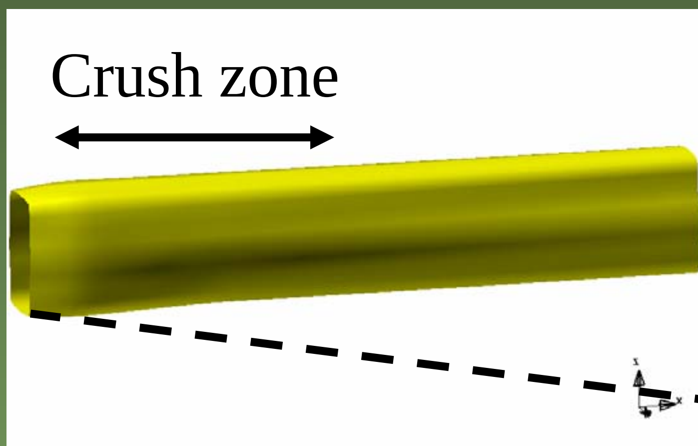
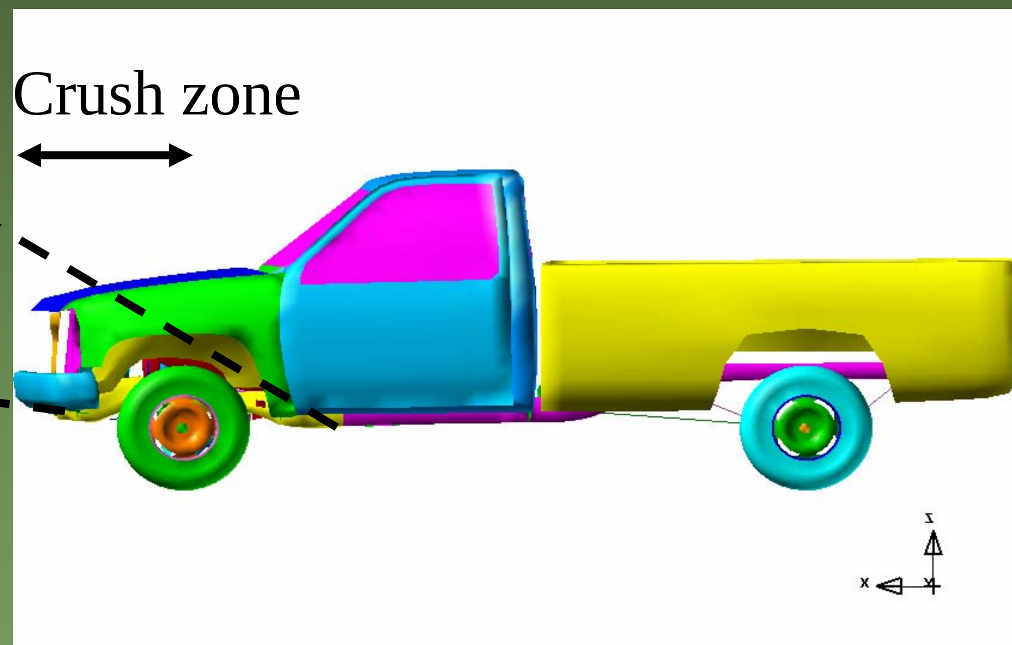
Different Agents, Different Approaches

Can decompose design space according to:

- Physical/spatial domain
- Temporal extent of simulation
- Number of design variables
- Resolution of design variables
- Stochasticity of variables
- Performance measures
- Analysis models
- Search methods
- …

Putting It Together -- Example: Hydroformed Lower Rail

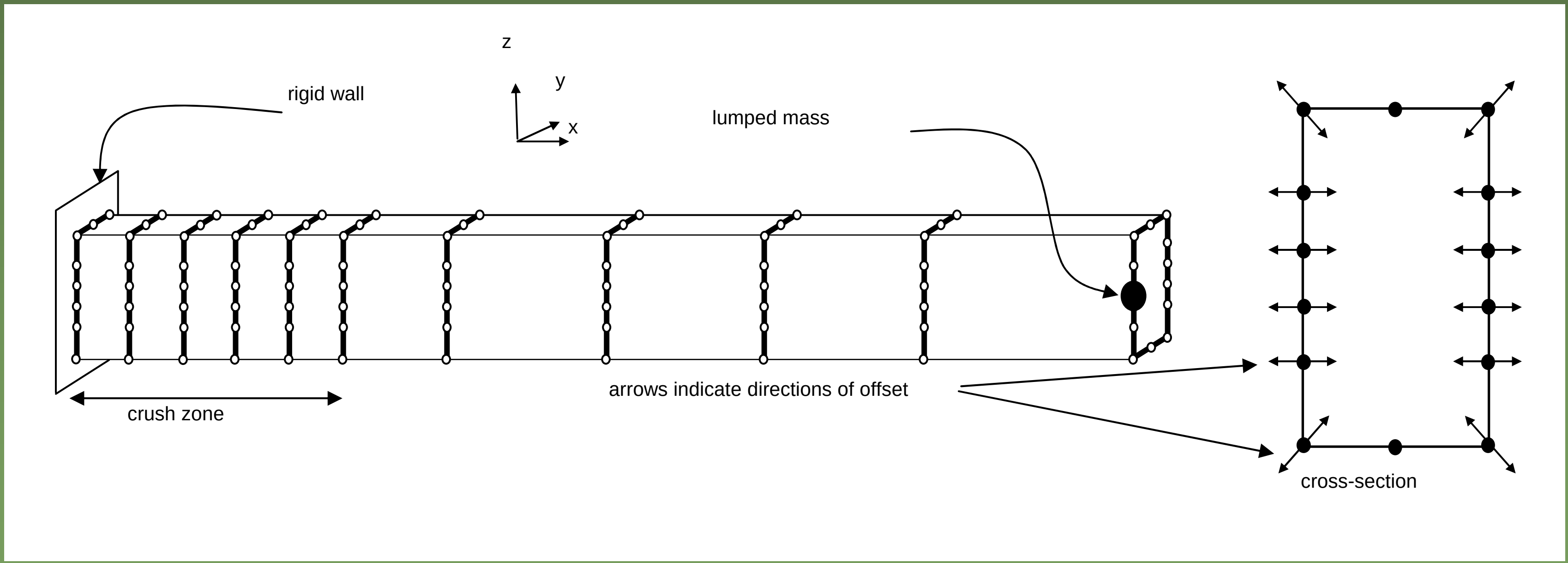




Shape Design Variables

67 design variables:

66 control points and one gage thickness



Optimization Statement

- Identify the rail shape and thickness
- Maximize energy absorbed in crush zone
- Subject to constraints on:
  - Peak force
  - Mass
  - Manufacturability

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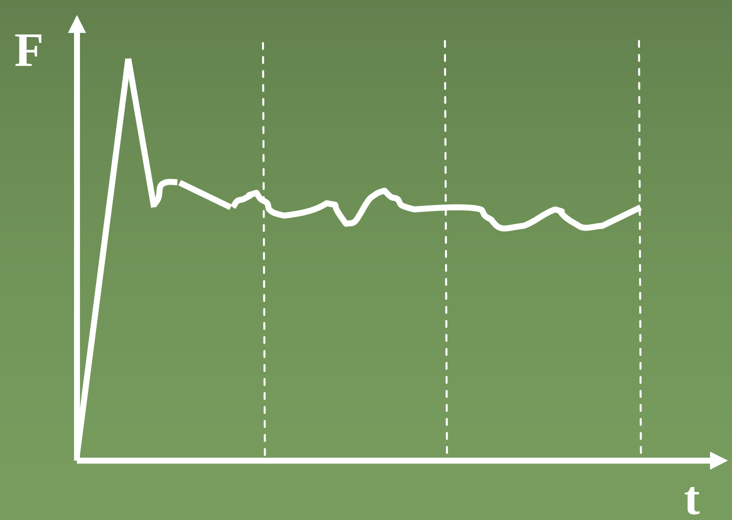
Three-Agent Topology

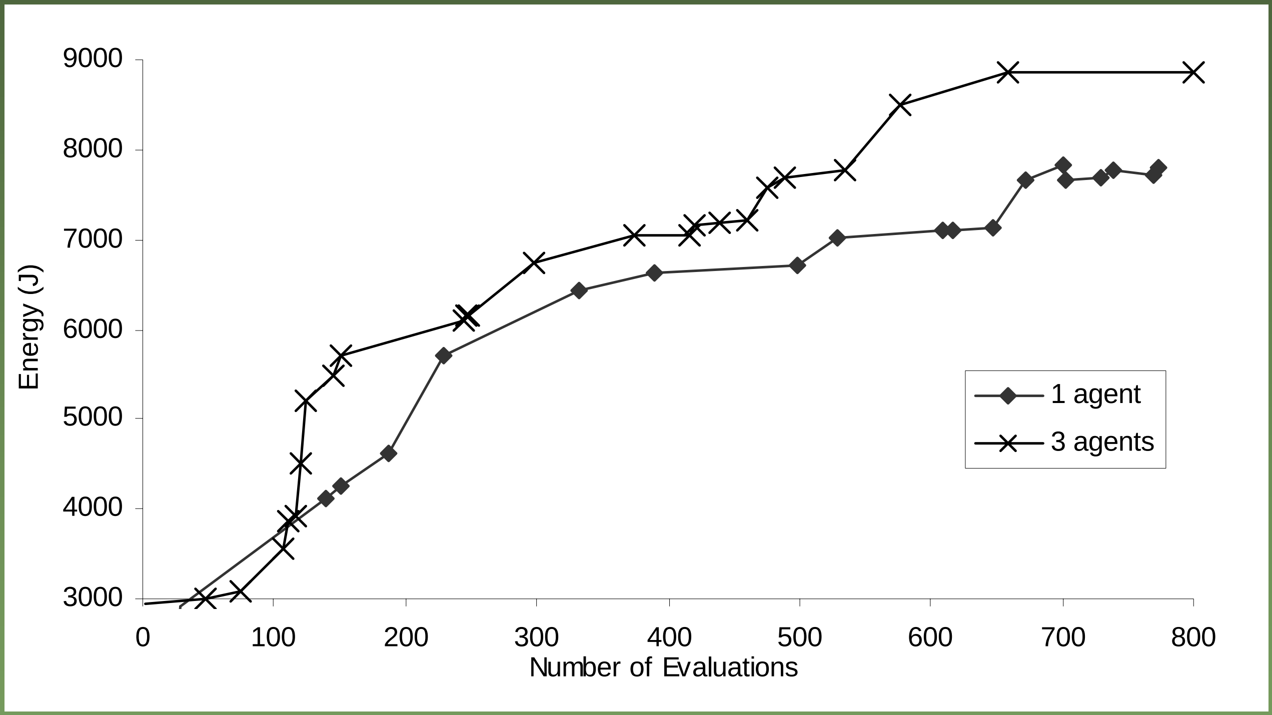
Discretize:

- crush time (reduces CPU time)
- design variables (reduces design space)

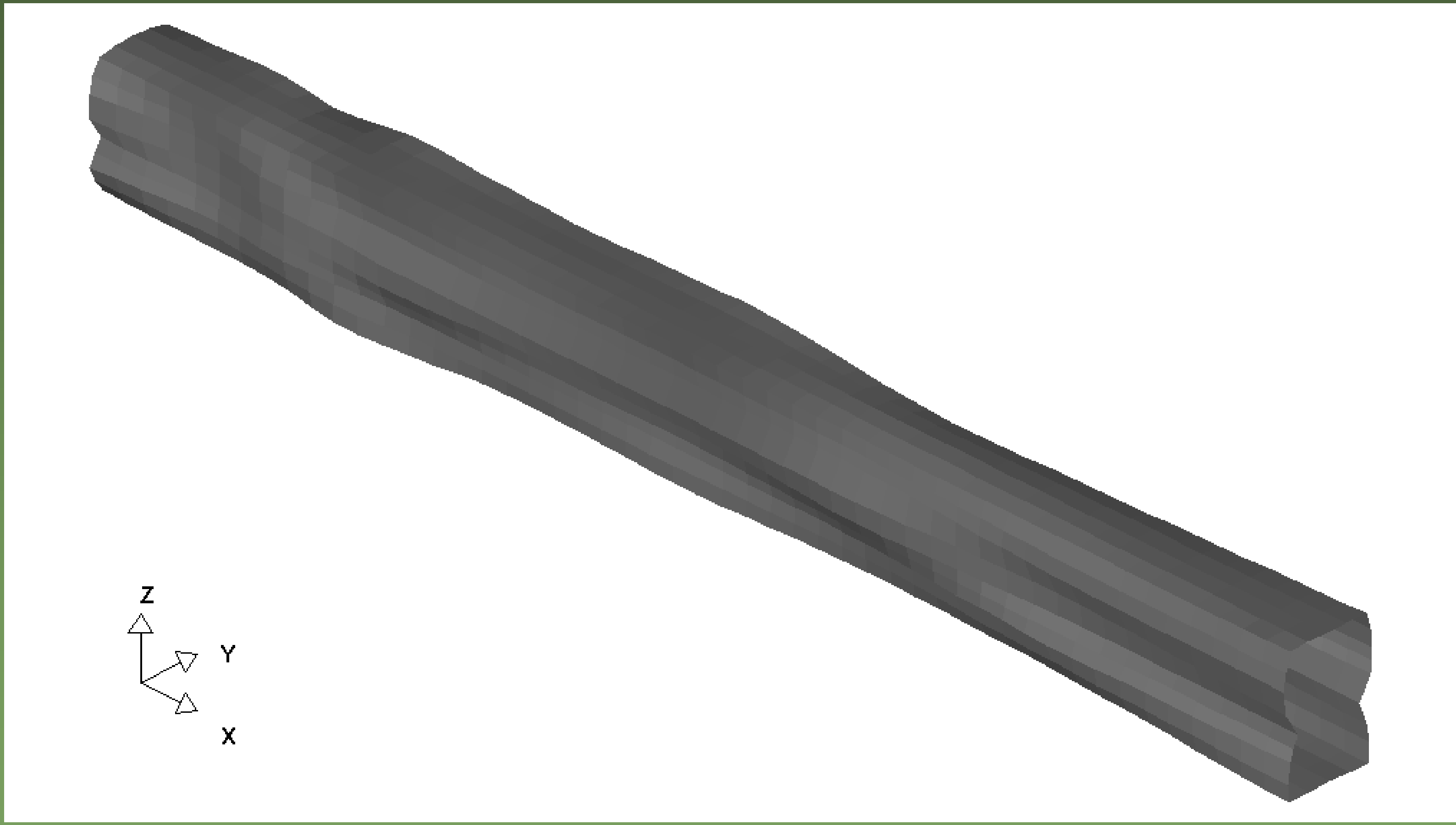


Crush Time	Agent Topology	Design Variable Discretization
t=6 ms	0	Coarse
t=10 ms	1	Medium
t=14 ms	2	Refined

Energy Absorbed



HEEDS Optimized Design



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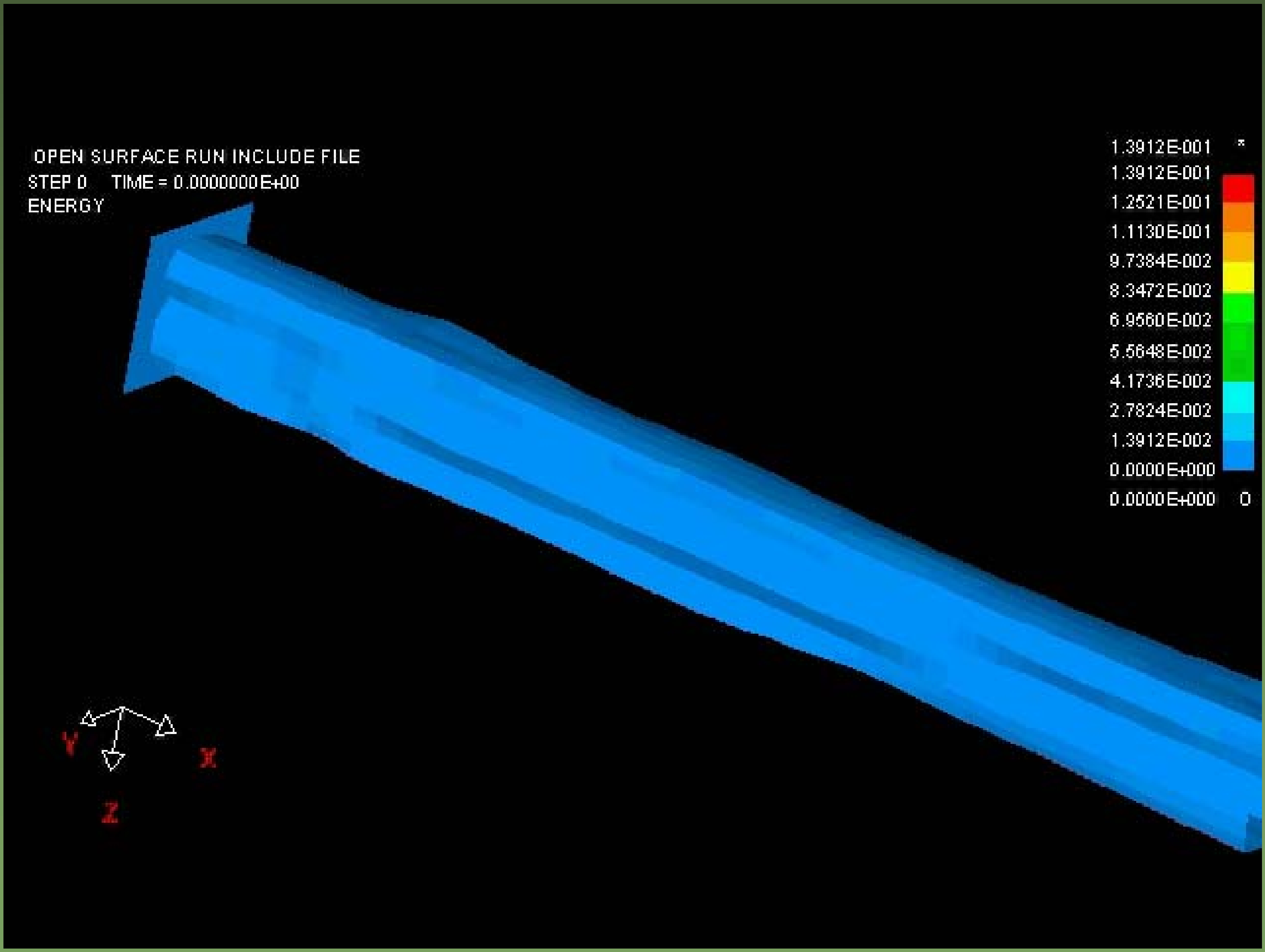
HEEDS Optimized Design



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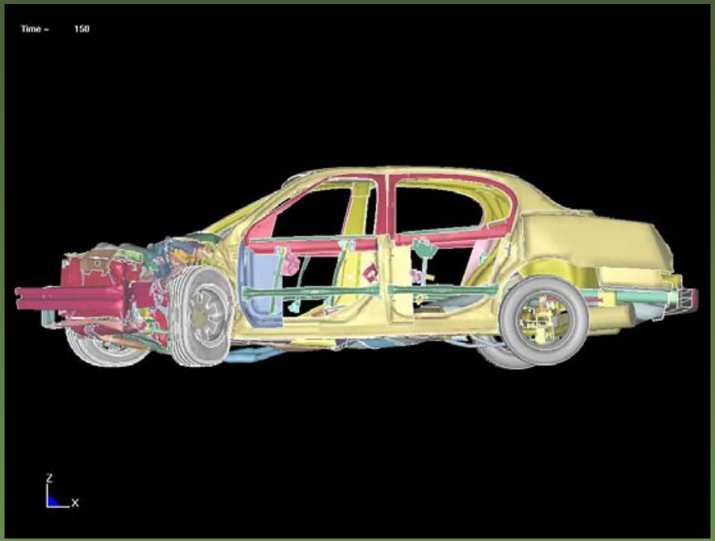
Validation



Lower Rail Benefits

- Peak force reduction by 30%
- Energy absorption increased by 100%
- Weight reduction by 20%
- Overall crash response resulted in equivalent of FIVE STAR rating

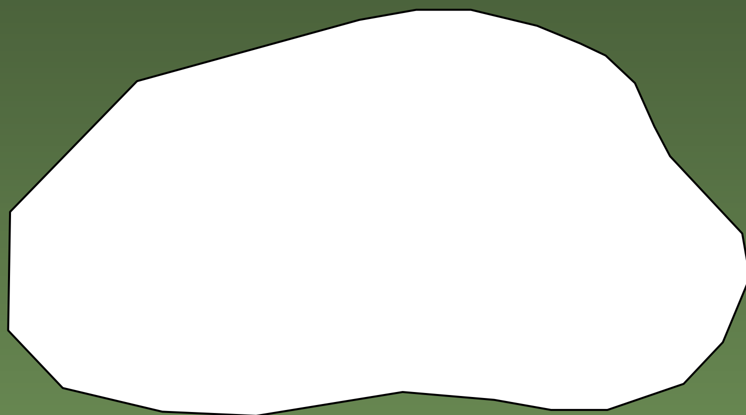
COMPOSE Breakthrough

COMPOSE –

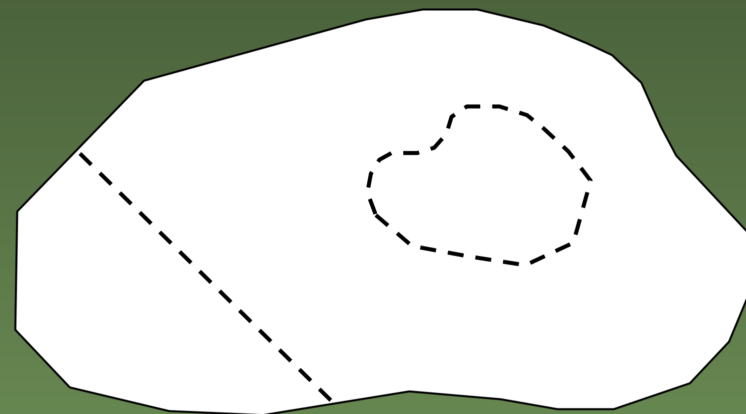
COMPonent Optimization within a System Environment:

- Pull out a component, optimize, put back in → failure
- Iterate above → failure
- COMPOSE allows subsystems (quick to simulate) to be optimized and retain their performance when reintegrated in whole system, but requires only a FEW system-level evaluations!!!
    - Reduces design time by factor of 10 – 1,000 for some problems
    - Allows search over large number of design variables
    - Makes many intractable problems practical to optimize

Spatial Decomposition



System

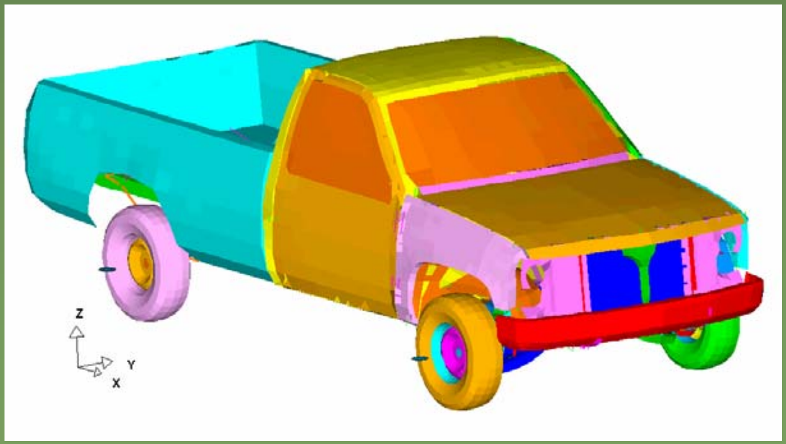


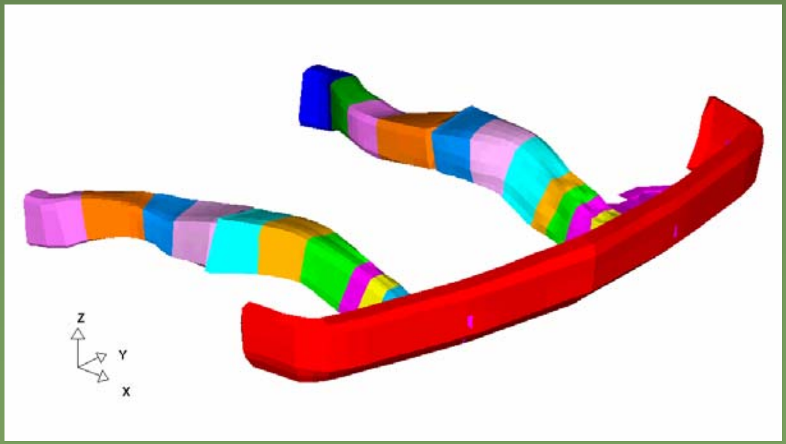
System with subsystems denoted

Subsystems

COMPOSE

- COMPOSE – COMPonent Optimization within a System Environment
- *Enables* high fidelity design of subsystems in *highly coupled* complex systems (10^{1} – 10^{3} times speedup)





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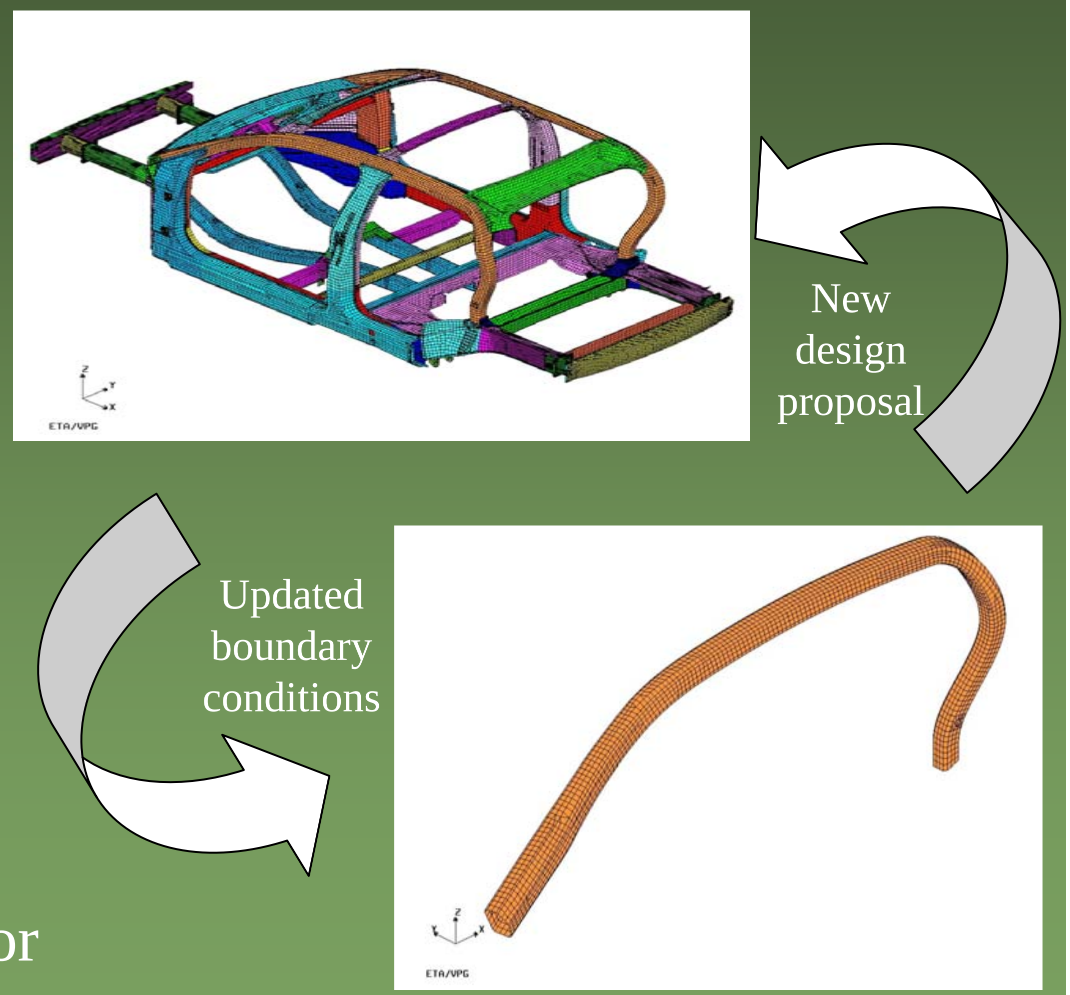
COMPOSE

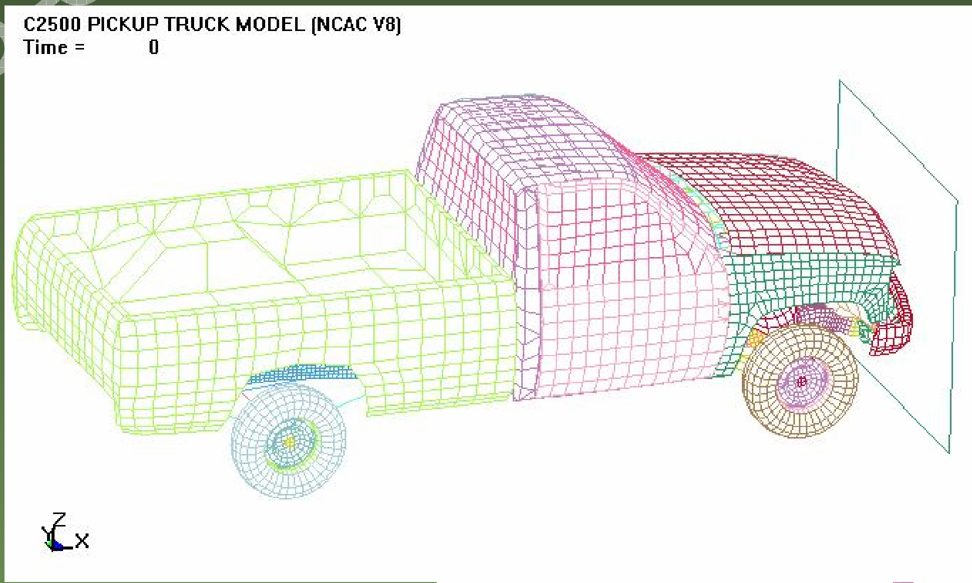
- Based on decomposition
- Most CPU effort to design subsystem (component)
- Small number (3-8) of system level analyses
- Full coupling maintained between system and subsystem
- Large number of variables can be studied
- CPU time reduced by factor of 10 – 1,000

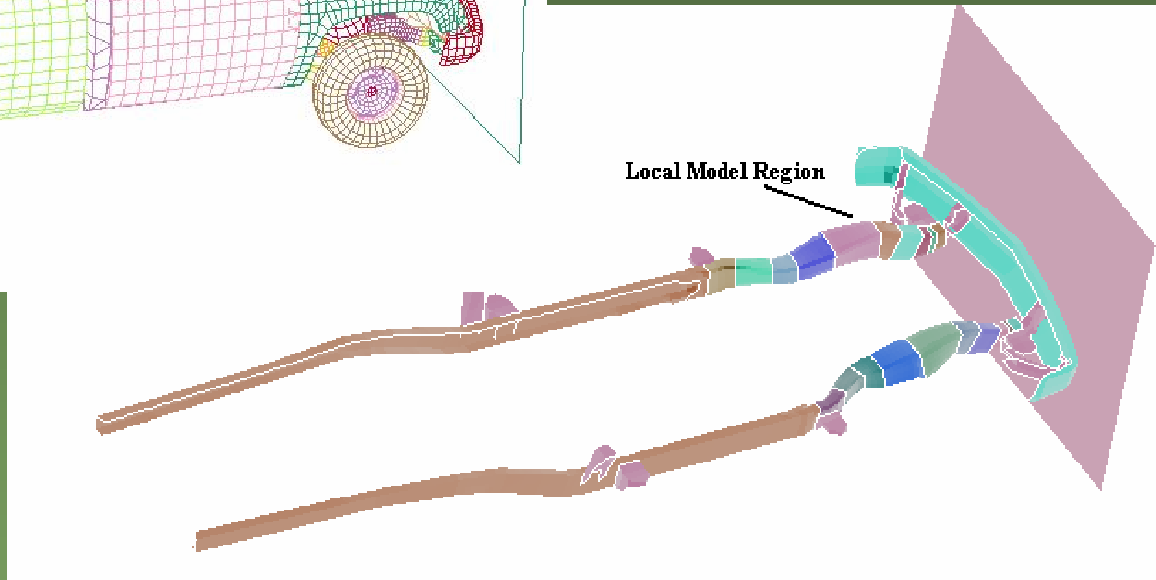


Keys to the Convergence Strategy

- Make subsystem design robust against changes in interactions (subsystem boundary conditions)
- Similar modality of response in sequential designs
  - Gradients
  - Eigenvectors
  - Etc.
- Consequence: Higher level of system robustness

Vehicle Rail –Shape Optimization



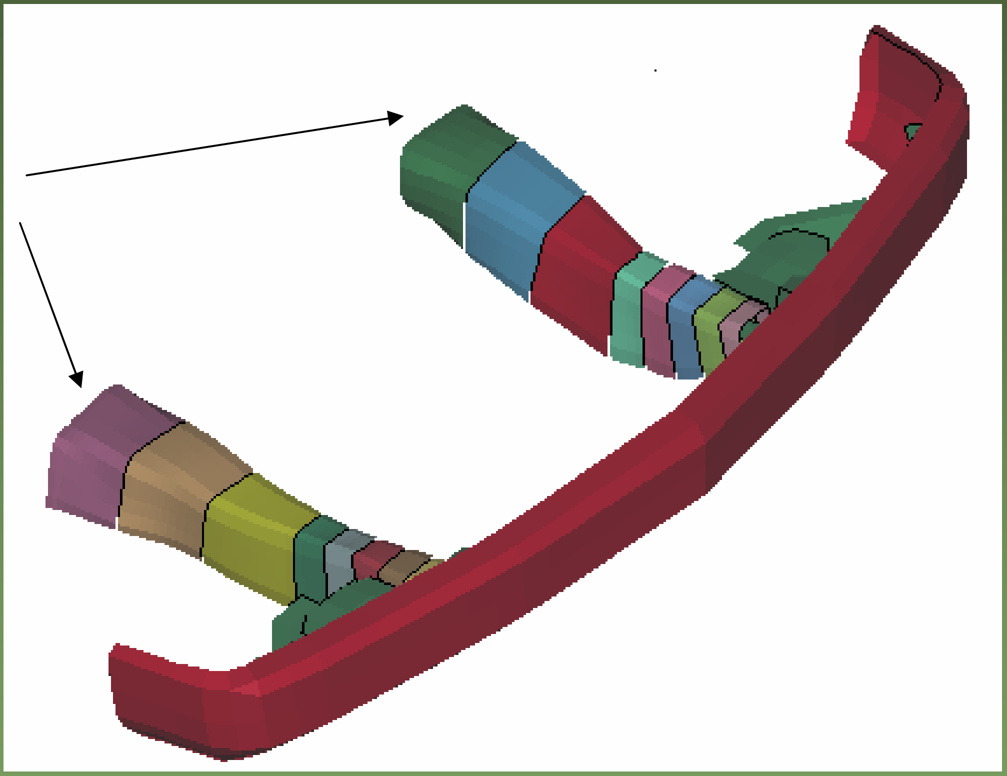


Objective : Maximize Energy Absorbed

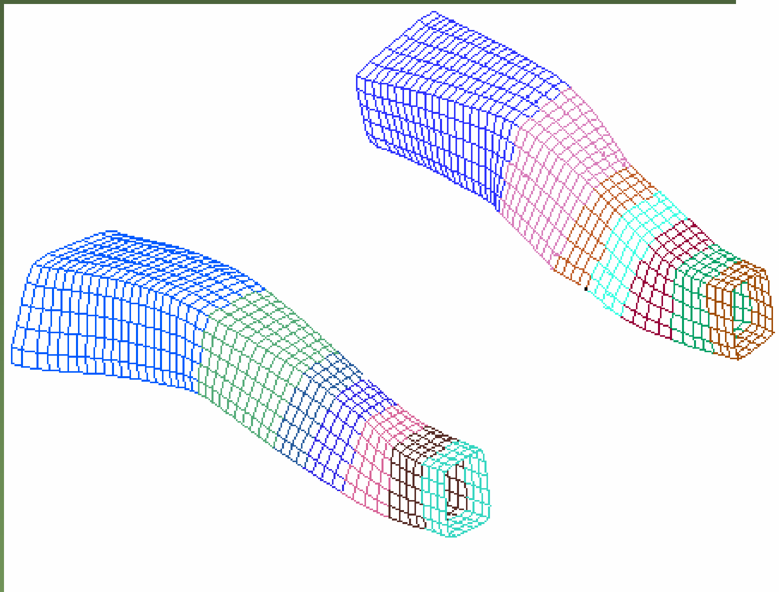
Constraint : Reaction Force

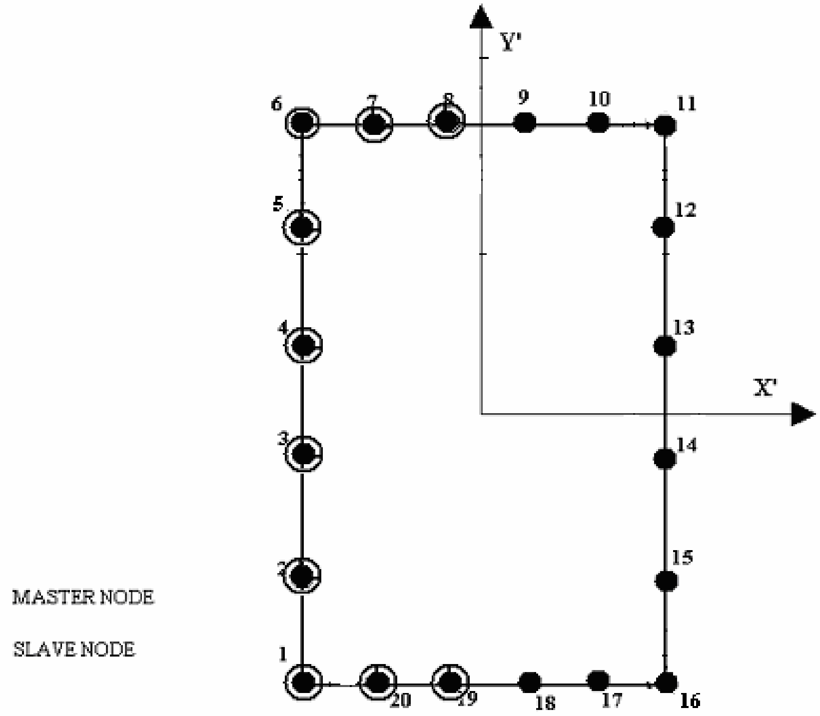
Subsystem Model

Boundary Conditions from System Model



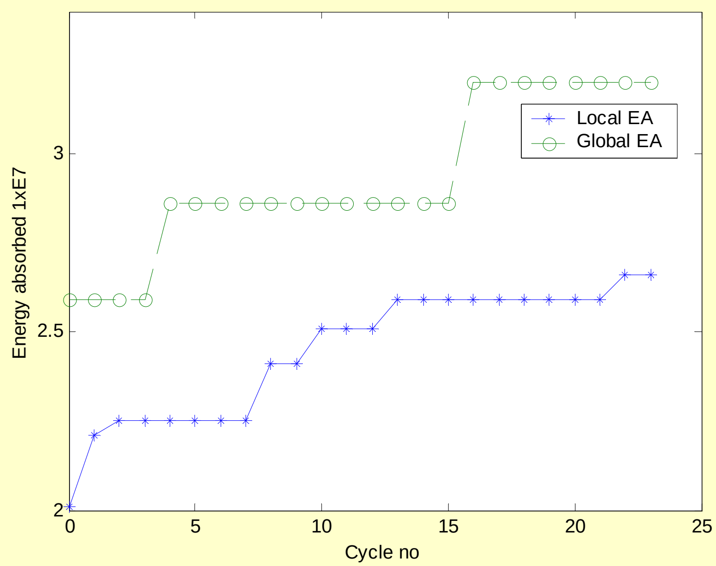
Subsystem Design Variables

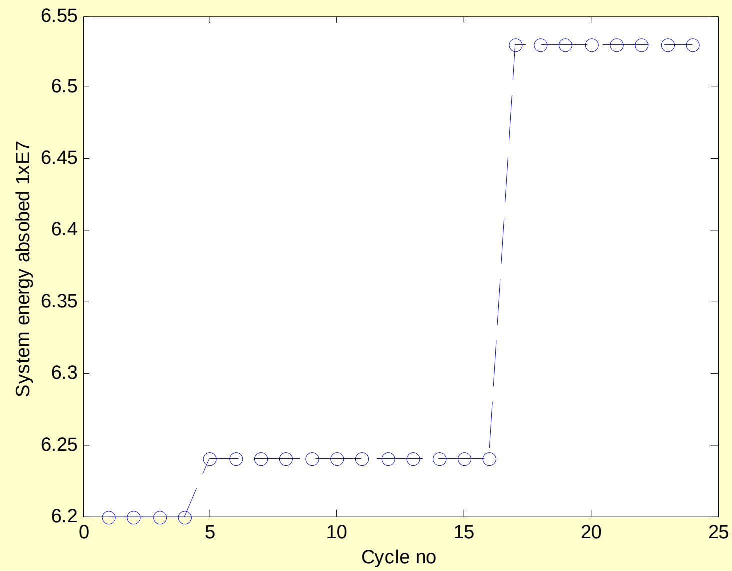




- Individually designed rails
- 7 Cross-sections on each rail
- 10 Design- master points on each cross-section
- Total of 70 shape design variables; symmetry fixes 140 values

Rail Optimization Results





Rail Energy Absorbed
(30% increase)

System Energy Absorbed
(5.5% increase)

(Optimization over 70 variables using only 6 system evaluations.)

There is no "Easy Button"

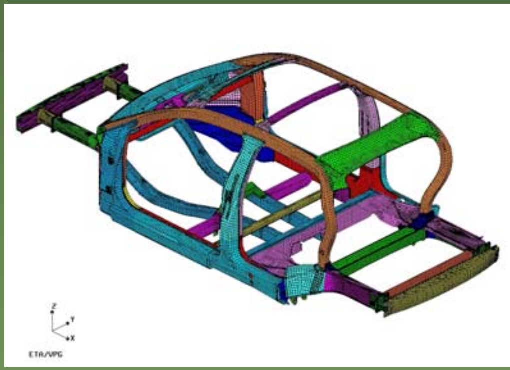
HEEDS is:

- An engineering tool
- Not "pixie dust" or an "easy button"

HEEDS requires:

- Good engineering
- Good ideas / concepts

Designing with HEEDS for Future Generation Passenger Compartment (US Auto/Steel Partnership)



- Stage 1 – Conceptual design for side impact, rollover
  - Topology optimization
  - Upper body, underbody load paths
  - Ignore fine details of the structural members
- Stage 2 – Screening
  - Design of Experiments
  - Identify members or subsystems that have greatest “effect” on performance
  - Primary factors include gage and material properties
- Stage 3 – Detailed design of cross-sections
  - Optimization of shape, gage, material to enhance performance while reducing mass