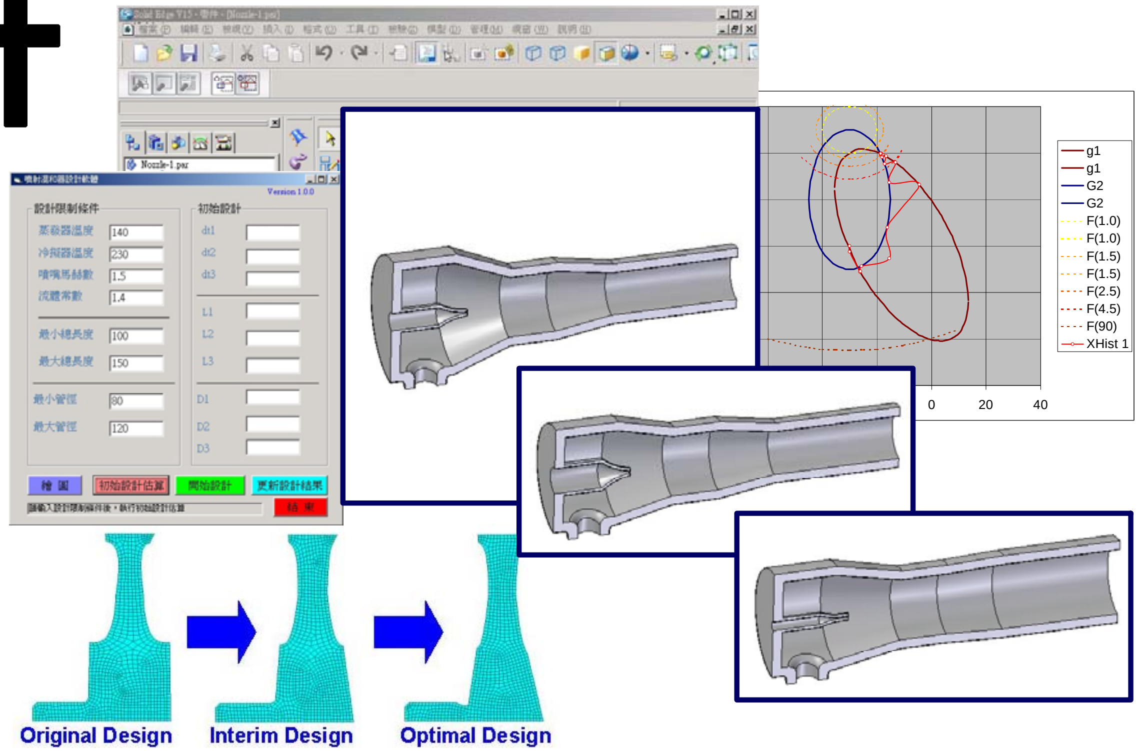
SmartDO
A Smart Design Optimization System

CAE最佳化與可靠度設計

2007/11/29



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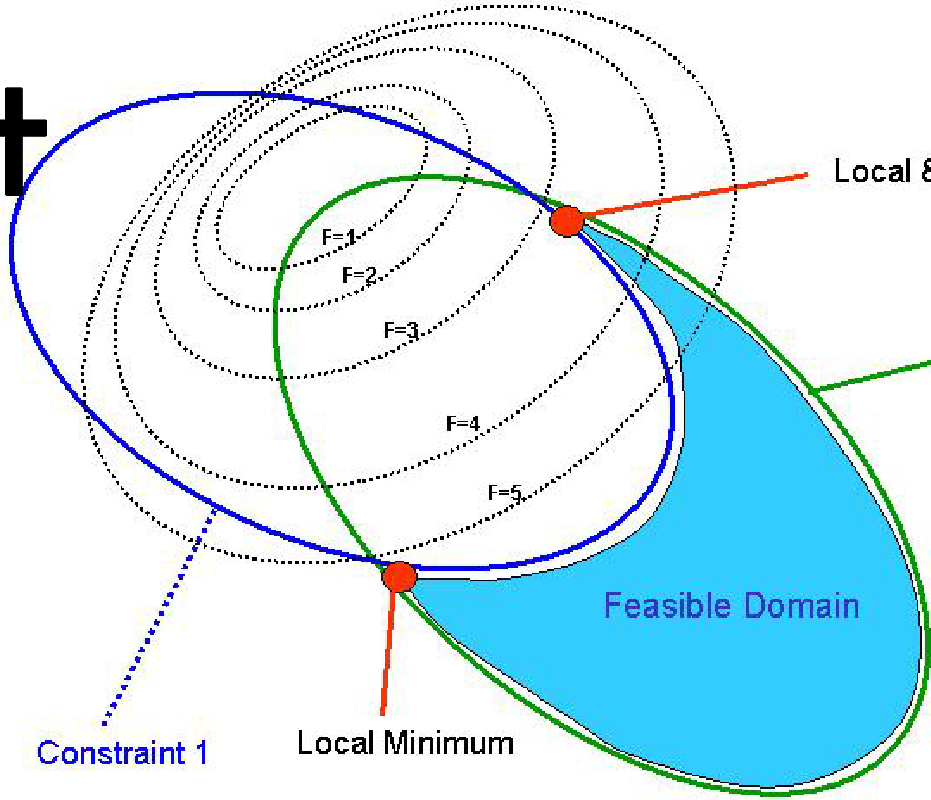
數值最佳化設計之基礎理論



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甚麼是設計自動化與數值最佳化
甚本概念

- 簡單地說, 我們希望用系統性的方法, 使設計的行為變得更快速, 更容易預測, 更容易成功, 更容易掌控且共自動化
- 數值自動化, 就是把設計問題, 設法以通用的數學模式來描述, 然後以系統性的方法將此數學模式求解,進而達到設計自動化的目標
- 透過數值最佳, 設計問題被轉變成數學問題, 而不再只是經驗,心理及藝術的交織行為

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人類摸索的過程與歷史

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- 首先找出所有設計問題的共同模式與特色
- 接著針對這些特色建立一般性的通用數學模式
- 開發出求解此數學模式的演算法
- 開發執行演算法的電腦程式
- 將電腦程式與CAE分析程式組合
- 真對特定產業及產品, 將系統客制化, 達到“單鍵設計” (push-button design)的目的

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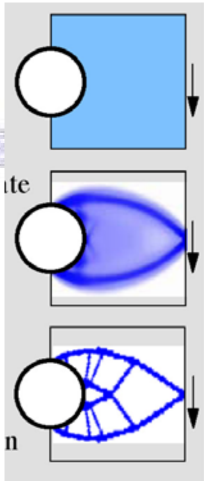
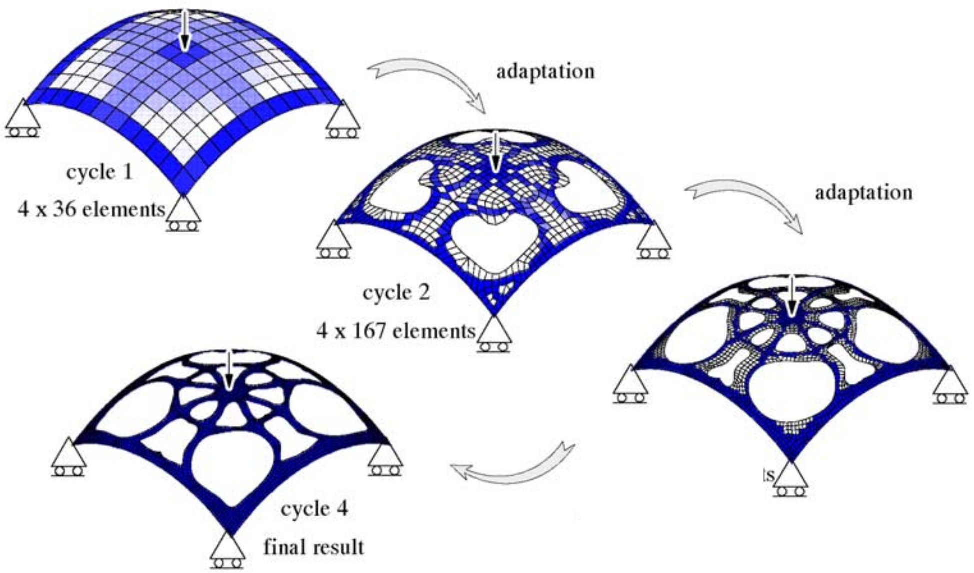
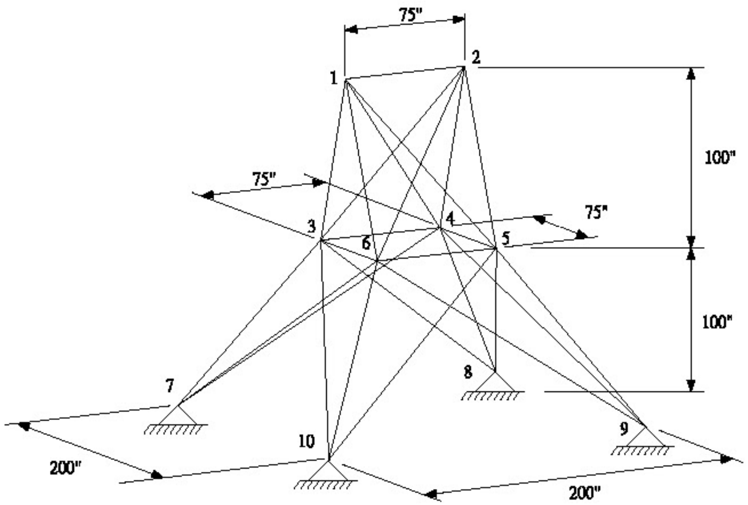
人類摸索的過程與歷史

- 早在1638年, 將設計問題數學化的想法已萌芽且付諸實現
- 1904年, Mitchell即成功地以數學方法, 求出特定結構物的最經濟設計, 此被稱作為Mitchell Structure
- 1970年代, NASA已能使用電腦作大型結構物的自動最佳化設計運算







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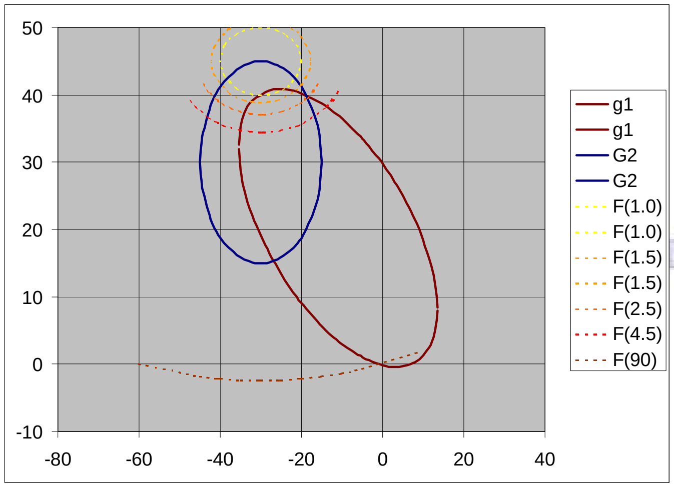
人類摸索的過程與歷史

- 我們發現, 許多的思考行為都可以套用類似的數學模式與理論. 也就是說,數值最佳化與設計自動化的原理, 事實上可以套用在許多的行為上
  - 設計, 排程, 決策, 人工智慧
  - 經濟行為(remember the movie "A Beautiful Mind" about John Nash's research and achievement)
  - 生物演化(The golden ration existing in the nature).



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人類摸索的過程與歷史

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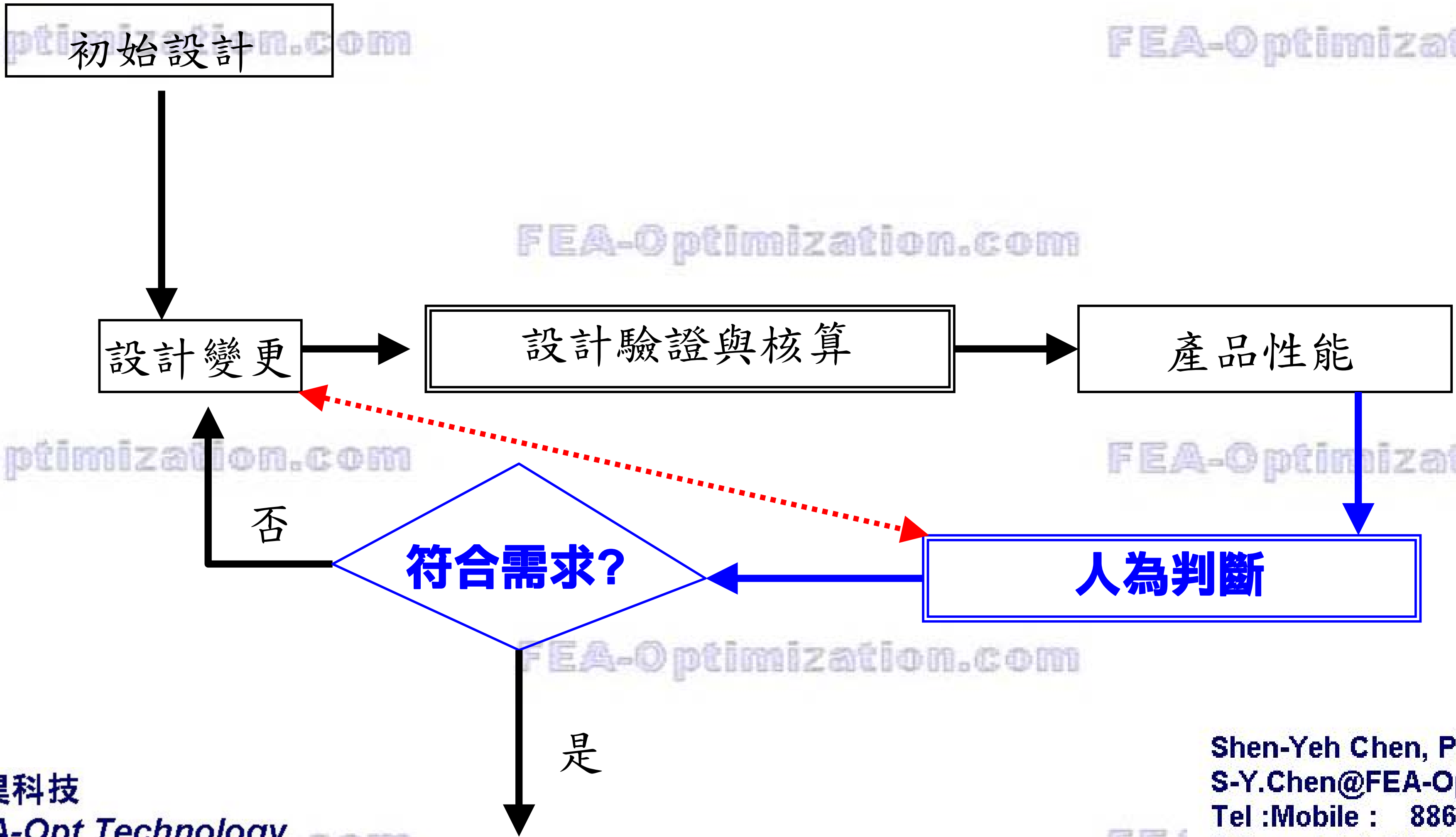
- 一般的設計通則



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人類摸索的過程與歷史

- 目前最通用的數學模式: Nonlinear Programming (NLP)

find	$\mathbf{x} = \{x_1, x_2 \ldots\ldots x_{NDV}\}$	Design Variables
to minimize	$f(\mathbf{x})$	Objective Function
subjected to	$G_i(\mathbf{x}) = \dfrac{g_i(\mathbf{x})}{g_i^0} - 1 \le 0 \quad i = 1, \ldots\ldots, NINEQC$	Inequality Constraints
	$H_j(\mathbf{x}) = \dfrac{h_j(\mathbf{x})}{h_j^0} - 1 = 0 \quad j = 1, \ldots\ldots, NEQC$	Equality Constraints
	$x_k^L \le x_k \le x_k^U \quad k = 1, \ldots\ldots, NDV$	Lower/Upper Bounds

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人類摸索的過程與歷史

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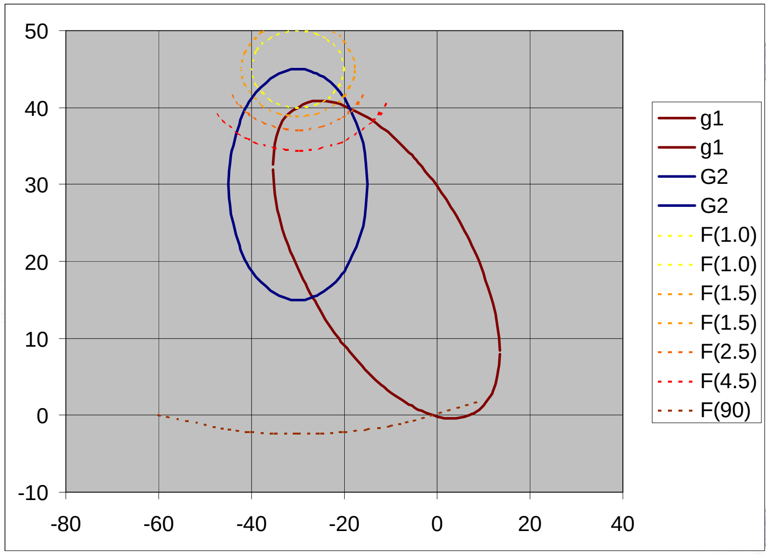
- 簡單地說, 目前的數學模式作以下的假設
  - 我們必需明確地知道那些參數是我們可以改變,而且會影響設計的
  - 設計必需符合許多不同的條件(稱之為"束制"), 例如, 應力, 變型, 干涉, 壓縮量, 效能, 時程, 而我們必需能以直接或間接的數學式來表示及運算
  - 在這些限制中, 當然通常有無限多個設計及決策都可以符合我們的要求, 但是我們希望能找到一個最佳(最大或最小)的目標, 例如, 成本,重量,效能, 強度等等
  - (我們會在後續的章節中作更多說明)



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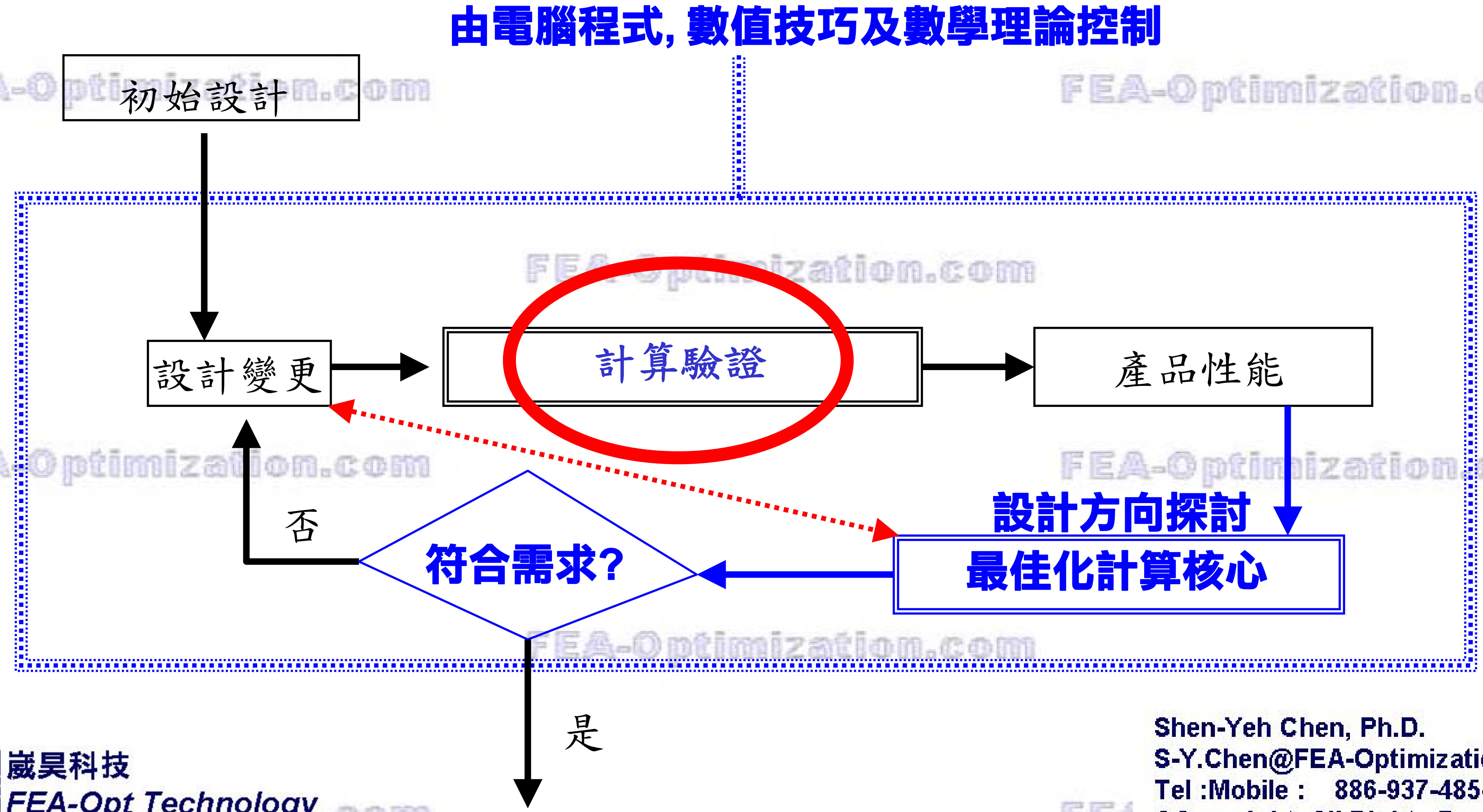
甚麼是數值最佳化設計與設計自動化

簡單原理



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為甚麼使用數值最佳化設計技術

- 一般而言,我們必需同時兼顧成本及其它許多考量, 而這些需求通常都是互相抵觸的
  - 以結構設計為例,我們一方面希望強度越高越好, 一方面又希望用料越省越好
  - 以空氣動力零組件設計為例(如壓縮機葉片或飛機翼), 通常我們希望葉片越薄越好以提高空氣動力效能, 但這卻會使結構強度過於薄弱
- 解決這些互相抵觸的複雜問題,通常不是人腦所能負擔
- 以今天的設計問題的複雜度而言,如果以暴力法嘗試所有的可能, 公司可能早已倒閉
  - 以10個設計參數為例,如果每個參數嘗試3種變化, 一共約有60,000種可能性
  - 假設每次設計的運算驗證為1分鐘, 至少要花40天

  - 最先進的SmartDO技術, 上述的題目,可能只需 200~300次運算

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Mathematic Formulation

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Typical Form

- Before we want to apply numerical optimization into any problem, we have to describe it in mathematical language – this is called the **Mathematical Formulation**
- If we can describe the design goal in the typical mathematical formulation, then the problem of design will become the problem of solving that mathematical formulation
- .

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Mathematatic Formulation

Typical Form

- This is the most typical form

find	$\mathbf{x}=\{x_1,x_2......x_{NDV}\}$	Design Variables
to minimize	$f(\mathbf{x})$	Objective Function
subjected to	$G_i(\mathbf{x})=\dfrac{g_i(\mathbf{x})}{g_i^0}-1\le 0 \quad i=1,......,NINEQC$	Inequality Constraints
	$H_j(\mathbf{x})=\dfrac{h_j(\mathbf{x})}{h_j^0}-1=0 \quad j=1,.......NEQC$	Equality Constraints
	$x_k^L \le x_k \le x_k^U \quad k=1,.......,NDV$	Lower/Upper Bounds

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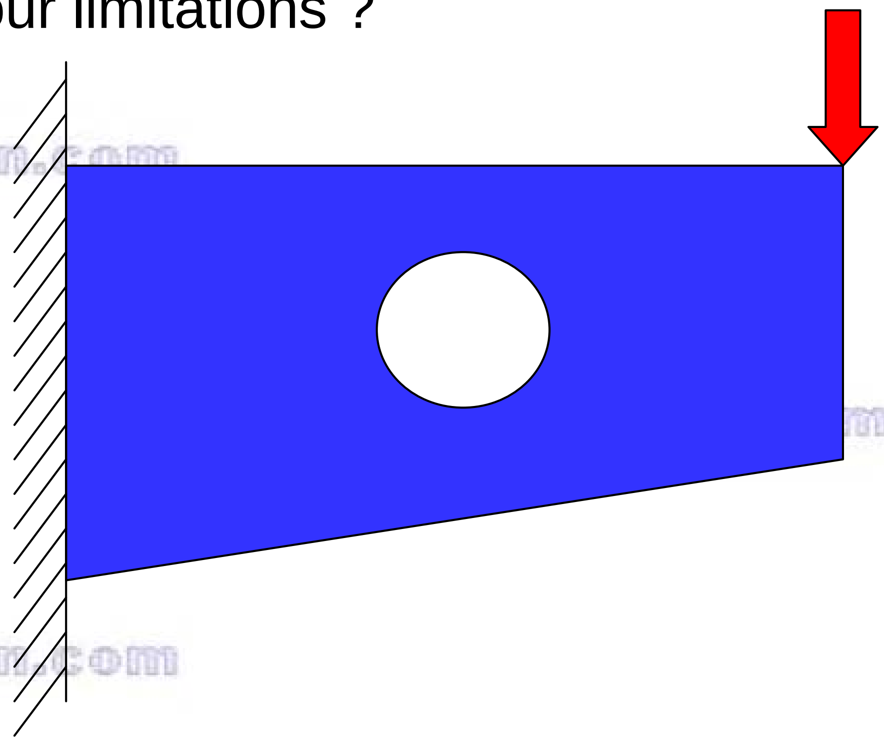
Mathematic Formulation

Typical Form

- For example, suppose we have to design a structure to support certain load, what should we consider for the design ?
  - What can be changed, and will effect out design tasks ?
  - What should we satisfied ? And What are our limitations ?
  - What goal do we want to achieve ?
  - What are the design variables ?
  - What are our constraints ?
  - What is our objective ?
  - .



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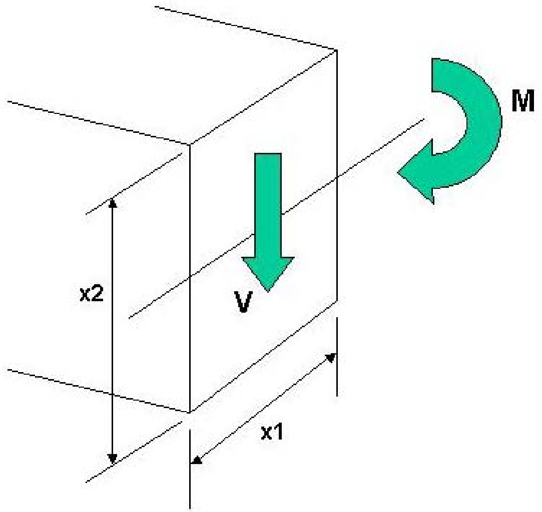
Mathematic Formulation

Typical Form

- Another example of mapping formulation into the real problem most typical form : find the cross-section with minimum area, that will satisfy the stress/strength requirement



find	(x1, x2)	Design Variables
to minimize	(Cross-section area x1*x2)	Objective Function
subjected to	(Max stress – allowable stress < 0)	Inequality Constraints
	$x_k^L \le x_k \le x_k^U \quad k = 1,.......,NDV$	Lower/Upper Bounds

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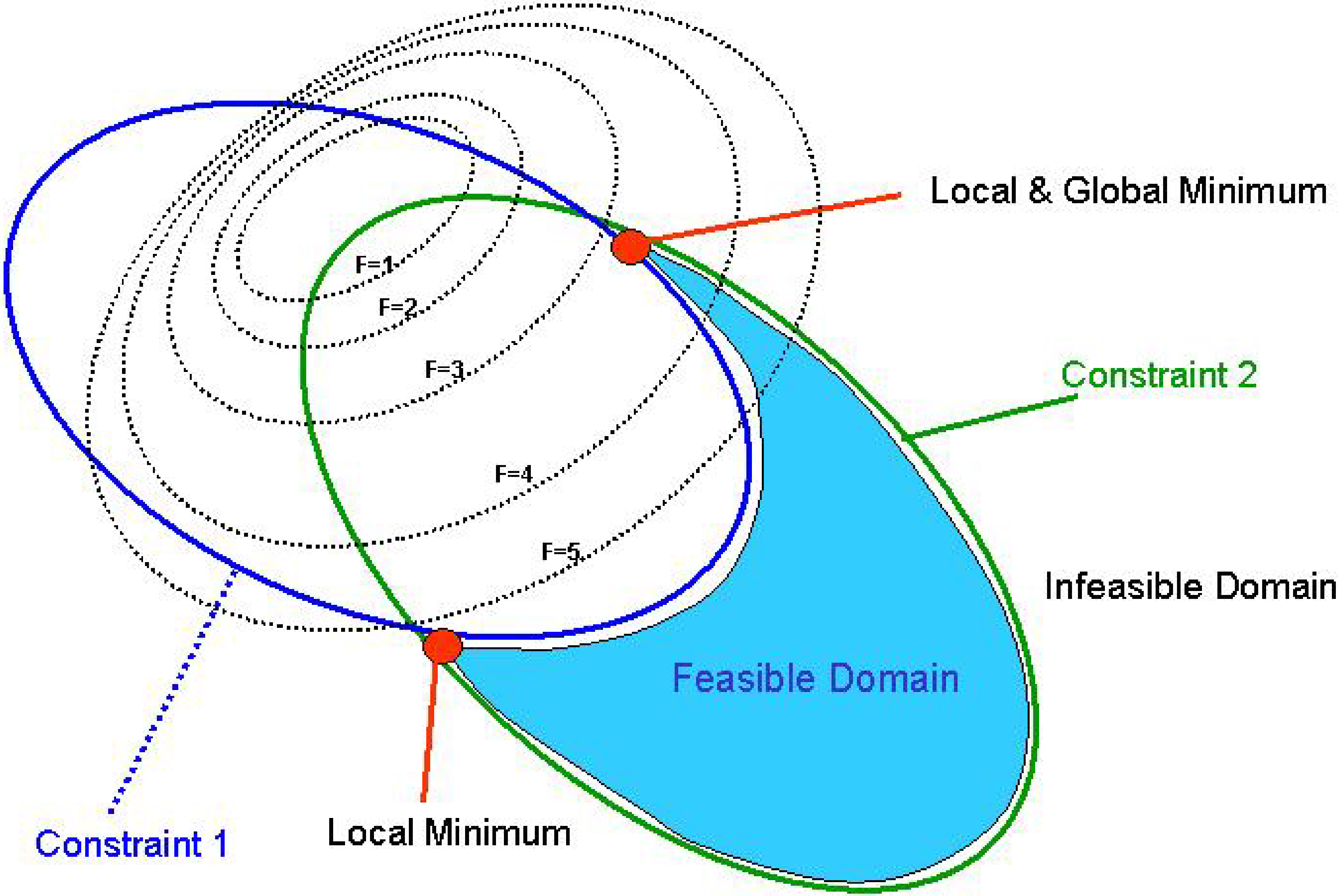
Mathematic Formulation

Typical Form



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Mathematic Formulation

The Significance and Importance

- Mathematical formulation is a mapping from the physical problem to the mathematical model
- Most of the engineering design problems can be simplified and fit into this formulation
- Formulation for one problem is generally not unique. Different formulation will result in different or the same solution
- Formulation is the first and the most important step in optimization
- .

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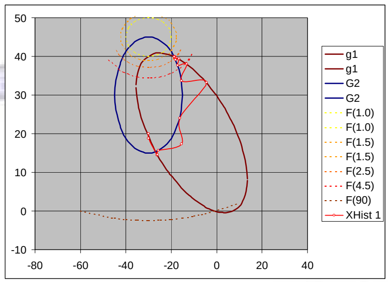
Solution Algorithms

What Do We Have Today

- There are two major categories of algorithms today

- Deterministic, and or gradient/function based
    - Sometimes also called NLP (Nonlinear Programming)
    - We figure out the math formulation through data points, and search the optimal based on our assumption.
    - The is “deterministic”, which means we pretty much know what we are doing, and it is predictable.
    - Sequential Linear Program (SLP), Sequential Quadratic Programming (SQP), Method of Feasible Directions (MFD), Conjugate Feasible Direction Method (CFDM), Recursive Conjugate Feasible Direction Method (RCFDM), Response Surface Approximation (RSA)



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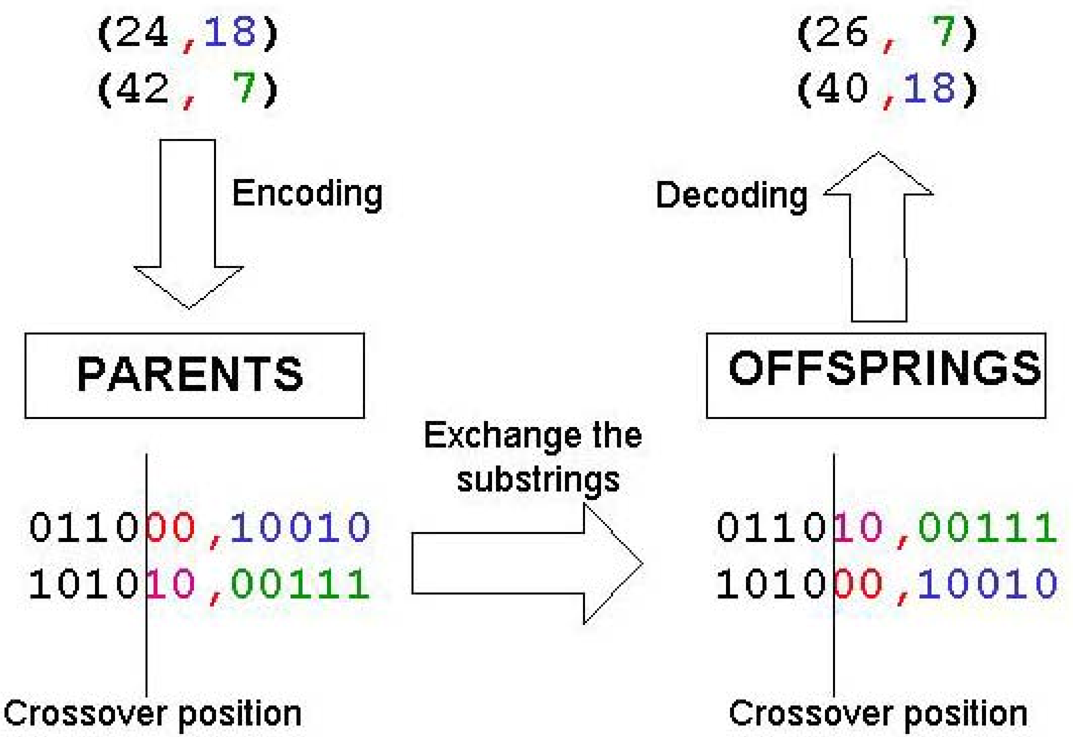
Solution Algorithms

What Do We Have Today

- Heuristic, and/or statistic based
  - Based on "ad-hoc" or statistical experience. Usually there is no strong math prove for convergent properties.
  - Genetic Algorithms (GA), Simulated Annealing (SA), Neural Network, Tabular Search



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Solution Algorithms

What Do We Have Today

- Simple Comparison

	Gradient-Based	Heuristic
Smooth Function Havior	Required (1)	Not required
Discrete DV	Not Suitable /Indirectly	Suitable
Combinatory DV	Not Suitable	Suitable
Global Optimization	No(2)	Yes
Descent Properties	Yes	Usually No(3)
Smooth Design Change	Yes	No
Deterministic	Yes	No
Design Sensitivity	Yes	No
Stable/Automatic Formulation for Parameters	Yes	No (4)

1. SmartDO Gradient-Based solver allows minor to medium numerical noise
2. SmartDO Gradient-Based solver can perform global optimization
3. SmartDO RGA has descent properties
4. SmartDO RGA uses automatic/adaptive parameters calculation

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Solution Algorithms

Comparison with a Simple Example

$$\text{find:}\quad \mathbf{x} = \{x_1, x_2\}$$

$$\text{minimize:}\quad f(\mathbf{x}) = \left(\frac{x_1 + 30}{10}\right)^2 + \left(\frac{x_2 - 45}{5}\right)^2$$

subjected to:

$$G_1(\mathbf{x}) = \frac{0.52 * x_1^{\,2} - 3.12 * x_1 + 0.72 * x_1 * x_2 - 21.6 * x_2 + 0.73 * x_2^{\,2} - 3.68}{100} \le 0$$

$$G_2(\mathbf{x}) = \frac{225 - (x_1 + 30)^2 - (x_2 - 30)^2}{225} \le 0$$

$$-60 \le x_1 \le 20$$

$$-10 \le x_2 \le 60$$

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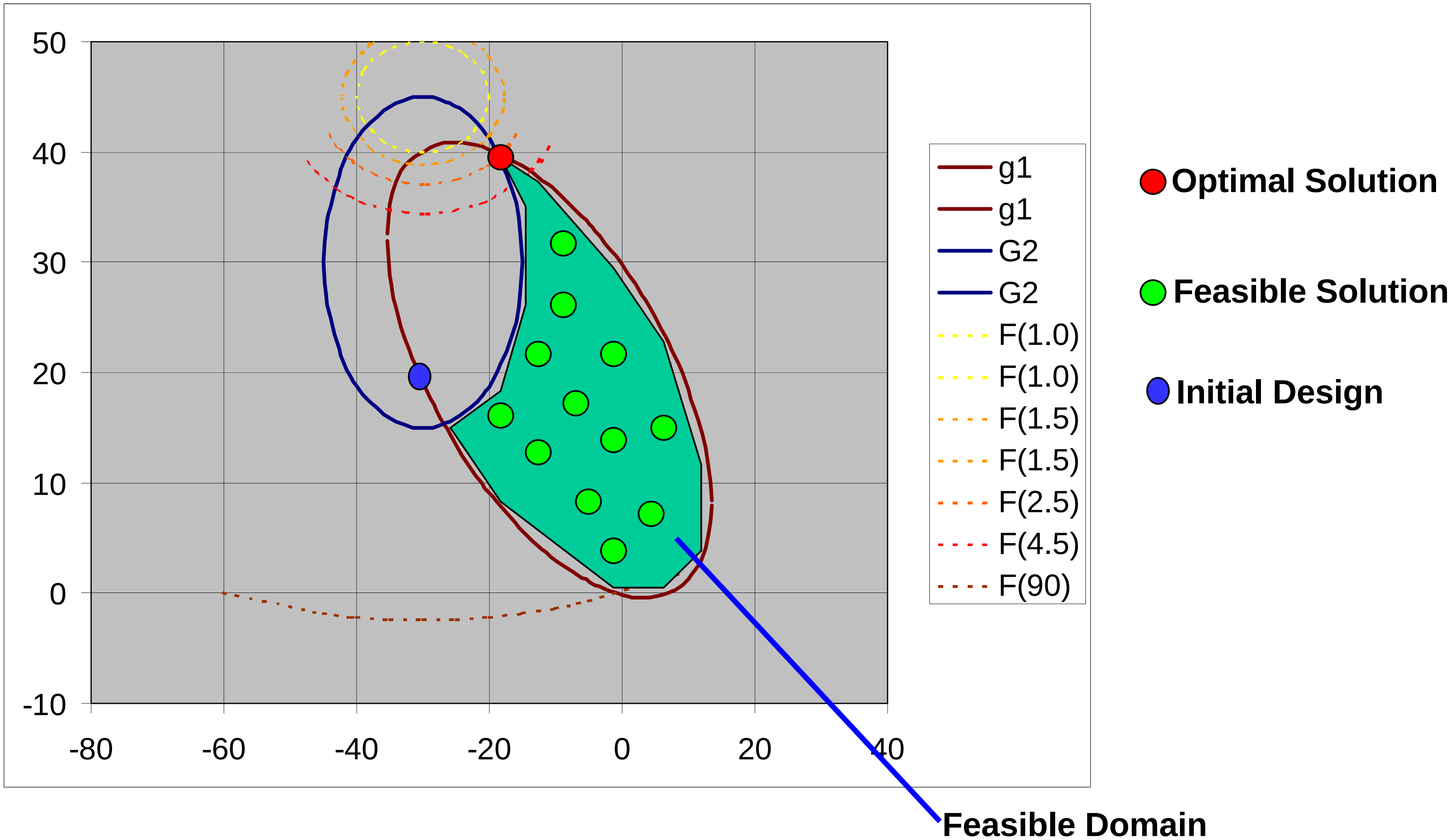
Solution Algorithms

Comparison with a Simple Example



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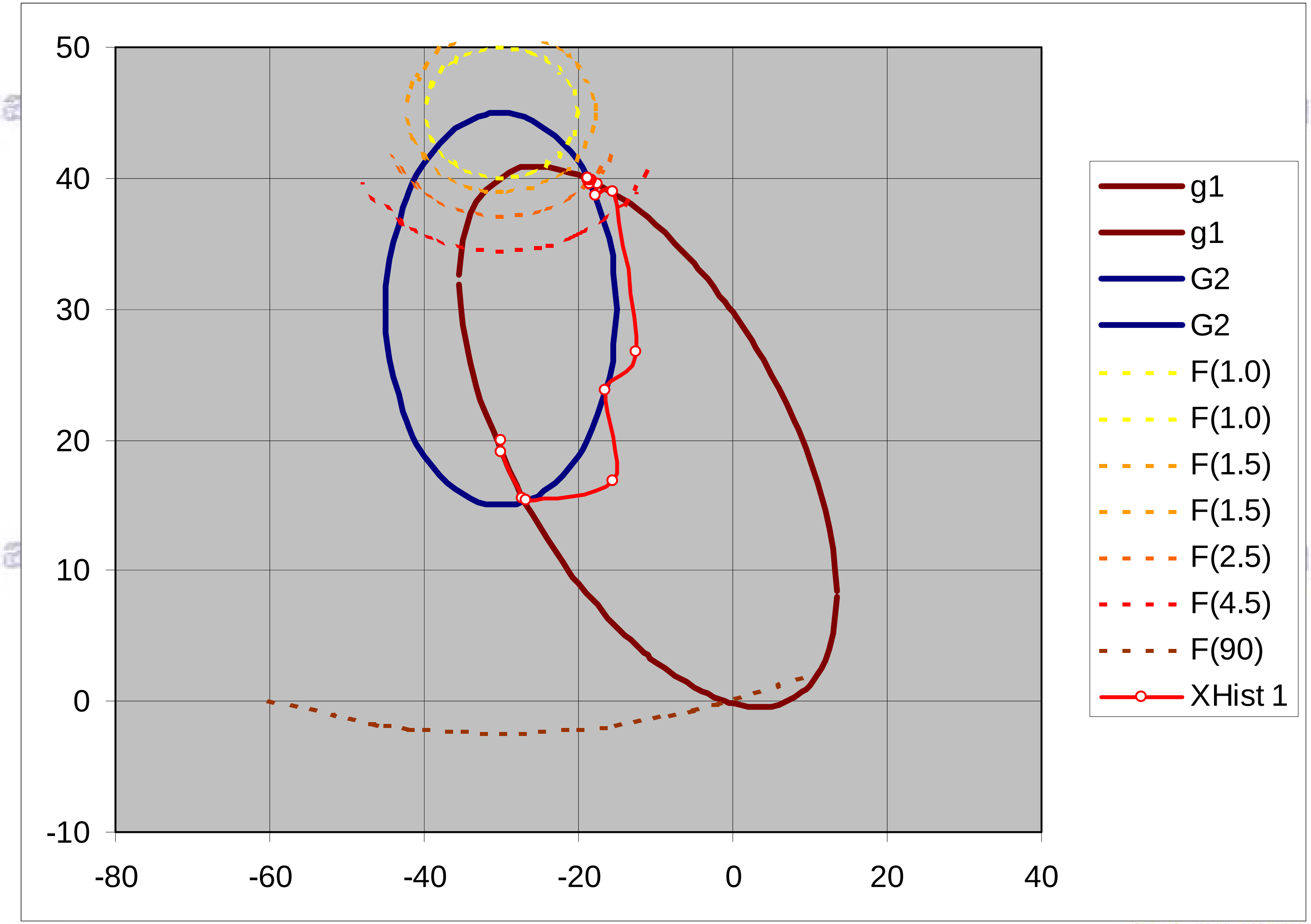
Solution Algorithms

Comparison with a Simple Example : Gradient-Based

- This is what the searching path looks like



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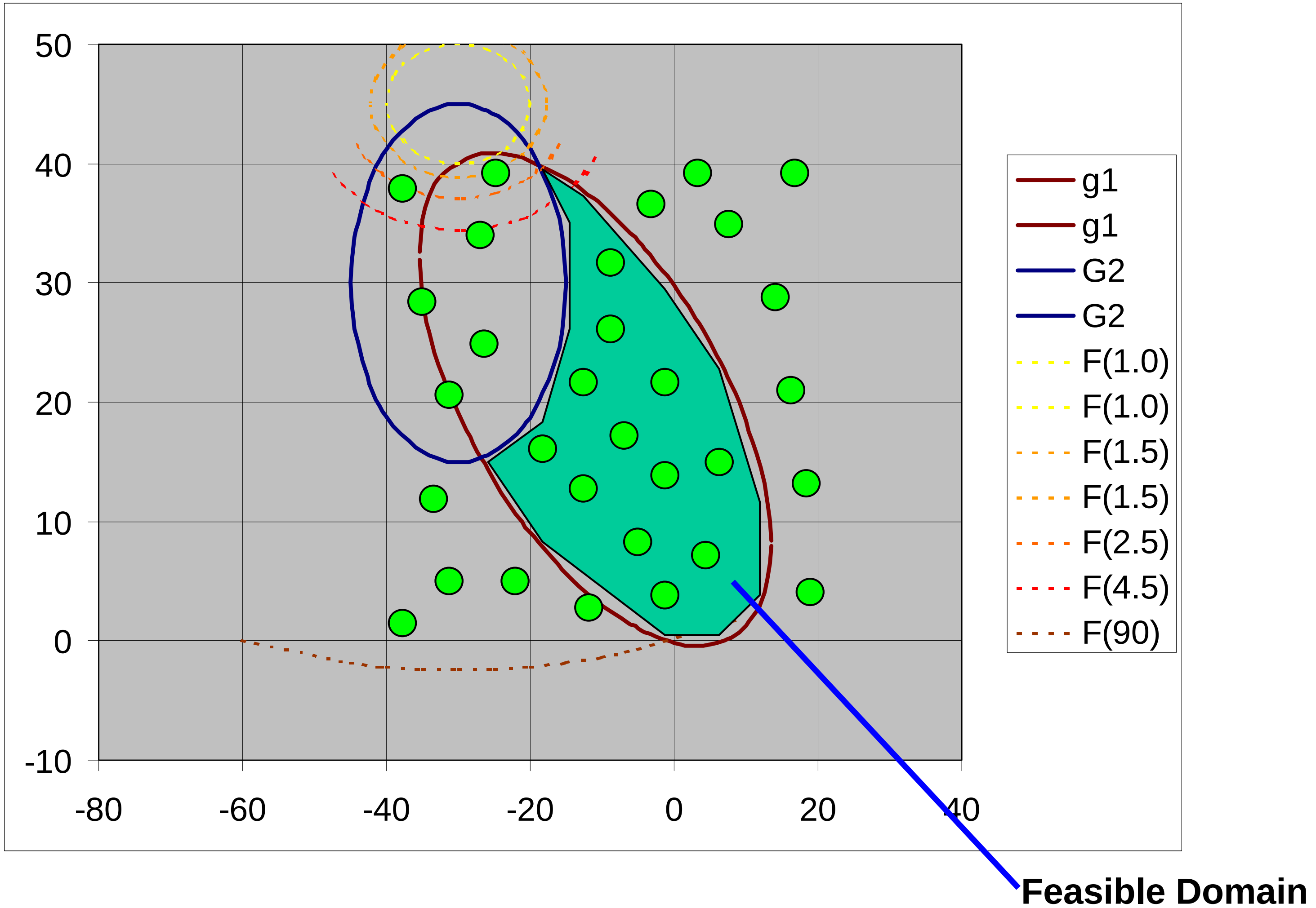
Solution Algorithms

Comparison with a Simple Example : GA-Based / Step 1



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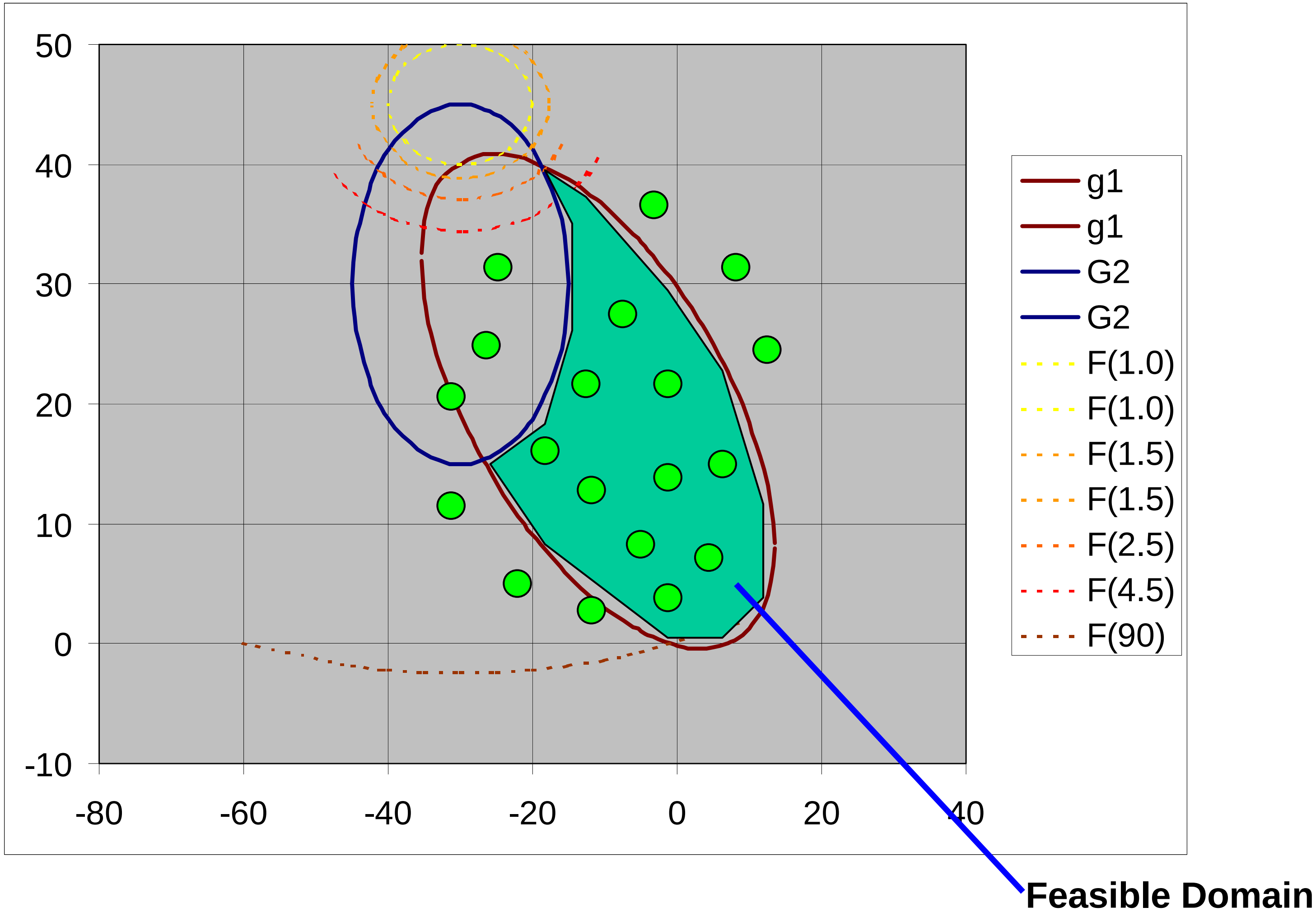
Solution Algorithms

Comparison with a Simple Example : GA-Based / Step 2



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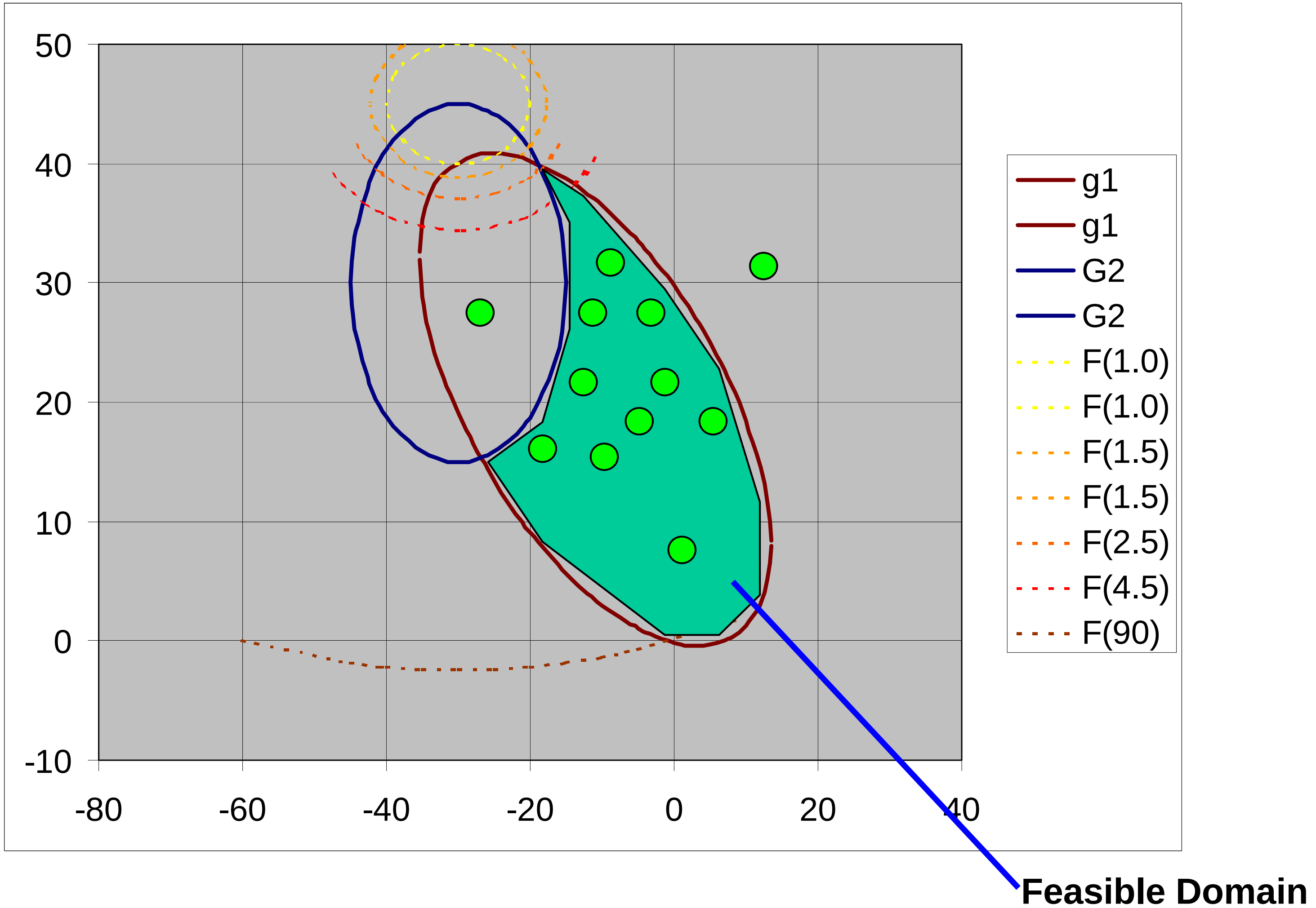
Solution Algorithms

Comparison with a Simple Example : GA-Based / Step 3



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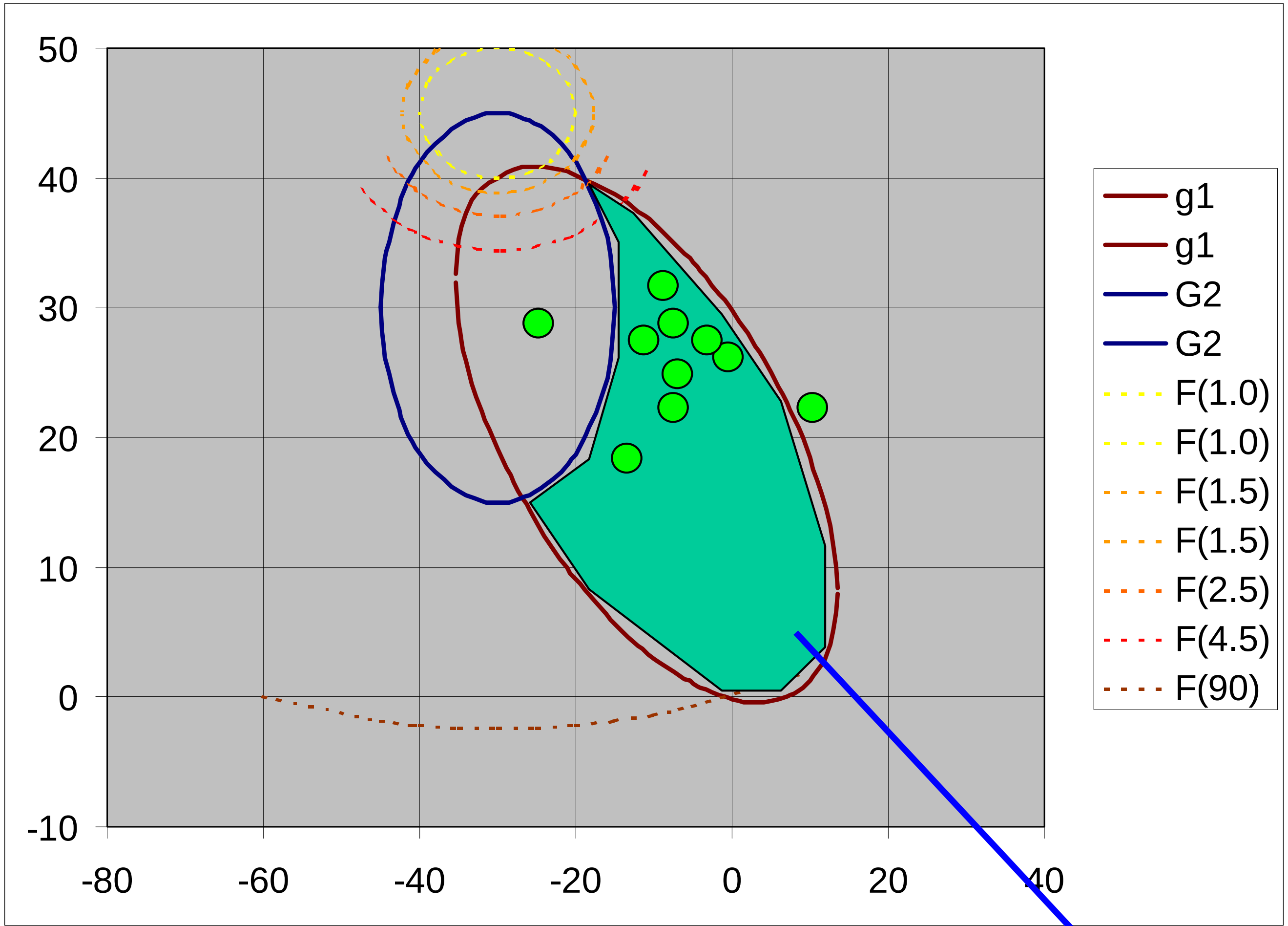
Comparison with a Simple Example : GA-Based / Step 4



Feasible Domain

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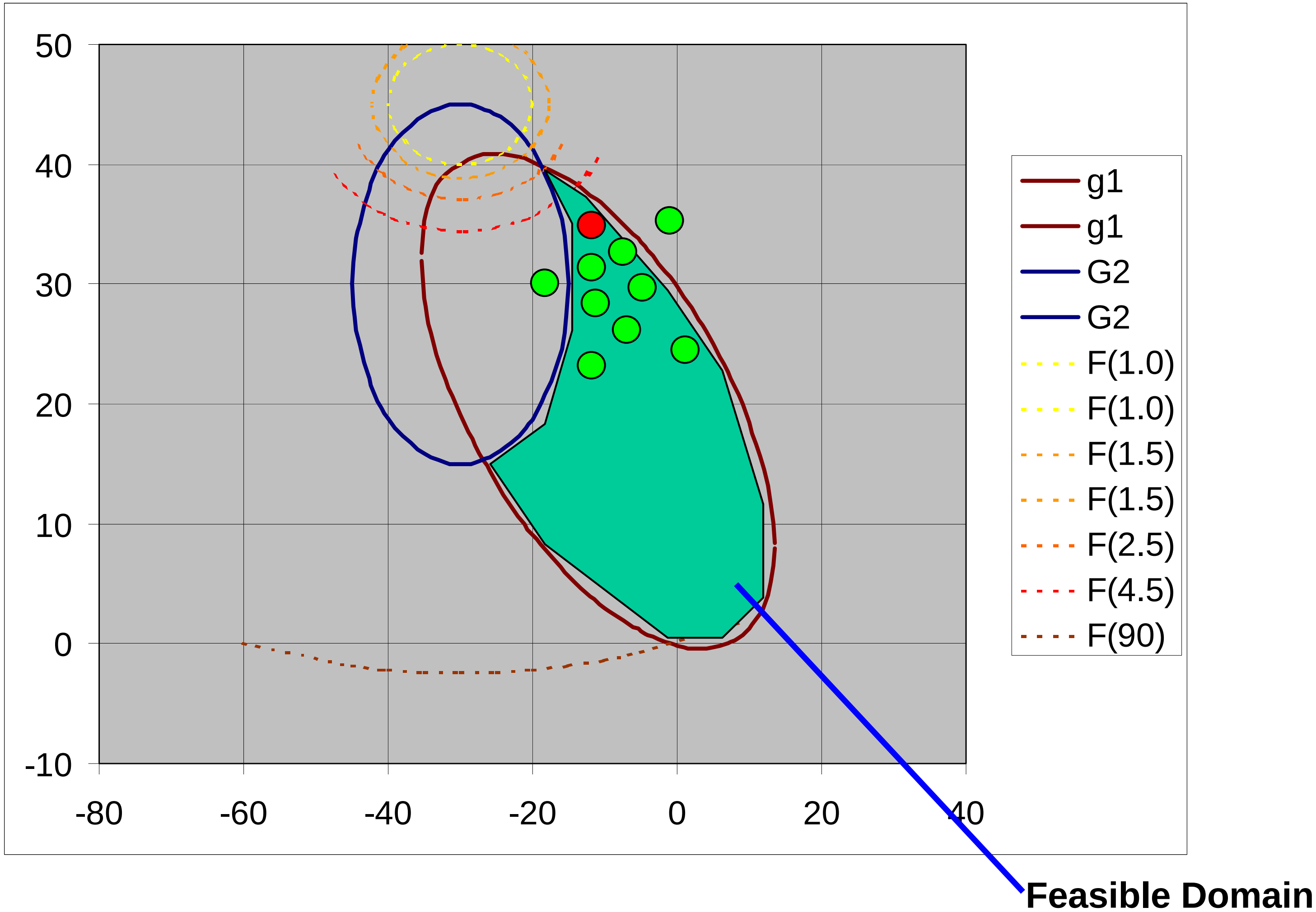
Solution Algorithms

Comparison with a Simple Example : GA-Based / Step 5



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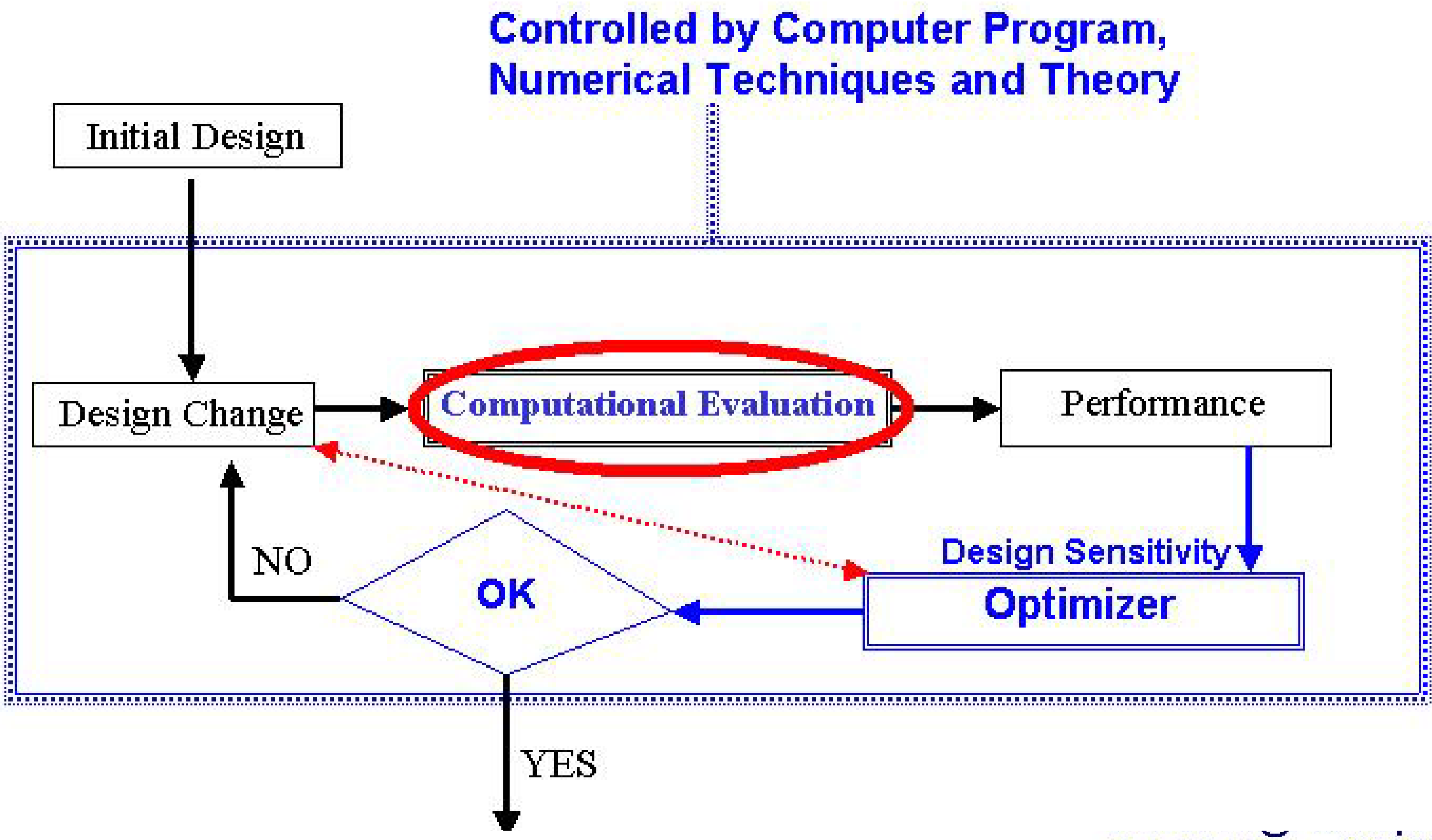
FEA-Based Optimization

Why CAE- or FEA-Based Optimization

- It is obvious that, for the purpose of numerical optimization, we need EXACT and COMPLETE mathematical formulation for response and performance evaluation, explicitly or implicitly



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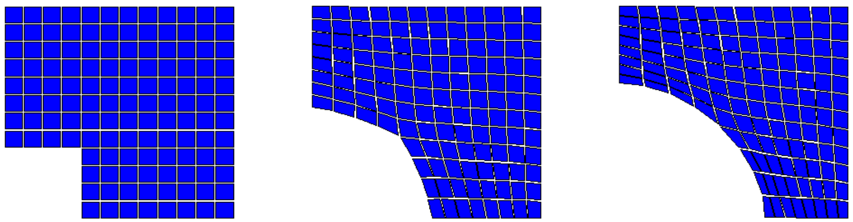
FEA-Based Optimization

Why CAE- or FEA-Based Optimization

- However, the analytical formulation is usually unavailable.
- It is impossible to perform hardware test for each design instance, because the cost will be too much.
- Empirical formulation is one possible option, however it usually does not cover full range of design space.
- The idea way of evaluating a design in a parametric, systematic and accurate way, is the CAE or FEA simulation.
- When using the CAE- or FEA-based simulation for the performance/response evaluation of numerical design optimization, we call it the ***CAE- or FEA-Based Optimization***.



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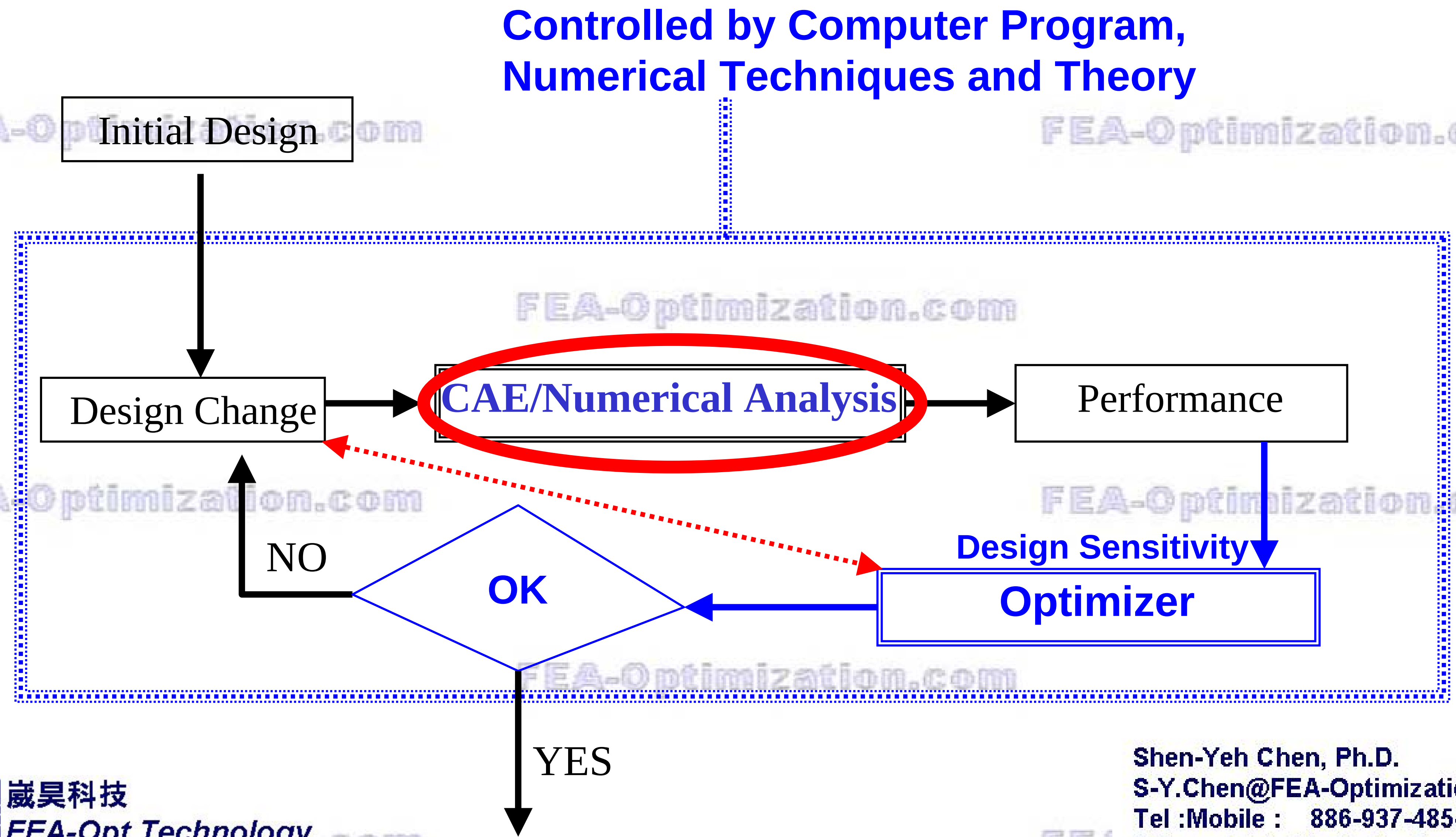
The Basic Logic



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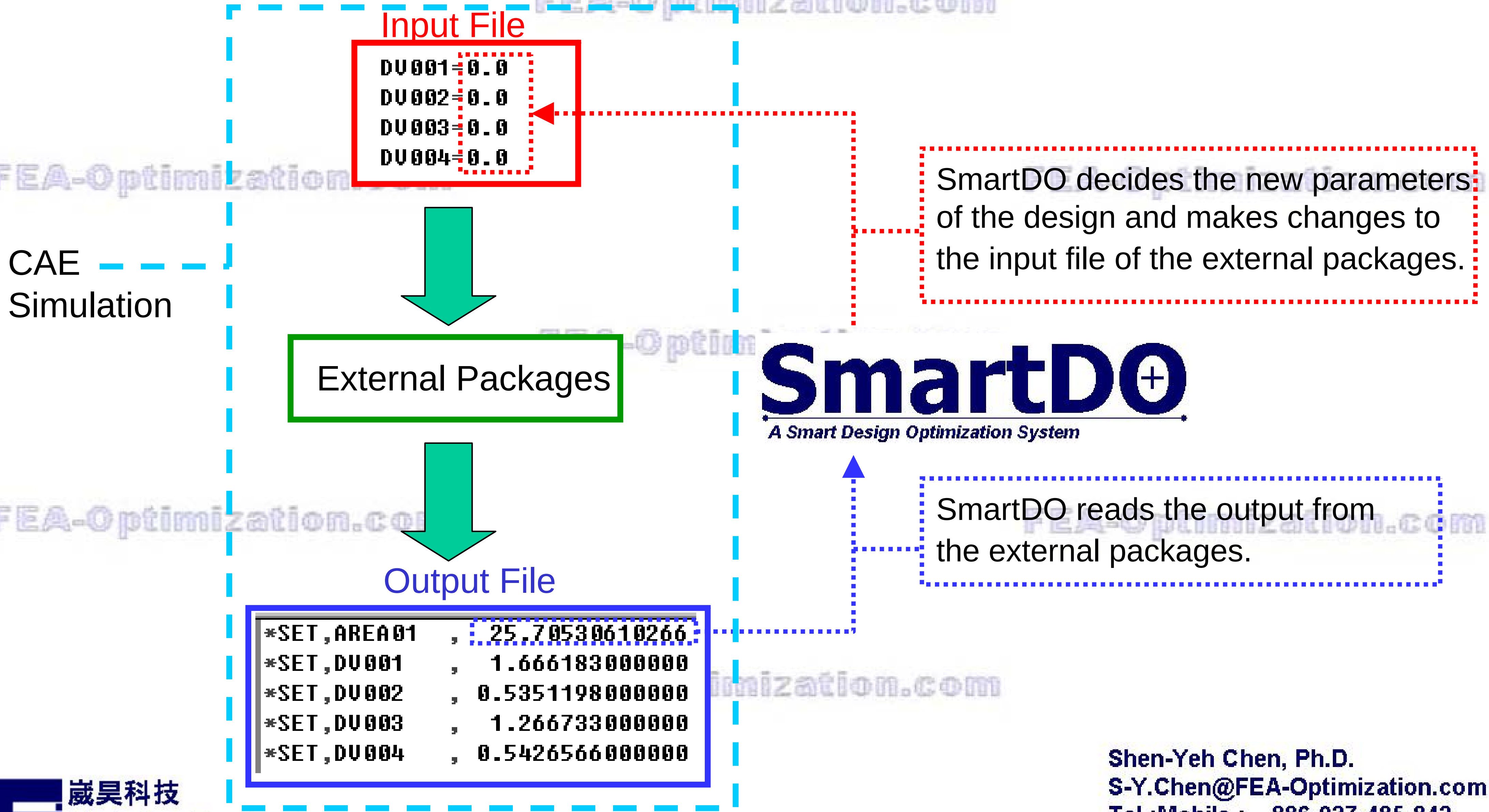
How Does Packages Like SmartDO Interact With Other Packages



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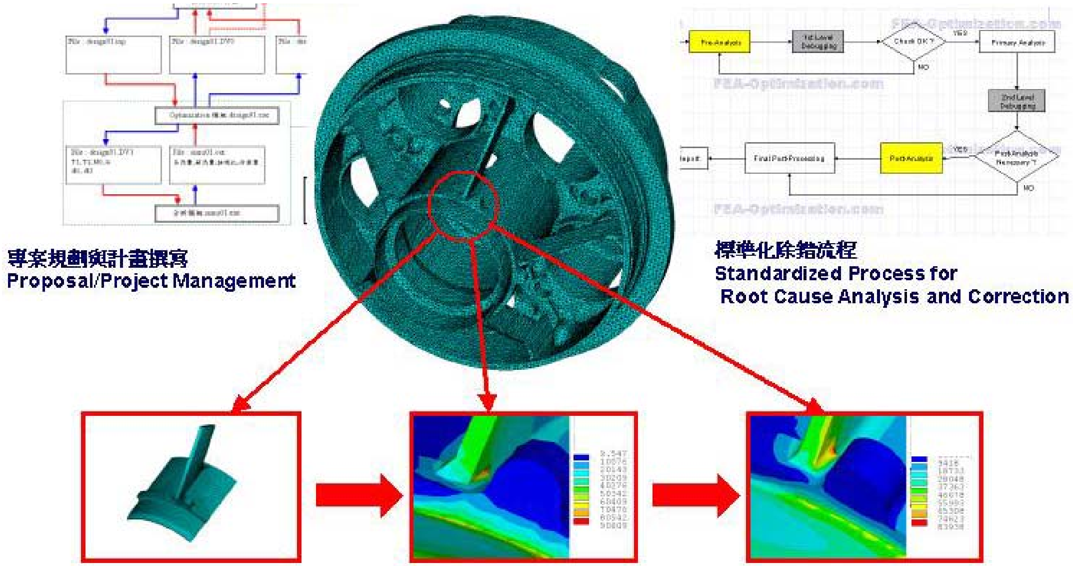
CAE, FEA and Optimization

- It is obvious now that CAE/FEA and numerical optimization are closely related.
- Reliable numerical design optimization replies on stable, accurate and confident CAE simulation
- In the next session, we will talk about the concept of product reliability analysis with CAE



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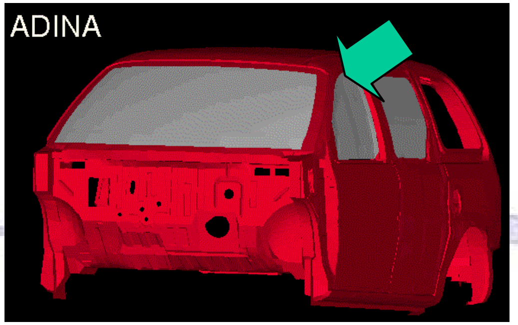
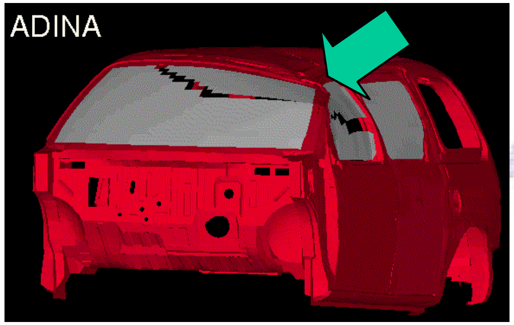
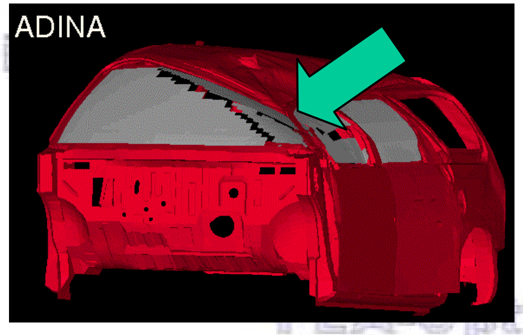
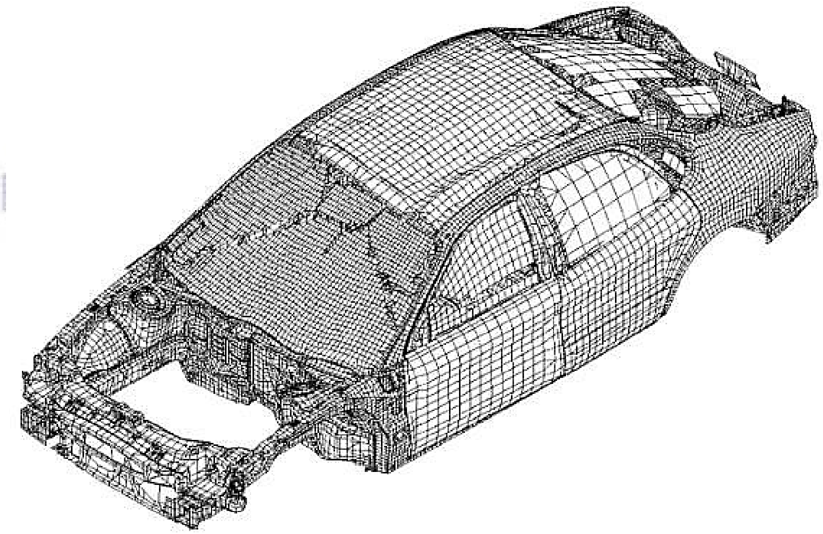
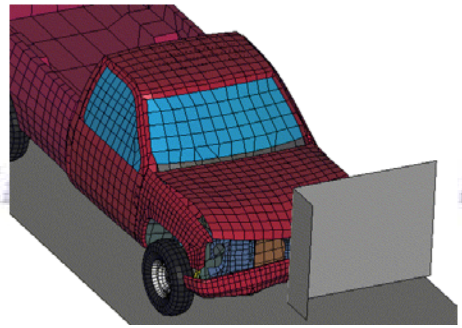


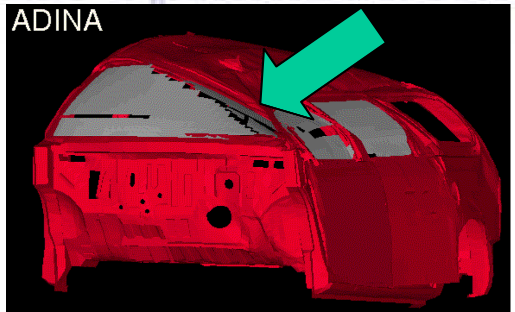


CAE可靠度設計之基礎理論









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Some Experience in Reliable Analysis
- The Philosophy

- If we do not know how it fails, we don't know how to avoid, or how to correct it. So reliability analysis is all about failure prediction
- Two major factors to find out
  - What is the loading on the structure ?
  - How does the material fail ?
- With Loading and Boundary Conditions, we can simulate, or "predict" the structural behavior
- After we have done the analysis, we need to judge from the numbers (the failure criteria)
- In this lecture, we will assume that the failure have already happens, but we want to know how it happens, and how to correct it, using FEM as the tool.
- After we have learned how to analyze the failure, we will try to predict the behavior

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Some Experience in Reliable Analysis
- The Basic Failure Criteria/Reason of Structures

- Strength
- Stiffness/Deformation
- Stability
- Durability/Life/Creep
- Defects/Fracture Mechanics
- Combinations of the above

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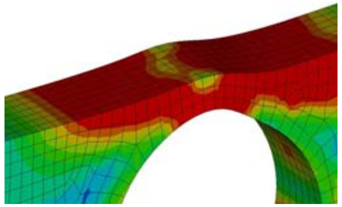
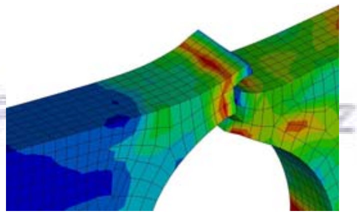
Some Experience in Reliable Analysis
- The Basic Failure Criteria/Reason of Structures

- Strength
  - When the structure is broken at one loading at certain magnitude, or only few loading cycles, it is probably failed by its strength
  - Strength failure is because the material has reached its static failure criteria. The followings are the most commonly used failure criteria
    - Brittle failure : for brittle materials. Failed by tension or compression. Judge by the Principle Stress
    - Ductile failure : for ductile materials. Failed by shear stress. Judged by the von Mises or the Shear Stress
    - Composite Failure : special failure criteria. Usually using energy approach or the combination of the above
    - Soil : combination of tension/compression and shear





  - Different structures and different codes will have different criteria, but from the micro view of the structure, the material strength only have certain failure criteria as the above
  - Strength can be caused by many different reasons, but the failure criteria is limited to certain categories

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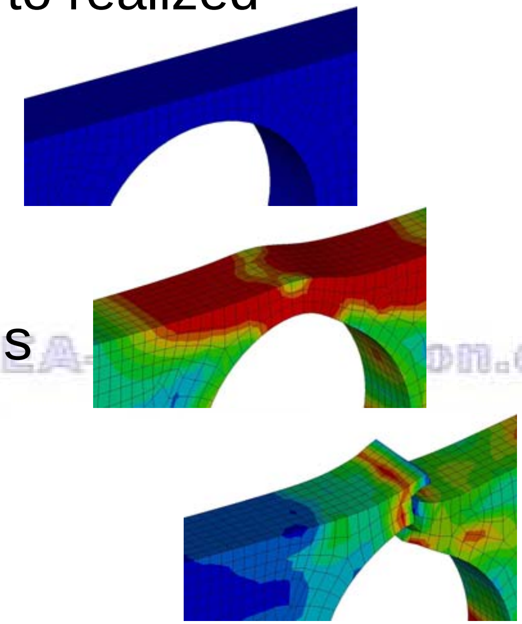
Some Experience in Reliable Analysis
- The Basic Failure Criteria/Reason of Structures

- Strength
  - For today's structure, strength failure rarely happens in static, normal loading. If it is caused by normal static loading, it can usually be easily realized.
  - Other sources of strength that may not be so easy to realized
    - Resonance/Vibration
    - Impact
    - Secondary Failure
  - Strength can be analyzed by CAE stress analysis



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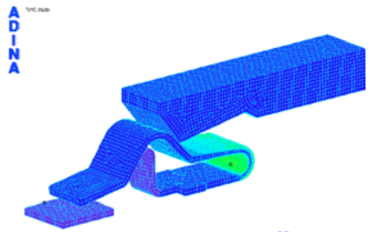
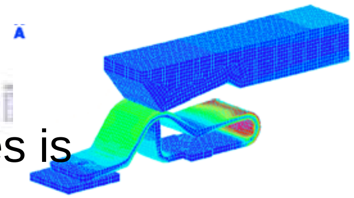
Some Experience in Reliable Analysis
- The Basic Failure Criteria/Reason of Structures

- Stiffness/Deformation
  - In a lot of situations,maximum deformation or stiffness is limited to be under certain range
  - For transportation vehicles, the performance/controllability can be a problem when the stiffness is not enough
  - Stiffness can effect the reliability and performance of many components
    - Seal
    - Snap-Lock mechanism
    - Bearing
  - In certain structures, large deformation is not allowed
  - Generally Speaking…………….
    - Deformation will be a problem, when the alliance of certain geometries is important
    - Stiffness will be a problem, when the reaction provided by the structure is important
  - Stiffness/Deformation can be analyzed by CAE stress analysis





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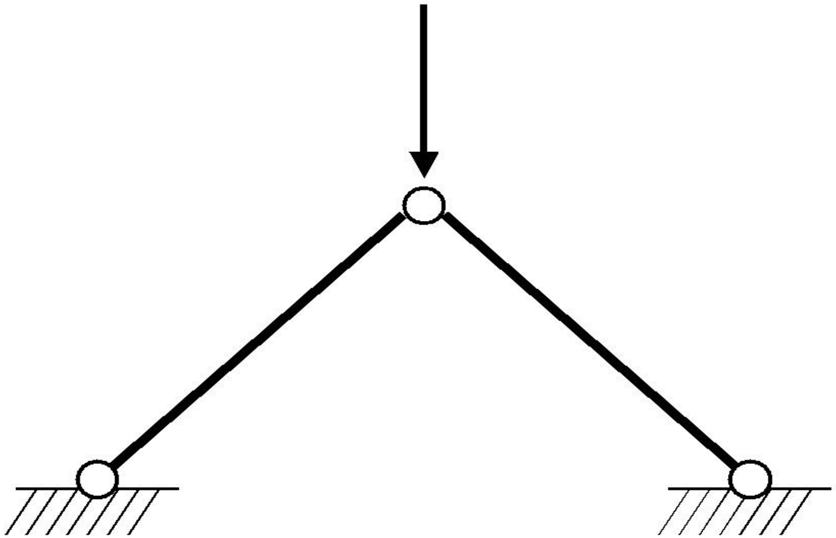
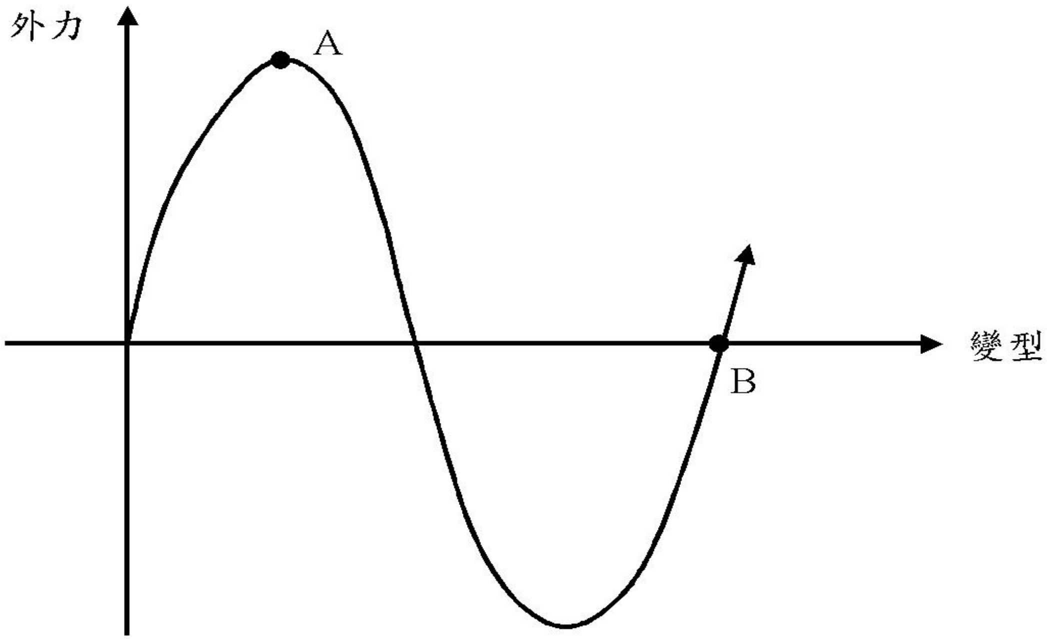
Some Experience in Reliable Analysis
- The Basic Failure Criteria/Reason of Structures

- Stability
  - Stability problem is best explained by the following example





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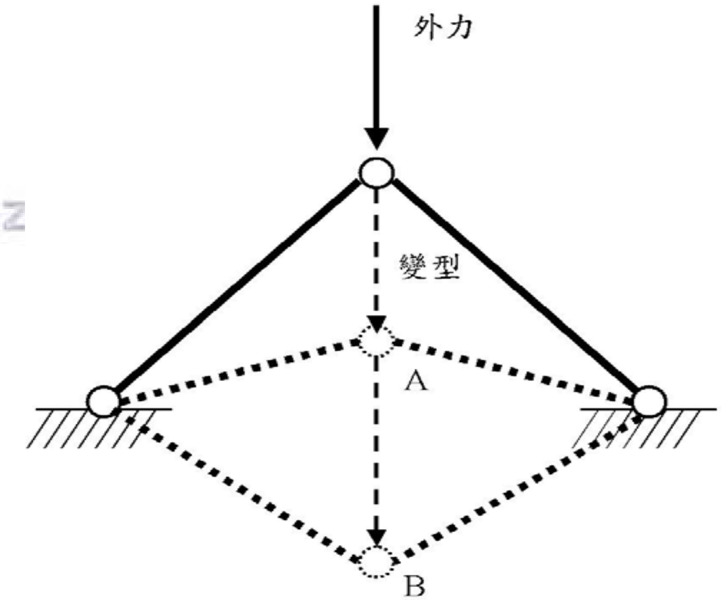
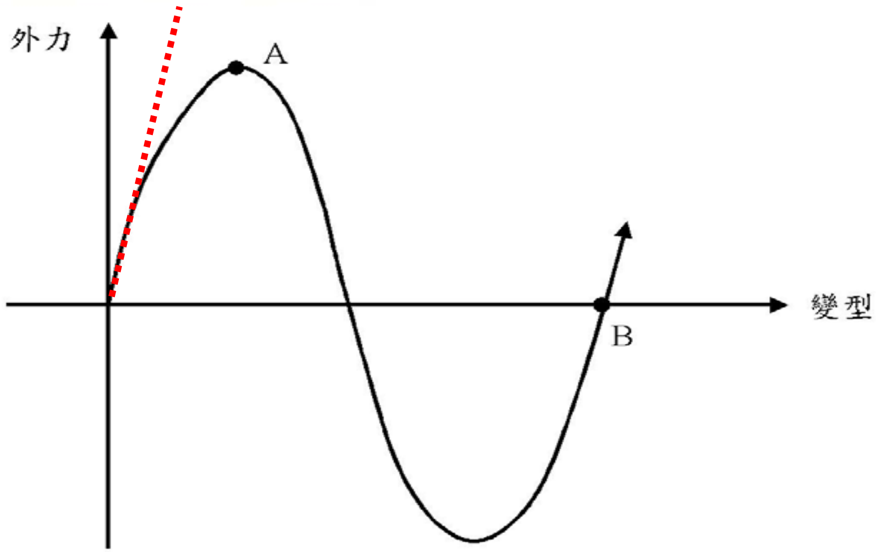
Some Experience in Reliable Analysis
- The Basic Failure Criteria/Reason of Structures

- Stability
  - In the ‘linear” case, the structure behaves like the dash line. In reality, the structure behaves like the figure in the RHS. That is, the structure will be “softening” under loading
  - When the “instant” stiffness becomes zero at point A, the structure is “snapping through”, this is what we call the stability problem





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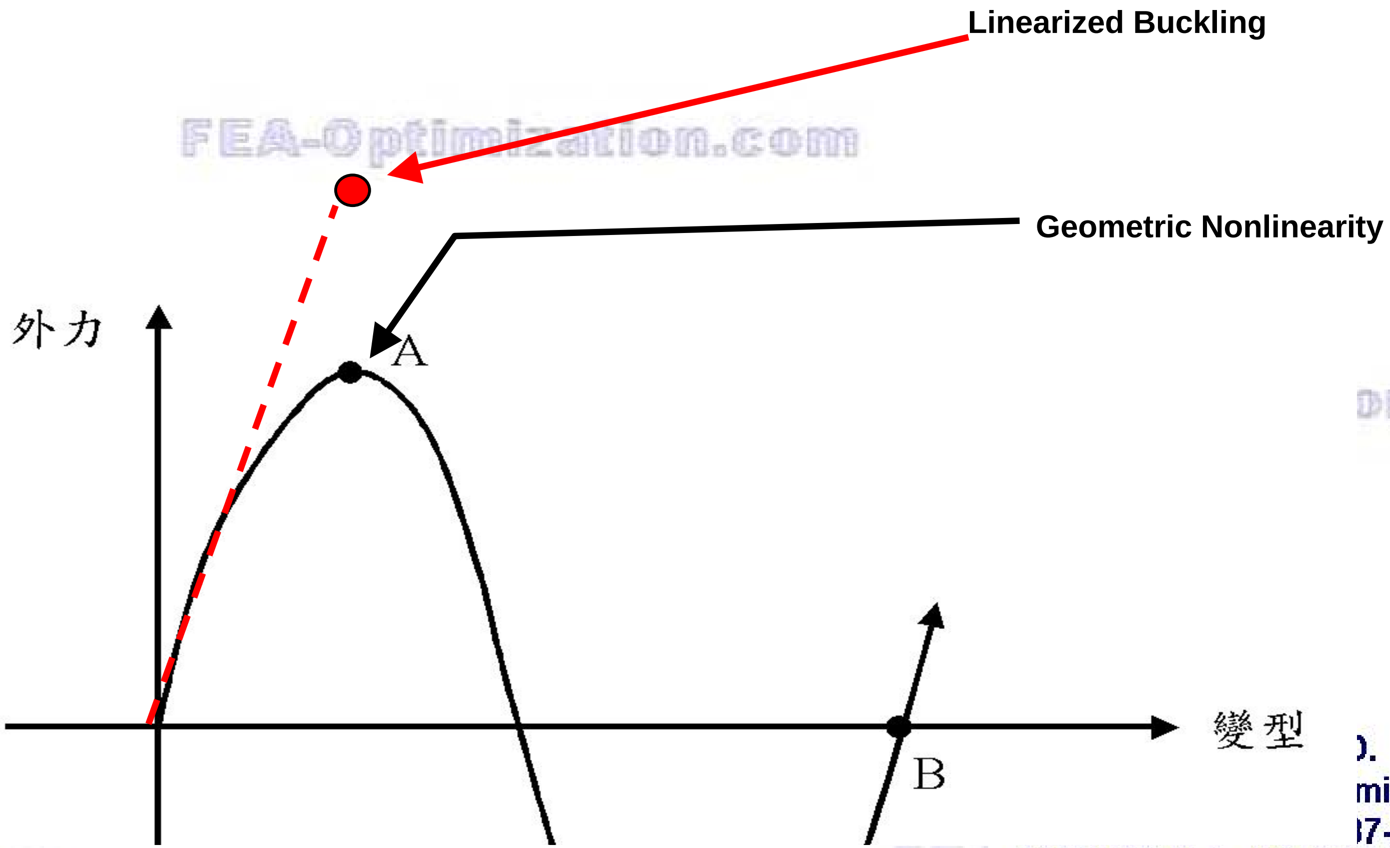
Some Experience in Reliable Analysis
- The Basic Failure Criteria/Reason of Structures

- Stability
  - Instability is usually analyzed by CAE in two ways
    - Linearized Buckling Analysis (less conservative)
    - Geometric Nonlinearity



Some Experience in Reliable Analysis
- The Basic Failure Criteria/Reason of Structures

- Stability
  - Stability problems usually happen in the components with slender aspect ratio, or with large relative deformation
    - Leaf springs
    - Long-span building roof
    - Plates
    - etc
  - Stability depends on the loading and boundary conditions. Therefore for a same components, the constraints and the loading will decide its stability
  - Instability causes permanent deformation. Sometimes even more serious problems

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Some Experience in Reliable Analysis
- The Basic Failure Criteria/Reason of Structures

- Durability/Life/Creep
  - Durability, Life and Creep is similar to strength. But they do not fail "at once"
  - According to the statistic data from USA during 1960 to 1970, 90% of the machine components are failed by fatigue, not strength
  - We know today the fatigue/creep are probably due to the micro defects in the structures
    - Due the defects and the non-homogeneous property, there will be stress concentration in some local spot. Each loading cycle will cause some small failure
    - As the loading cycle goes on, the damage was accumulated, and finally extended to the whole structure
    - We know that in the aerospace industries, single crystal material rarely has the problem of fatigue. This is probably a good prove of the statement above.

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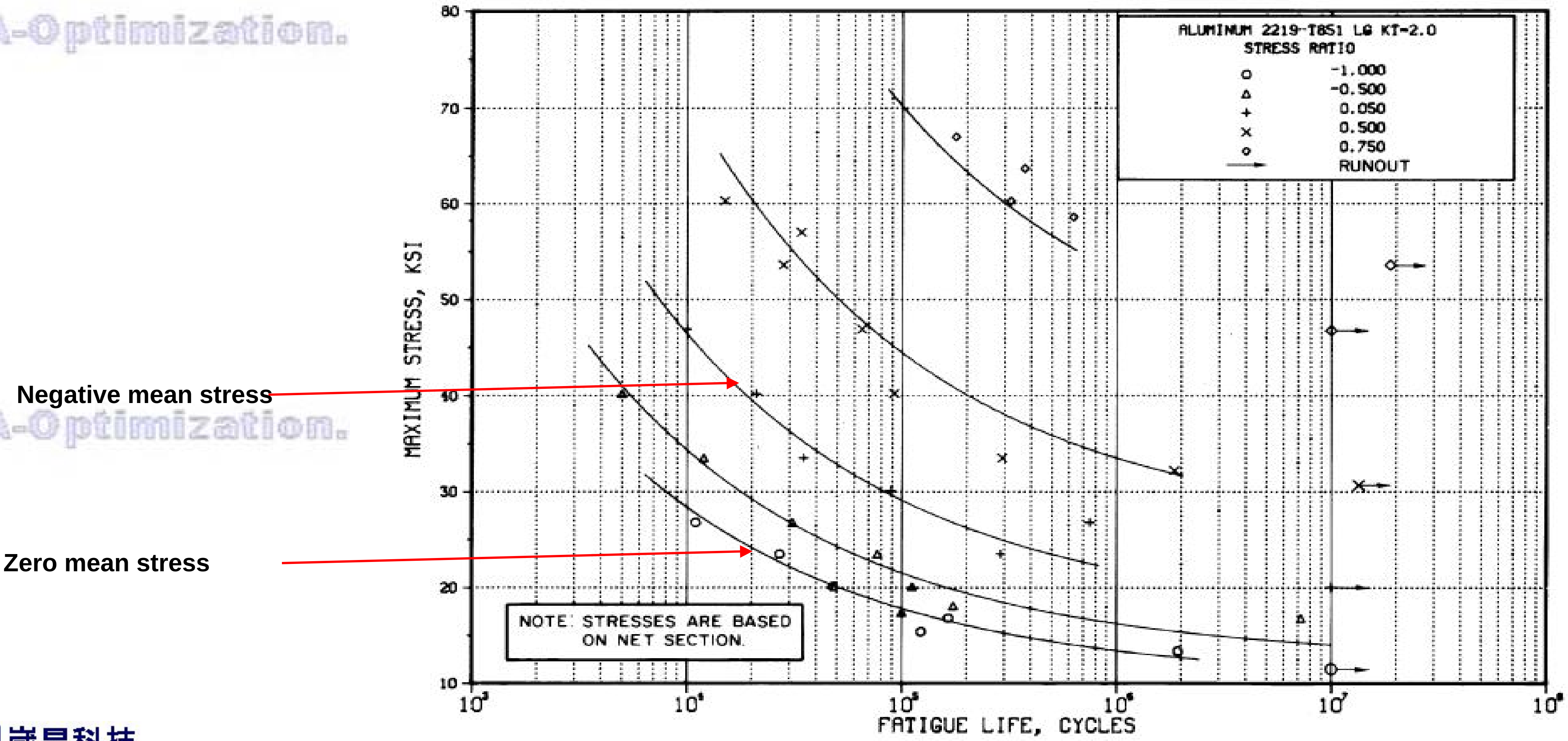
Some Experience in Reliable Analysis
- The Basic Failure Criteria/Reason of Structures

- Durability/Life/Creep



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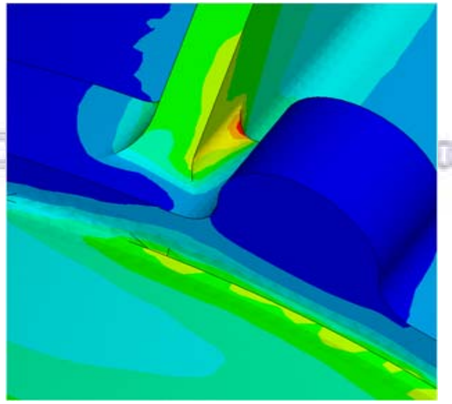
Some Experience in Reliable Analysis
- The Basic Failure Criteria/Reason of Structures

- Durability/Life/Creep
  - For today's technology, it is still very difficult to predict the fatigue
    - We still don't quite understand the fatigue behavior
    - Usually even in material test, it is normal to have +/- 30% error
    - No matter what kind of software/algorithm you are using, no one can promise you any better answer
    - Design/analysis of fatigue is rather root cause finding and failure prevention rather than prediction
  - Two key points to analyze/understand fatigue behavior
    - Complete and accurate stress analysis
    - Complete material testing database (field experience)



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Some Experience in Reliable Analysis
- The Basic Failure Criteria/Reason of Structures

- Durability/Life/Creep
  - Typical indication of fatigue failure
    - If the structure does not fail "at once", it is probably failure under fatigue
    - When stress analysis indicates that the high stress spots coincide with the fatigue points, but way behind the yielding stress or failure stress, it is probably worthwhile to check the S/N curve
    - When the loading cycling consists of several different cases, and can not find the match between the fatigue failure point and high stress spot, it is probably worthwhile to check fatigue using accumulative damage counting
    - It is possible to have a trained and experience engineer to do microscopy exam on the failure section, and judge if it is failure by strength or fatigue
  - Fatigue is more for the strength problem with respect to time, creep is similar but for the stiffness problems

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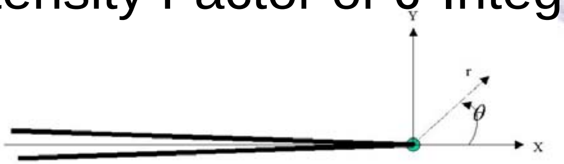
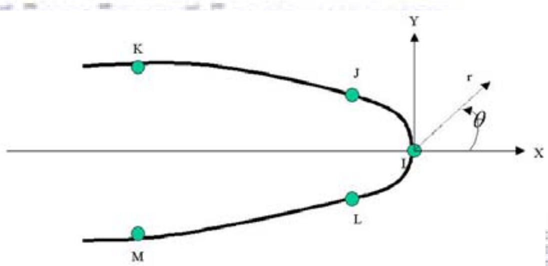
Some Experience in Reliable Analysis
- The Basic Failure Criteria/Reason of Structures

- Defects/Fracture Mechanics
  - All structures have defects/cracks. But not all defects are fatal.
  - Usually we will hope to prevent defects/crack before it happen. They are usually considered under the strength/fatigue criteria
  - However unexpected defects/cracks can still happen, such as
    - During manufacturing
    - During assembling
    - By weather or chemical eroding
  - Since not all defects are fatal, if unexpected defects/cracks do happen, we need to know if they are fatal or not
    - “Fatal” means that the crack will extend or get worse
    - If it is “not fatal”, sometimes we may be able to ignore the cracks
  - Fracture mechanics can be calculated by CAE through Stress Intensity Factor or J-Integral





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Some Experience in Reliable Analysis
- The Basic Failure Criteria/Reason of Structures

- Combination of the Above
  - Sometimes the failure can be caused by the combination of all the above modes. For examples, many codes are concentrated on the macro view of the failure mode of the structures
    - ACI Code
    - AISC ASD Code
    - AISC LRFD Code
    - NUREG
    - ECE R66
  - However, to be surprised, in most of the case, it is rather ambiguous than combinatory.
  - Actually in the micro view of the structure, it only failed under two mode : strength and creep (time factor). So it is just a matter of how you look at it
  - There is no definite answer, it is usually subjective
  - It is a good approach to keep a "check list", and go through each item for every case

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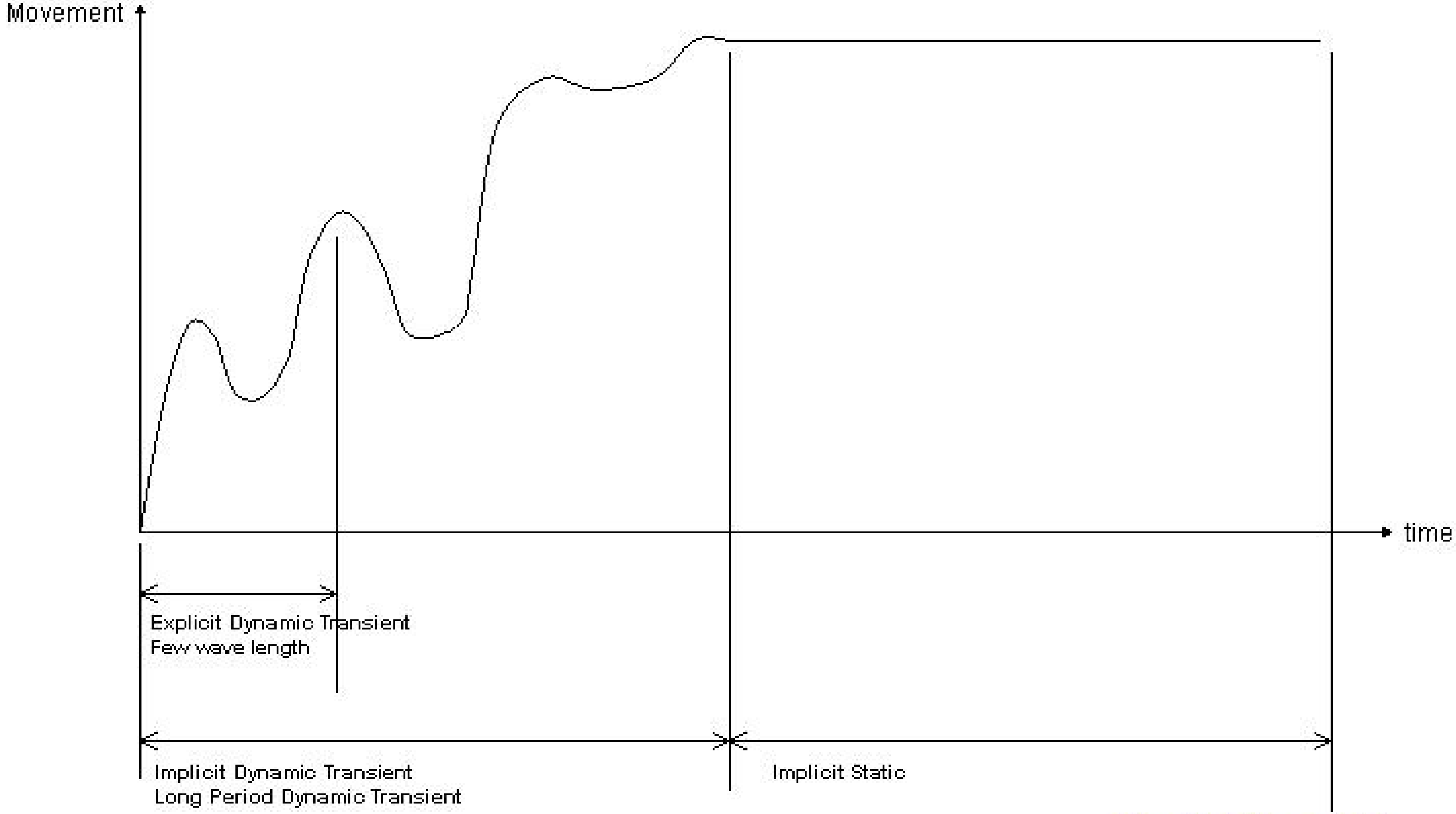
Some Experience in Reliable Analysis
- The Response Phase : Static or Dynamic



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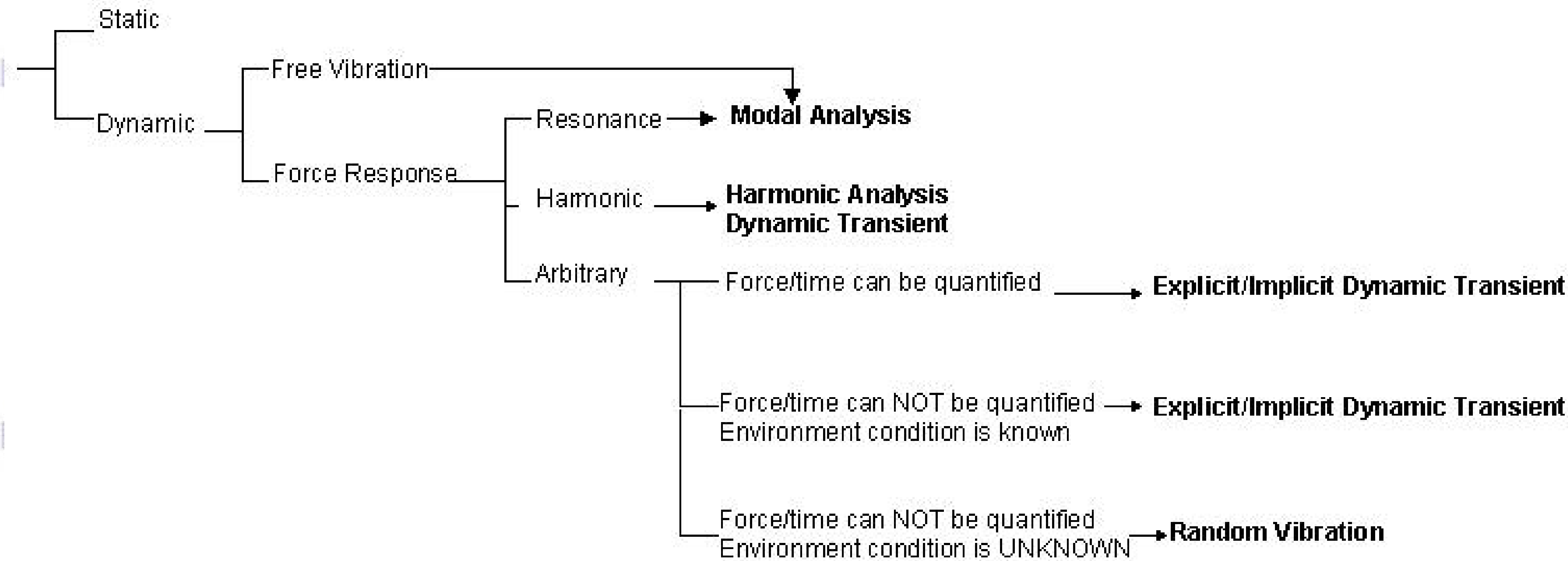
Some Experience in Reliable Analysis
- The Response Phase : Static or Dynamic



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The Concept of the Standard Process Control
- Why Standard Process

- The standard process is like a “check list”. It prevents the operator from known mistake
- No one can guarantee 100% accuracy from analysis prediction. But standard procedure can provide minimum error and maximum accuracy
- Quality control of FEA is possible, if all known errors are avoided
- Different companies should have different process control, and should be improved/modified from time to time, to reflect the lessons learned

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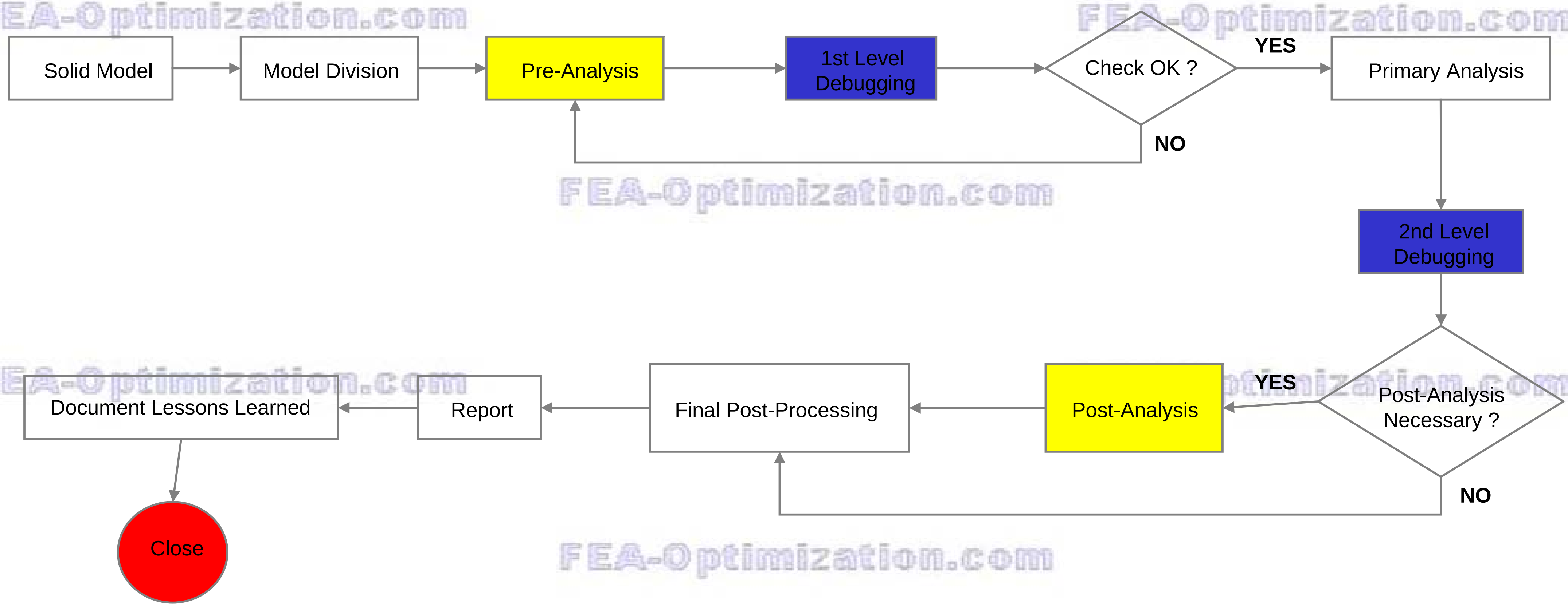
The Concept of the Standard Process Control
- The Suggested Procedure



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The Concept of the Standard Process Control
- The Suggested Procedure

- **Model Division**
  - Document Search
  - Interface Definition
  - Workload Allocation
- **Pre-Analysis**
  - Basic Information Collection
  - Overall Response Study
  - Load & BC
  - Interface Analysis
  - Primary Mesh Definition
- **1st Level Debugging**
  - Material Check
  - Load and BC Check
  - Mesh Check
  - Numerical Algorithms/ Options Check
- **2st Level Debugging**
  - History Check
  - Equilibrium Check
  - Response Sanity Check
  - Singularity
  - Numerical Stability Check
  - Error Estimate Check
  - Post-Analysis Definition

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Behavior Prediction
- Is 100% Behavior Prediction Possible ?

- The answer is : yes and no
- Yes, if and only if we are able to control all the environment variables
- Yes, if and only if we already know how the environment is going to affect the behavior.
- However, we will never know if we already understand all the physical phenomena, until the problems happen. So it is rather controversial

- So, theoretically speaking, it is impossible. However, technically, we know engineers and scientists around the world have done a pretty good job of predicting structural behavior.
- The bottom line is, it is too dangerous to believe we can predict all the structural behavior. However in certain areas we do know how to safely design a structure

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Behavior Prediction
- How did other people do it ?

- From the author's understanding and knowledge, no one on earth can do that (100% prediction) for sure
  - Too difficult to understand all the physical phenomena for one person
  - If we have more than one person working together, there will be communication problems
  - Even if we can understand each other's thought perfectly, there will be new phenomena when coupling two disciplines
- Usually, people or a group of people can do pretty good job of prediction by accumulation of experience
  - From accumulation of experience, we know what can goes wrong in a product or in a structure.
  - Prediction is actually based on simulating these possible events only
  - We predict "if this will happen" rather than "if something unthinkable will happen"

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Behavior Prediction
- How does the Virtual Lab Technology work ?

- The concept of the Virtual Lab Technology has been mentioned for decades. The idea is to use computation to predict the physical phenomena, so that the hardware test can be replaced by the "Virtual Lab".
- In 1998, Dodge placed a commercial on the TV, stating that they put a car in the Virtual Lab to test its crashworthiness. However that commercial was off the broadcast quickly, due whatever reason…………………………..
- Let's see some of our examples here…………

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Crashworthiness/Impact/Penetration

: Auxiliary Power Unit (APU)

Animations and Pictures will be Shown in the Class

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Crashworthiness/Impact/Penetration

: Armored Composite Fabric Penetration

Animations and Pictures will be Shown in the Class

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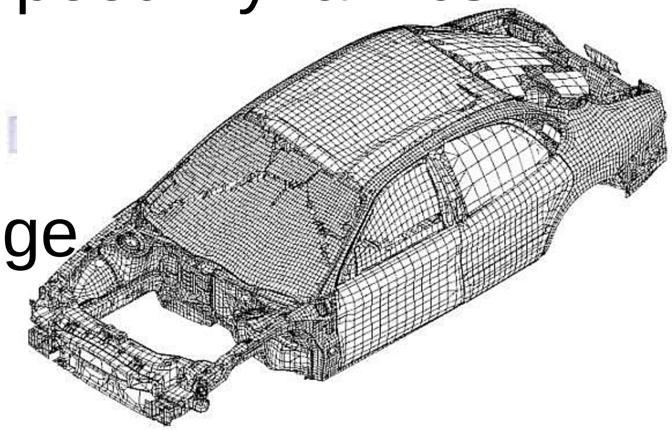
Automobile Roof Crush

: An Alternative to Turn-Over Test

- Automobile roof crush test is considered to be equivalent to the turn-over test.
- It is more repeatable, controllable, stable, and we can see the events more easily (because it's slower)
- ECE R66 allows roof crush test and simulation to certify a vehicle

- For today's technology, we can use the "Low-Speed Dynamics" technology to simulate roof crush test.
  - Faster and less expensive
  - More stable. Easies to perform design change
  - More predictable



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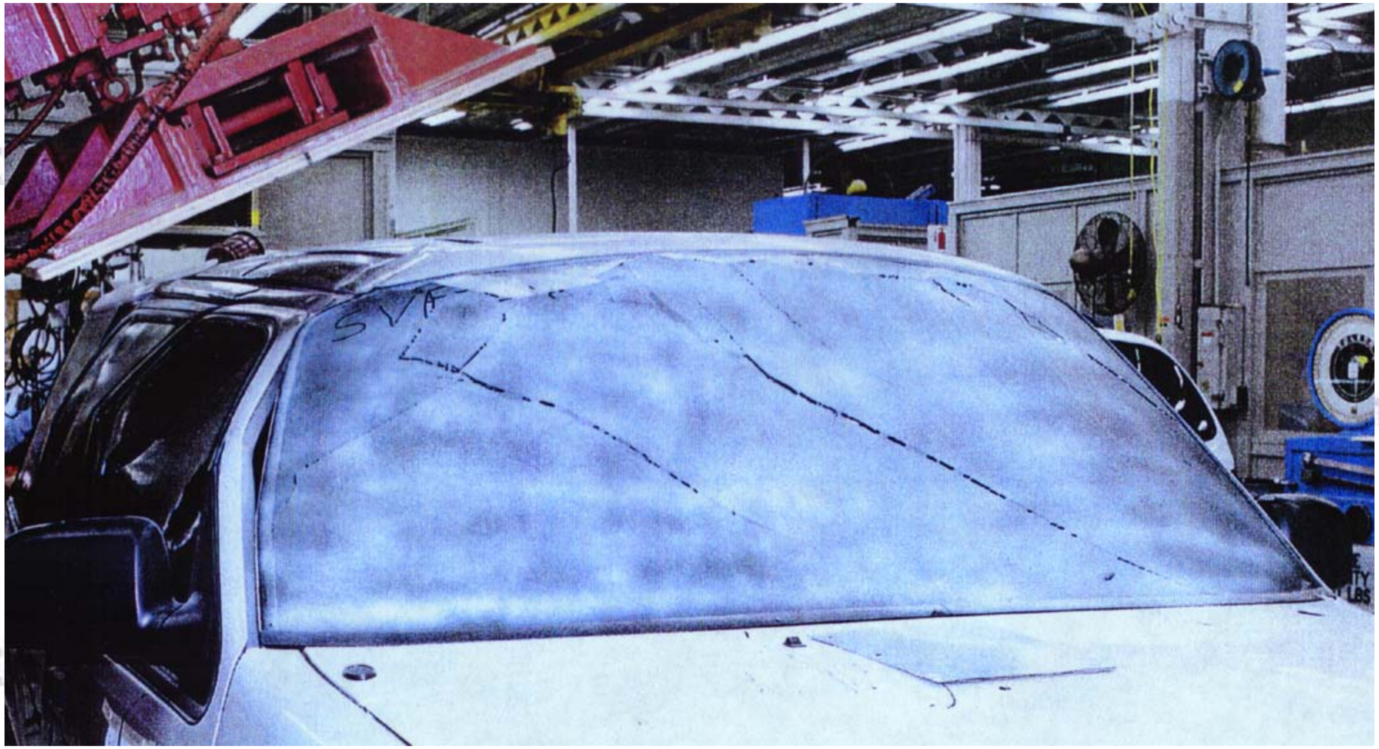
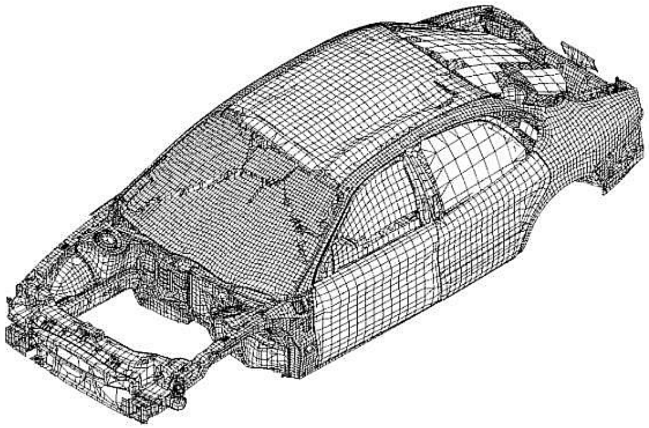
Automobile Roof Crush
: An Alternative to Turn-Over Test





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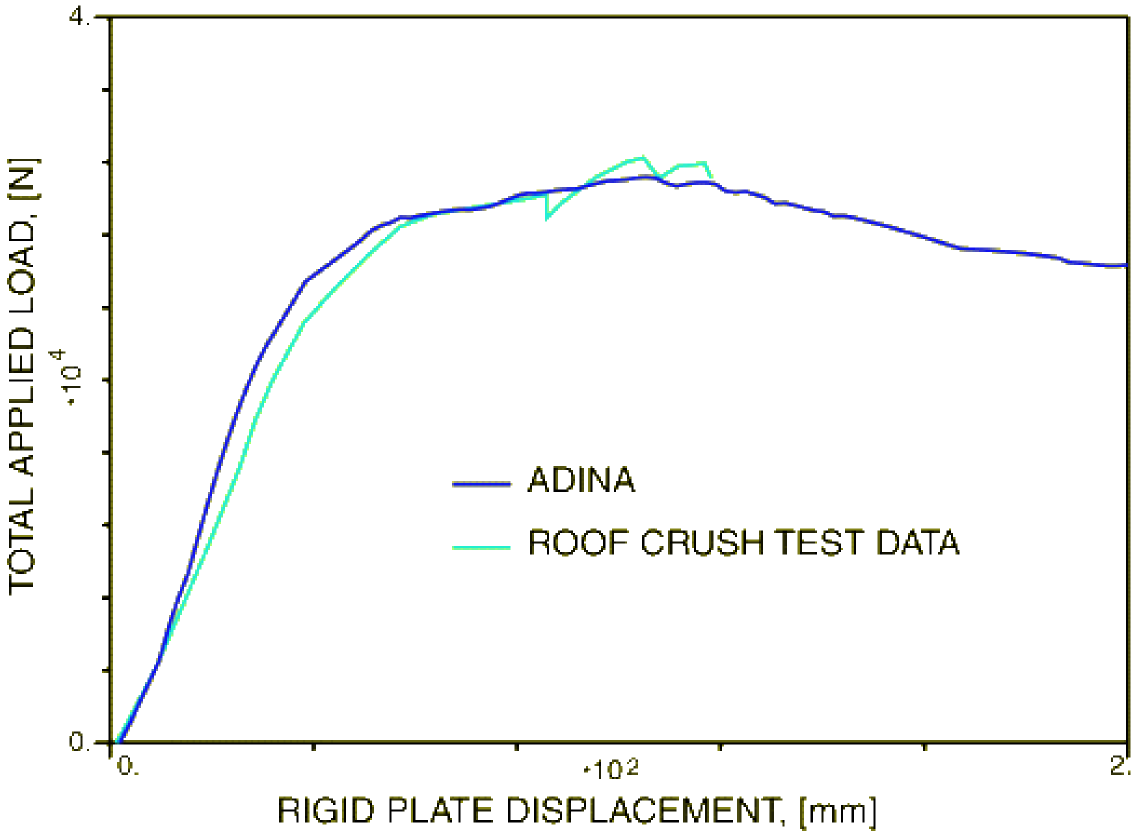
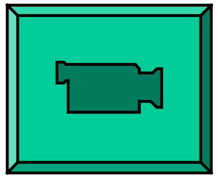
Automobile Roof Crush

: An Alternative to Turn-Over Test

Roof crush analysis





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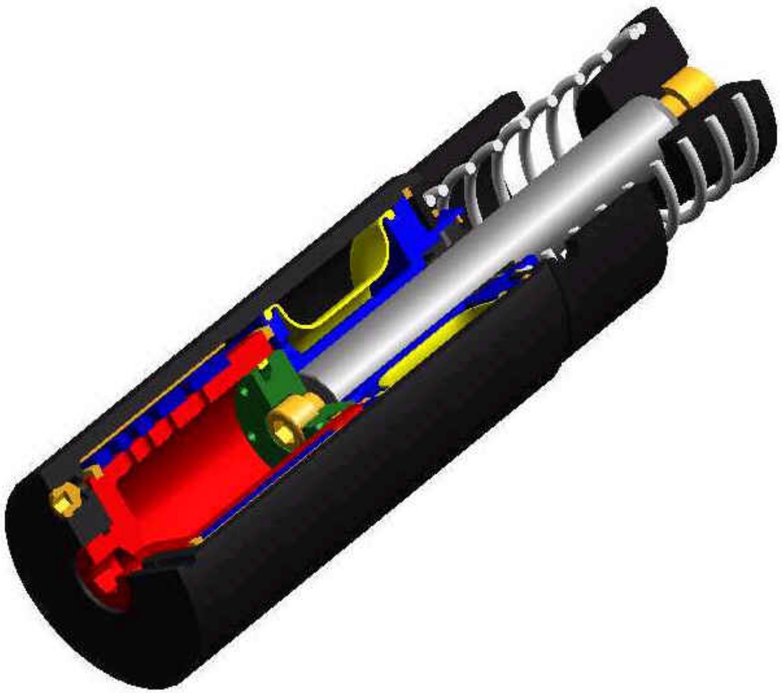
Automobile Shock Absorber

: Stoke Reaction Force FSI Simulation

- The action in a shock absorber is an FSI phenomena
- Such phenomena requires special program and techniques to simulate the complicate action



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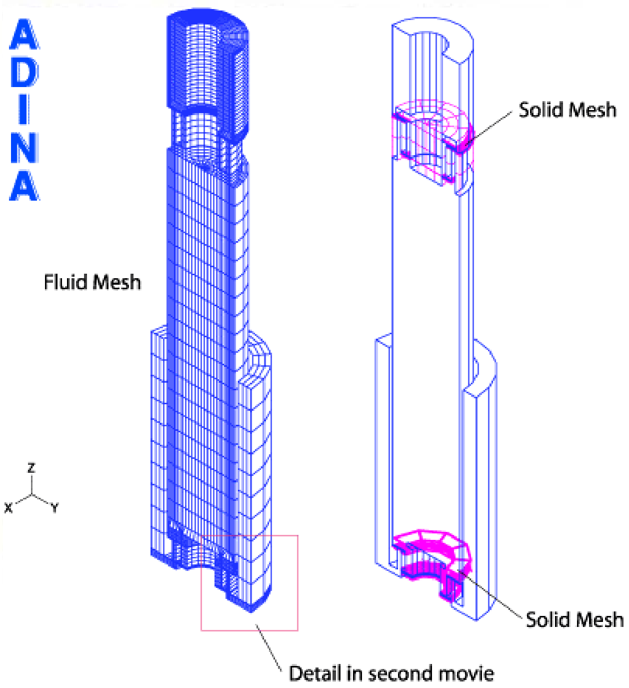
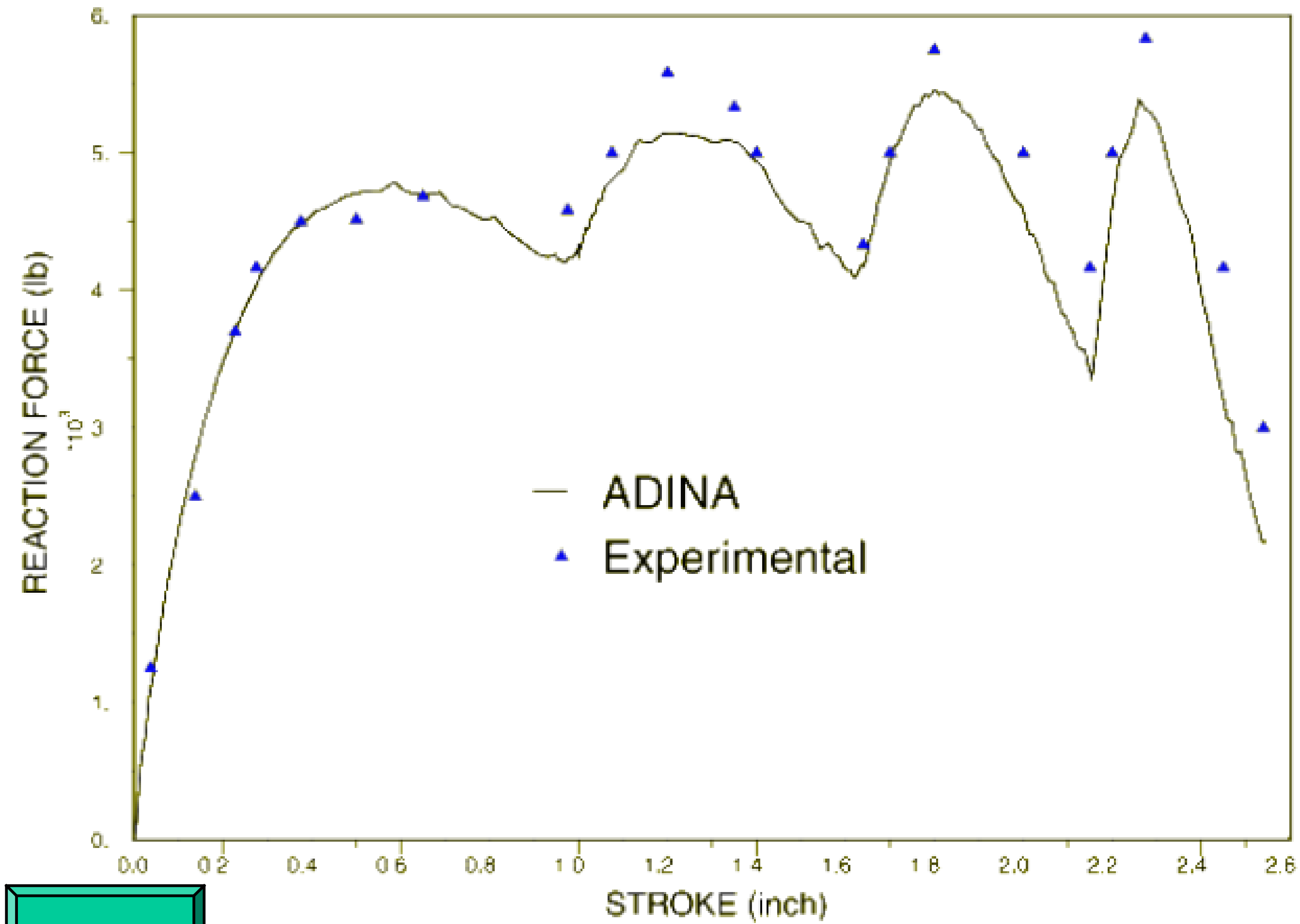
Automobile Shock Absorber

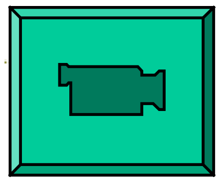
: Stoke Reaction Force FSI Simulation

SmartDO
A Smart Design Optimization System



Comparison of ADINA Results with Experimental Results





adina_shock_absorber_01_02.gif

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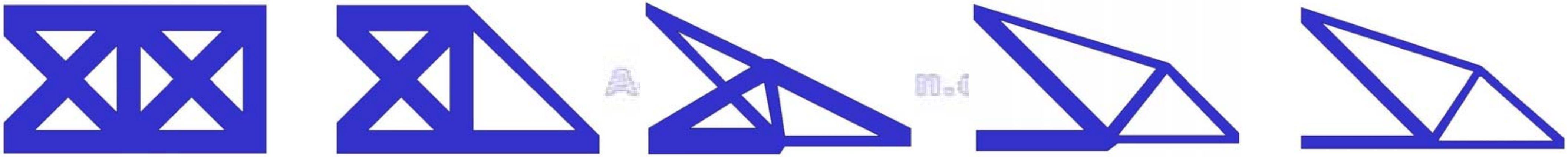
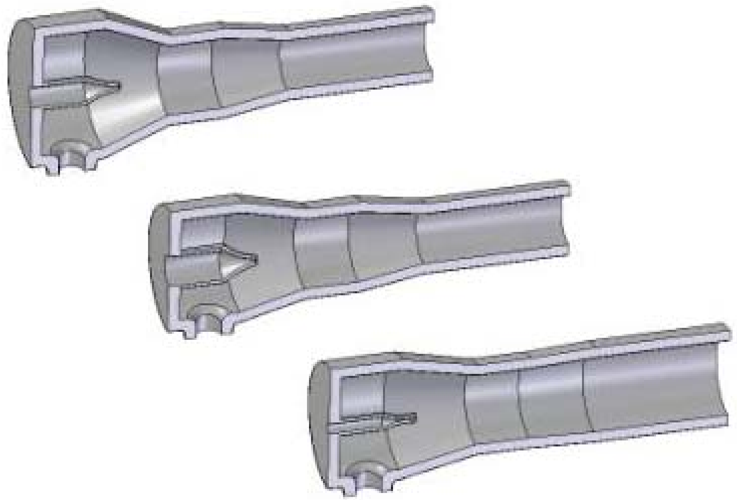


CAE最佳化與可靠度設計於車輛產業之應用



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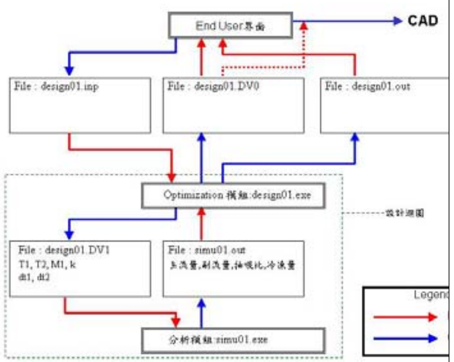
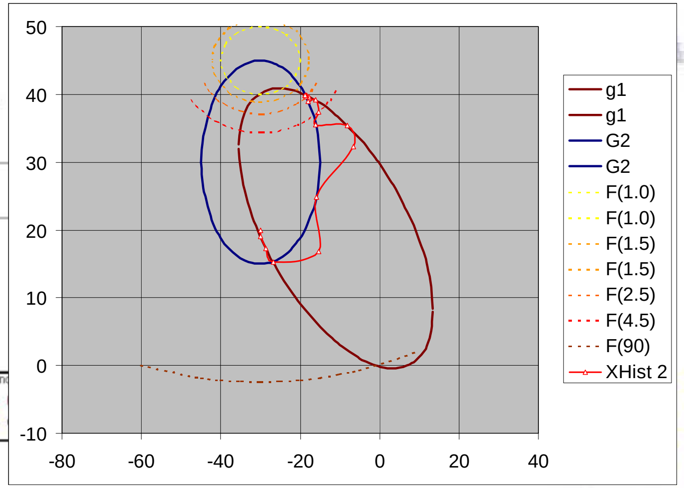
Coupling CAE and Numerical Design Optimization

SmartDO A Smart Design Optimization System

- CAE- or FEA-Based Optimization is only possible when the CAE is fully calibrated and reliable.
- However the CAE model used for design verification is usually not the one numerical design optimization. We should know that
  - A CAE model is usually not parametric
  - A parametric CAE model is not always suitable for design optimization
- Manual iterations between CAE and Numerical Design Optimization is usually necessary





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Coupling CAE and Numerical Design Optimization

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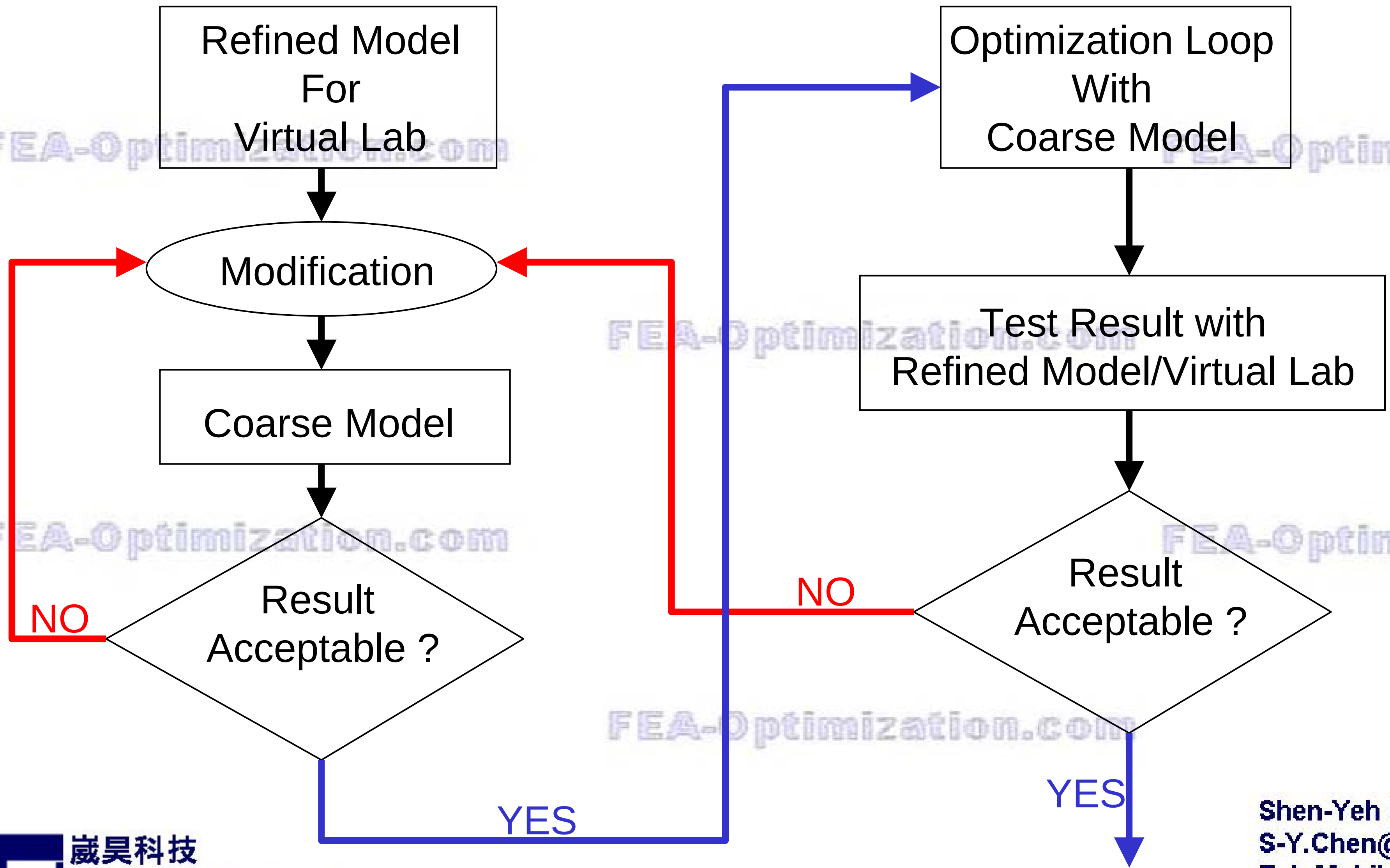

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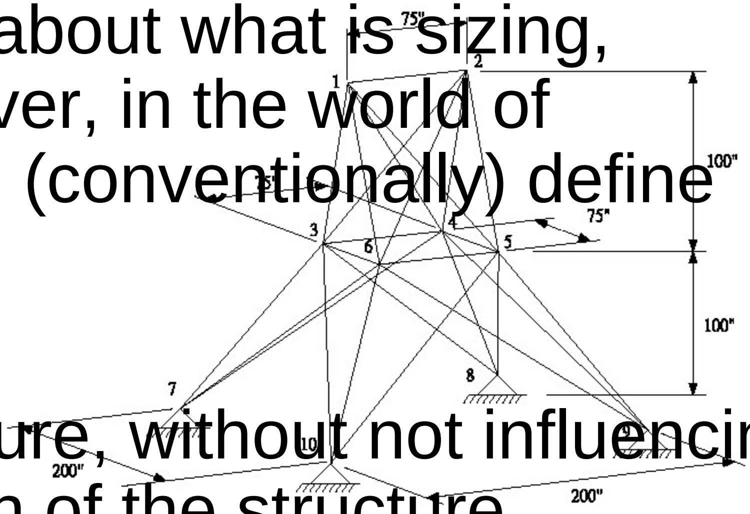
What Is Sizing, Shaping And Topology Optimization

- Usually we use CAE and Numerical Optimization to perform three kinds of parametric optimization : ***<u>Sizing, Shaping and Topology</u>***
- There is actually no very clear definition about what is sizing, shaping or topology design today. However, in the world of numerical structural optimization, we can (conventionally) define each of them in the following sense.



- **Sizing –**
  - changing the parameters of the structure, without not influencing the geometry, shape and configuration of the structure.
    - Thickness of the <u>shell element</u>
    - area of a <u>truss member</u>
    - cross-sectional dimension of a <u>beam member</u>
    - Variables in the analytical solution

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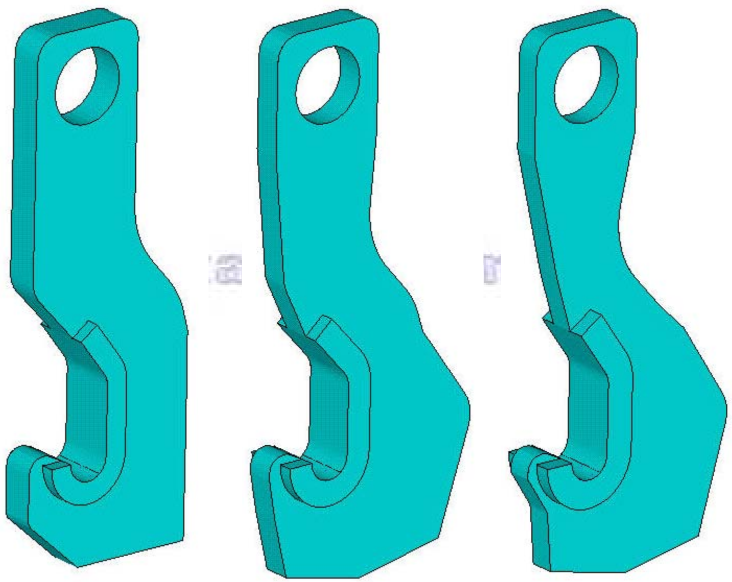
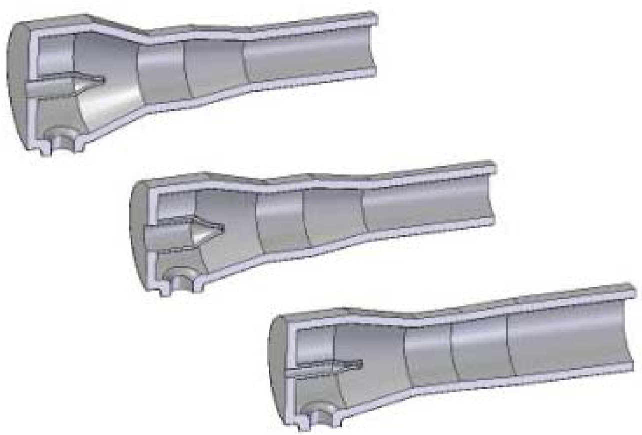
What Is Sizing, Shaping And Topology Optimization

- **Shaping –**
  - changing the parameters of the structure, which will alert geometry, shape and configuration of the structure.
  - However, the shaping is limited in the cases that the ***topology*** of the structures is not changed





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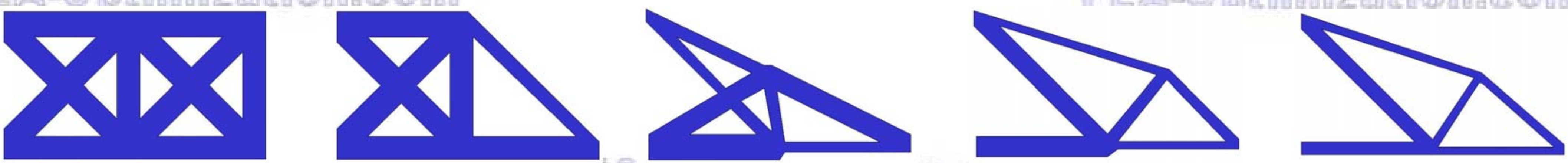
What Is Sizing, Shaping And Topology Optimization

- **Topology –**
  - To understand topology optimization, it is necessary to understand the term “topology”.
  - Topology is very conceptual. However, for our case, it is all about two things (so far)
    - Connectivity
    - Void/Holes



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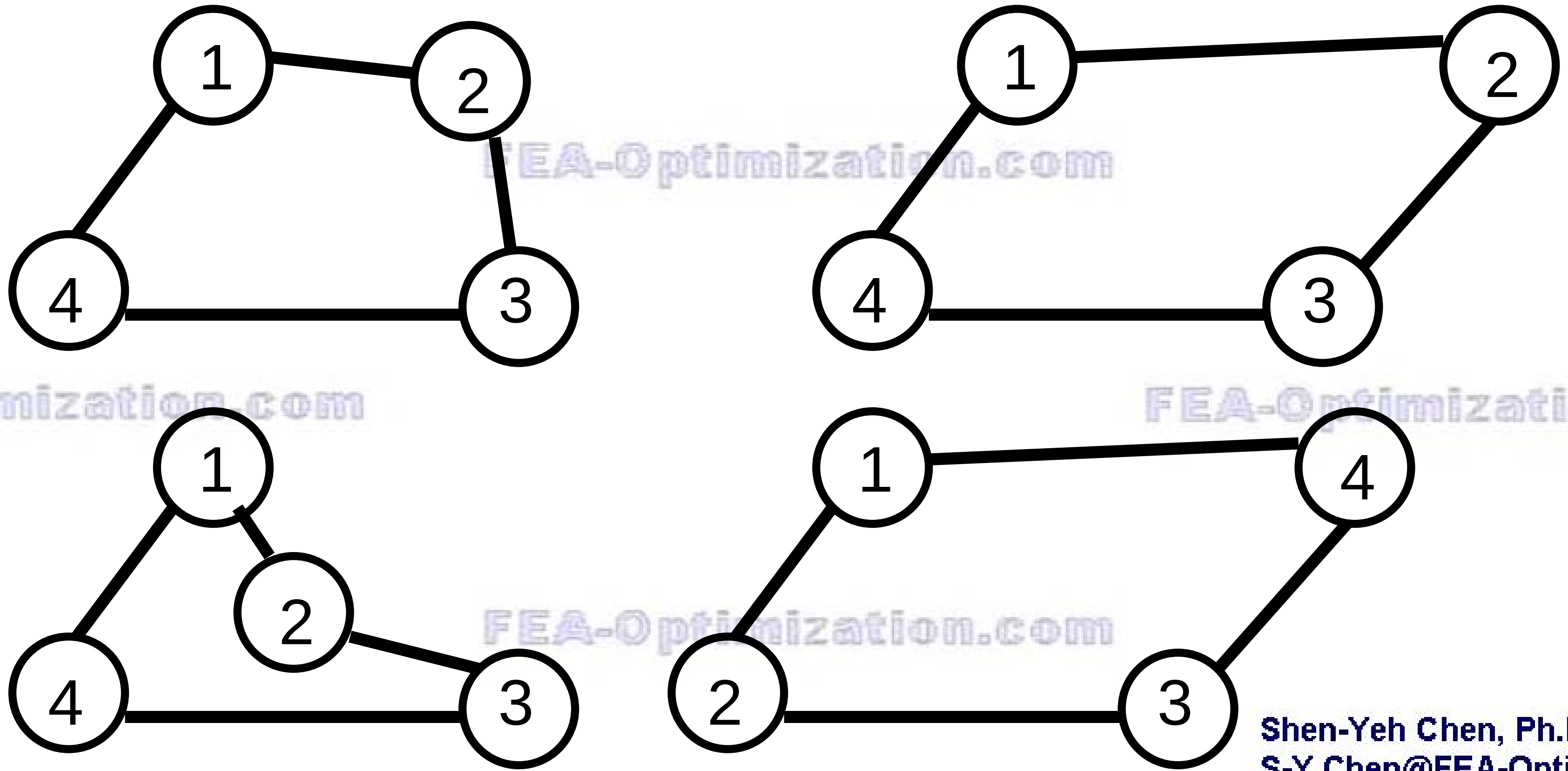
What Is Sizing, Shaping And Topology Optimization

- **Topology of Connectivity**
  - The following structures/network has the same Topology of Connectivity



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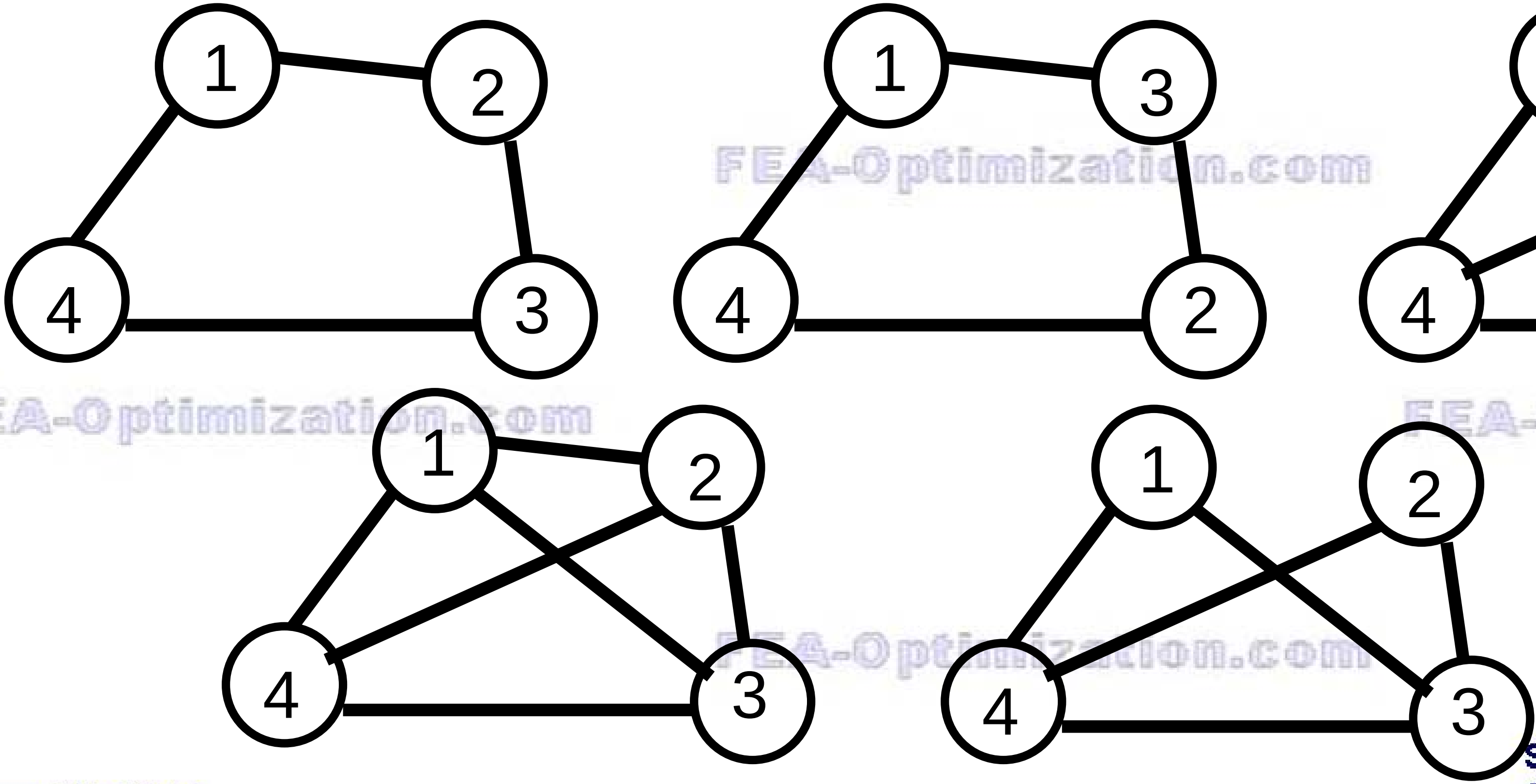
What Is Sizing, Shaping And Topology Optimization

- **Topology of Connectivity**
  - The following structures/network has the different Topology of Connectivity



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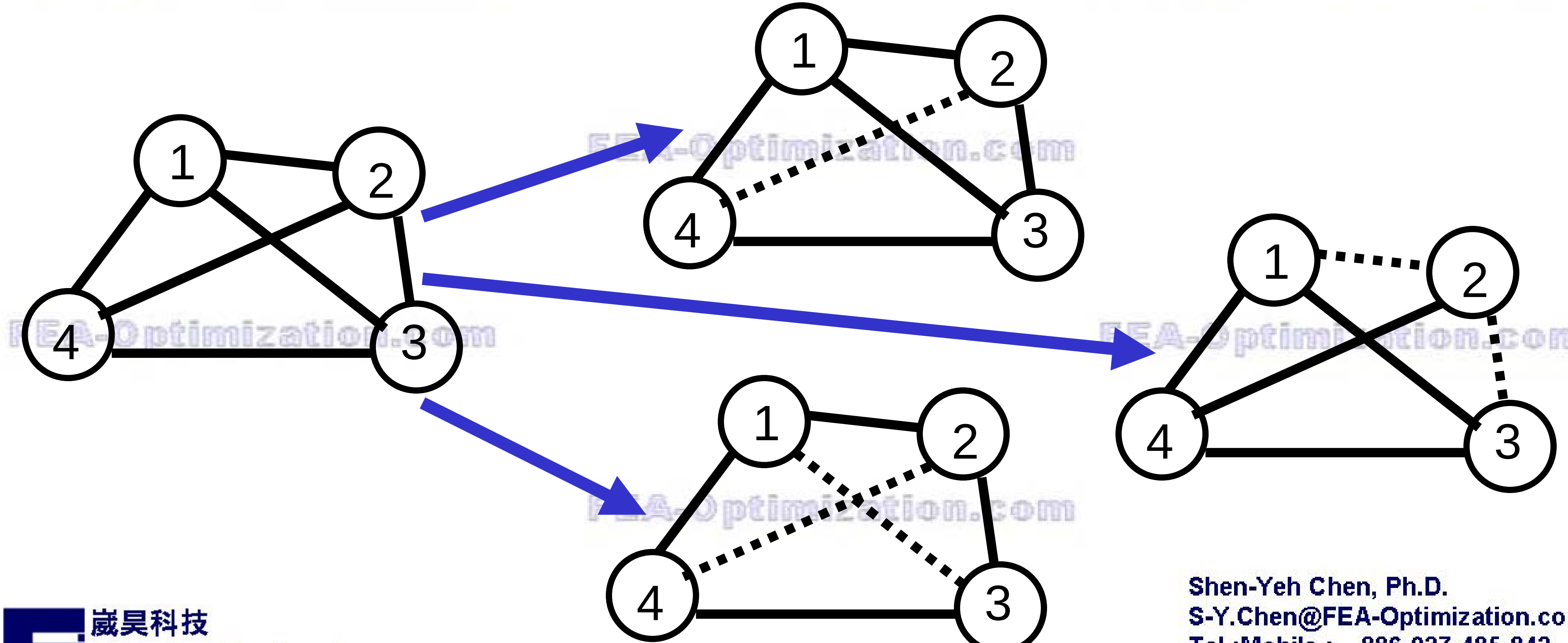
What Is Sizing, Shaping And Topology Optimization

- **Topology of Connectivity**
  - The design domain for topology of connectivity can sometimes be defined by the "ground structure"



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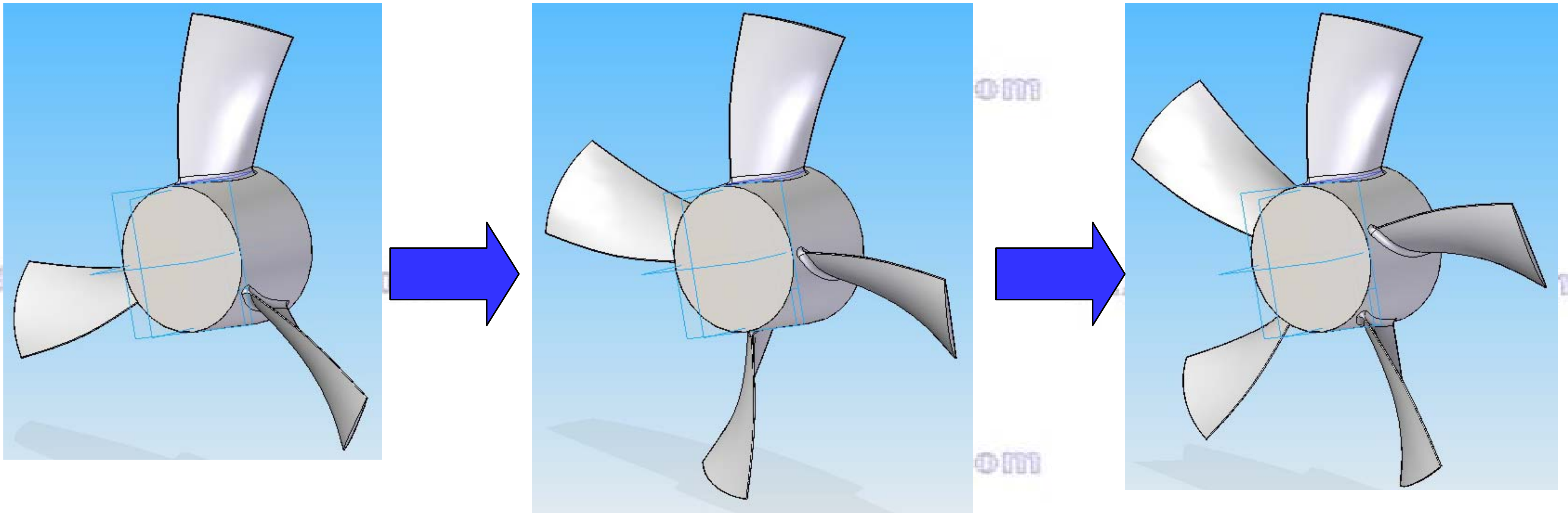
What Is Sizing, Shaping And Topology Optimization

- **Topology of Connectivity**
  - The design domain for topology of connectivity can also be defined by the Boolean operation of geometry



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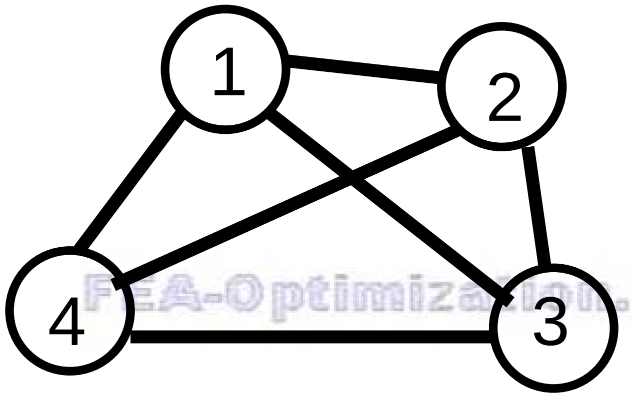
What Is Sizing, Shaping And Topology Optimization

- **Topology of Connectivity**
  - In the “ground structure” with n nodes, we establish the ground structure by connecting every two nodes. This will create a structure with (n*(n-1)/2) connecting lines
  - If each line is associated with one binary DV (0 or 1) to represent its elimination or existence, there are totally 2^n possible combination of topology for this group structure.



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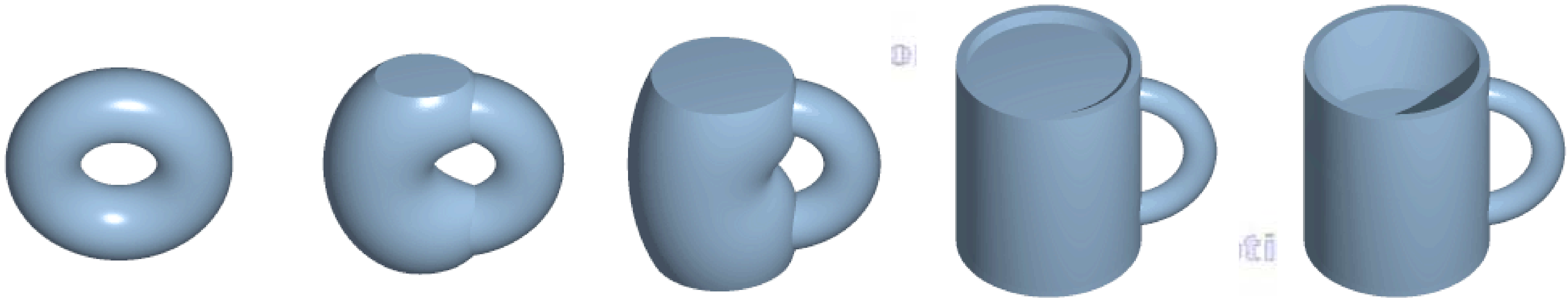
What Is Sizing, Shaping And Topology Optimization

- **Topology of Voids/Holes**
  - The following geometry has the same topology of voids (pictures from www.wikipedia.org)



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What Is Sizing, Shaping And Topology Optimization

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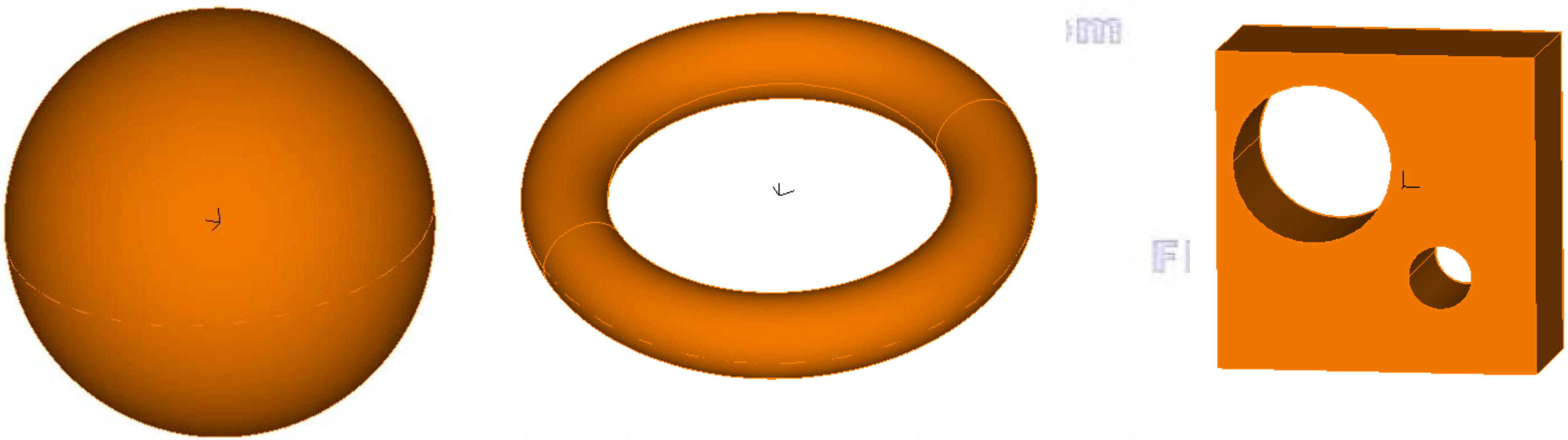
A Smart Design Optimization System

- **Topology of Voids/Holes**
  - The following geometry has the different topology of voids



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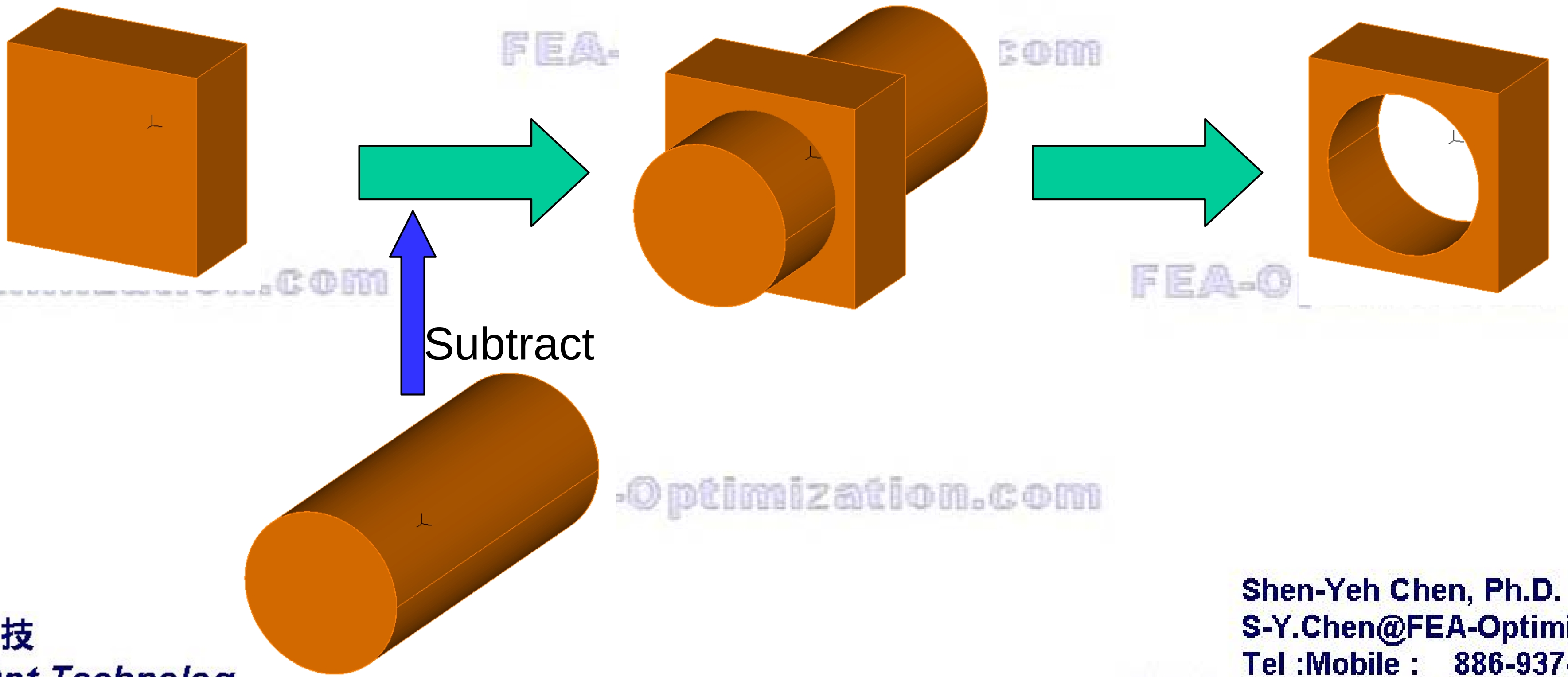
What Is Sizing, Shaping And Topology Optimization

- **Topology of Voids/Holes**
  - The design domain for topology of voids and holes can sometimes be defined by Boolean operations of geometry



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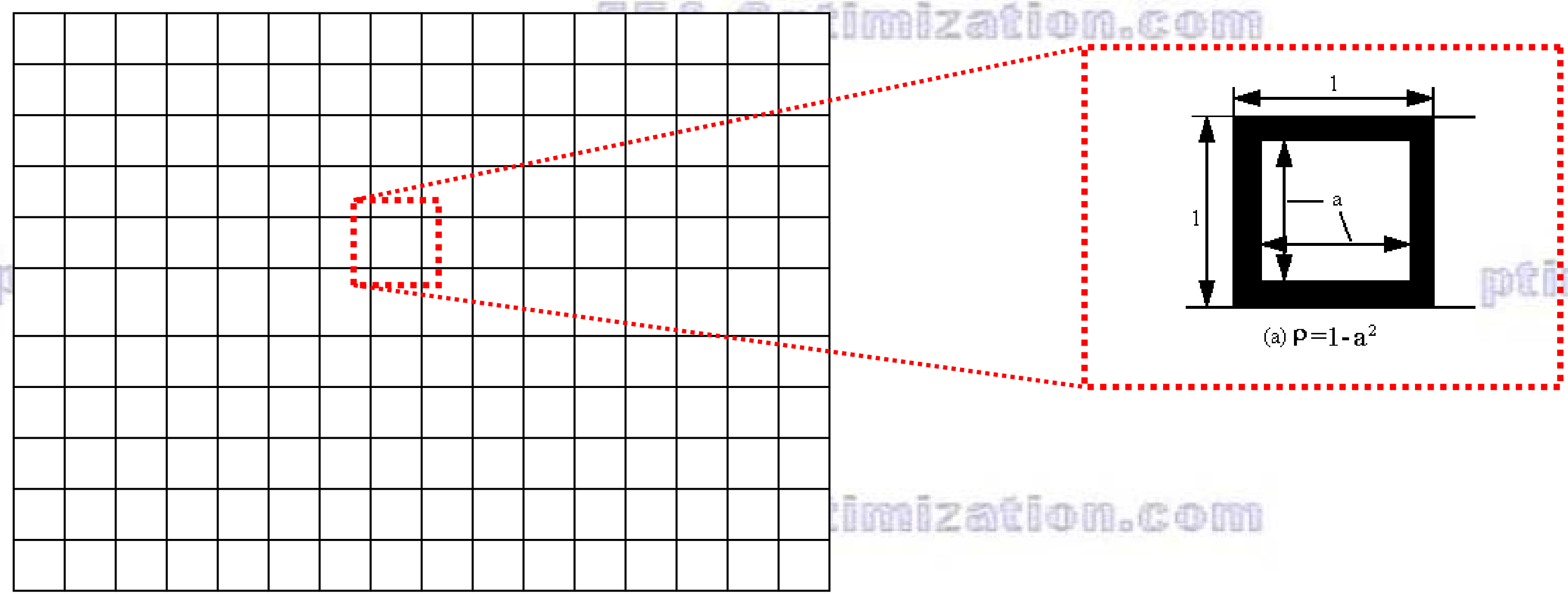
What Is Structural Sizing, Shaping And Topology Optimization

- **Homogenization Method for Structural Topology Optimization**
  - The homogenization method is one of the FEA-Based approach for the structural topology optimization method.
  - It take the "density" (or "amount of void") of each element as the design variables, and calculate the distribution of voids



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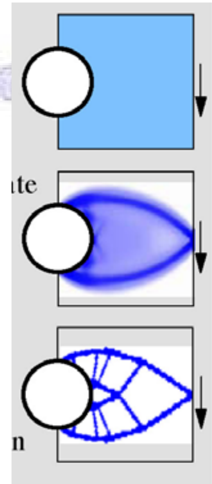
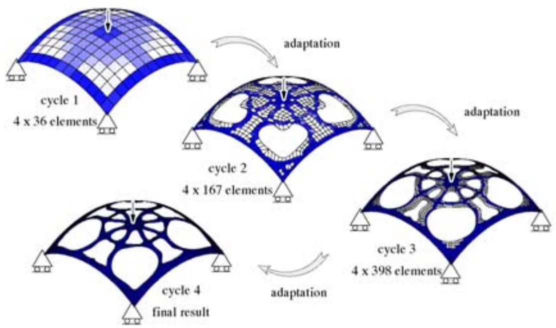
What Is Structural Sizing, Shaping And Topology Optimization

- **Homogenization Method for Structural Topology Optimization**
  - The problem is formulated as
    - Find : density of each element
    - To maximize : stiffness of the structure
    - Subjected to : (total volume) < specified value
  - It only gives you the “conceptual configuration” for the distribution of density.
  - The density of each element can not be zero. Therefore there is no real “void” in the result. We consider the cell as a “void” when it reaches a thread hold.





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What Is Structural Sizing, Shaping And Topology Optimization

- **Homogenization Method for Structural Topology Optimization**
  - You should be aware of few things
    - It is not deterministic. It is conceptual.
    - The final result depends heavily on the image processing, and even your imagination.
    - It maximizes the stiffness. It is not always optimal.
    - Usually, you have to perform Shaping optimization again to obtain your final result.

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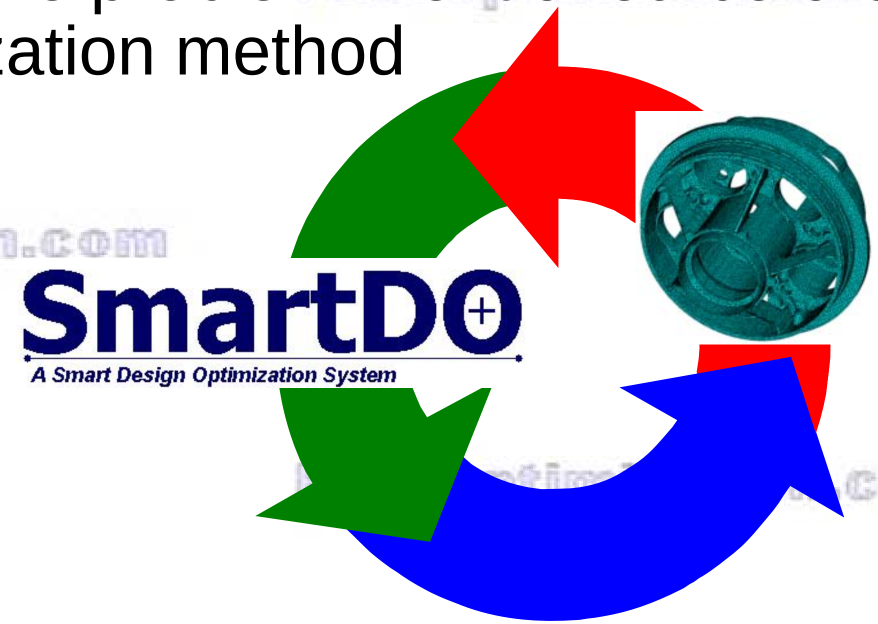
What Is Structural Sizing, Shaping And Topology Optimization

- **Homogenization Method for Structural Topology Optimization**
  - SmartDO can not directly perform topology optimization with the homogenization.
  - If you have access to the stiffness matrix of each element in a finite element element code, you can couple with SmartDO, formulate the problem mentioned before, and perform the homogenization method



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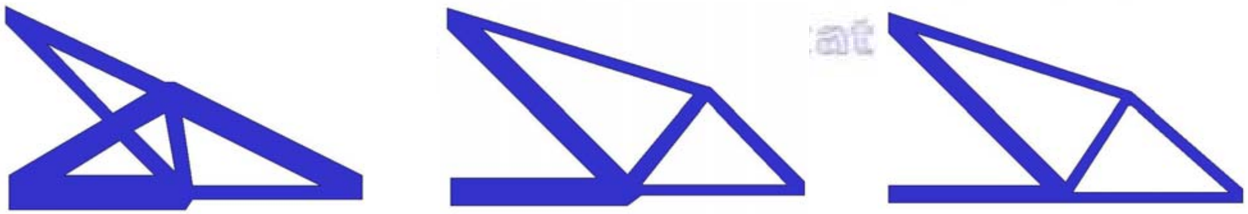
Concurrent Sizing, Shaping And Topology Optimization in SmartDO

SmartDO 的 尺寸,外型及拓樸 同步最佳化

SmartDO
A Smart Design Optimization System

- SmartDO is able to perform concurrent Sizing, Shaping and Topology optimization, because the RGA in SmartDO can handle three kinds of design variables
  - Binary DV : for linking with Boolean operations and connectivity, usually used for topology design parameters
  - Integer DV : for linking with table search and combinatory optimization, usually used for sizing or shaping design parameters.
  - Real DV : for linking with (floating point) real numbers, usually used for sizing or shaping design parameters.
- These three types of DV can be used in SmartDO concurrently.



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Common Problems of CAE- or FEA-Based Optimization

SmartDO A Smart Design Optimization System

Numerical Noise/Local Minimum

- The following items are common source of numerical noise and local minimum
  - Meshing (discretization)
  - Stress Oscillation (or, differentiation over the discretized region)
  - Integration over the discretized region
  - Non-smooth or discrete operator during modeling (for example, Boolean operation)
  - Nonlinear convergence tolerance
  - Combination of the above

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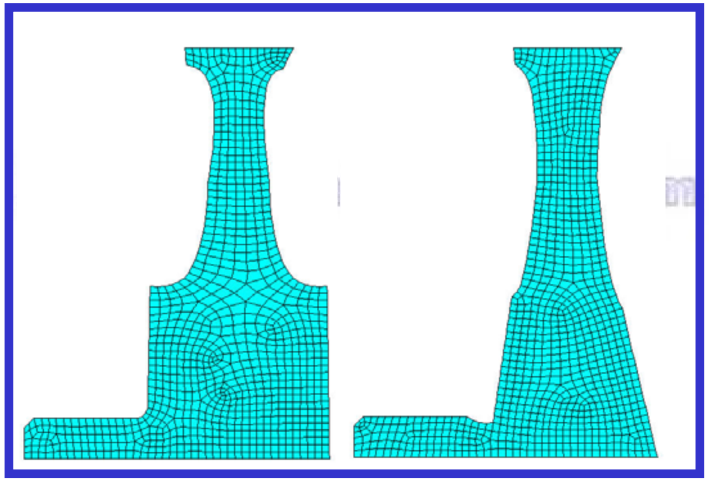
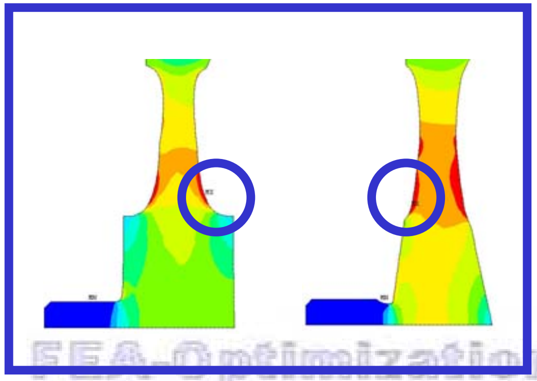
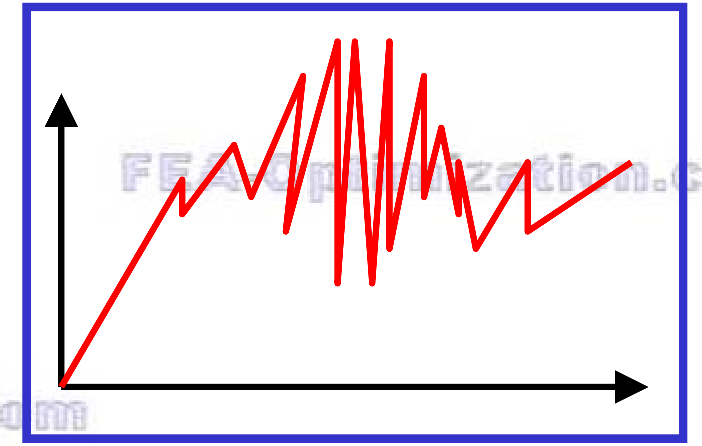
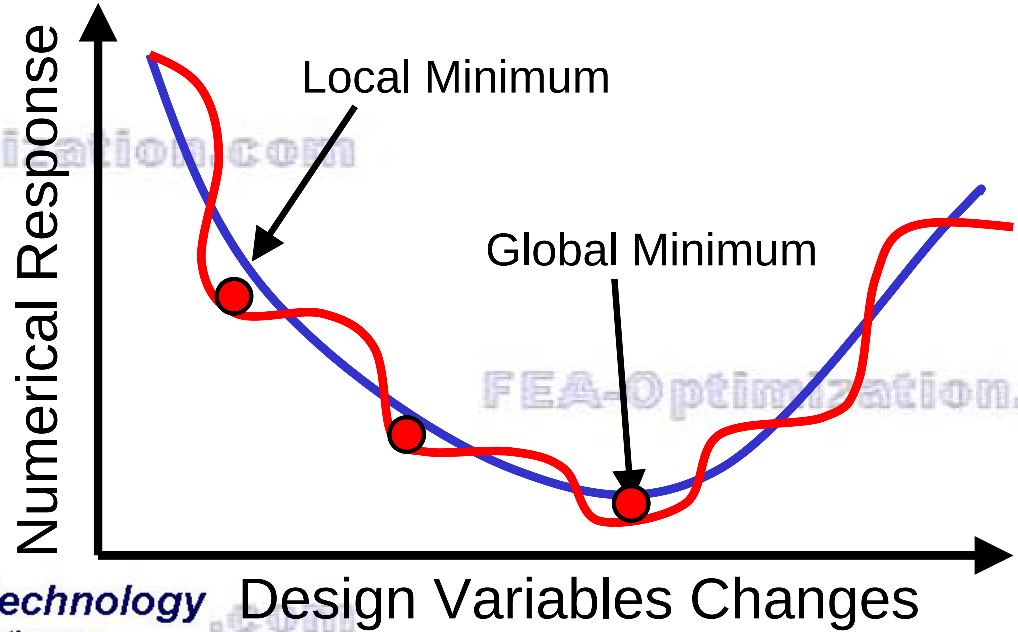
Common Problems of CAE- or FEA-Based Optimization

Numerical Noise/Local Minimum


Meshing Perturbation


Stress Oscillation


Dynamic Response



Theoretical Value

Actual Value (with noise)

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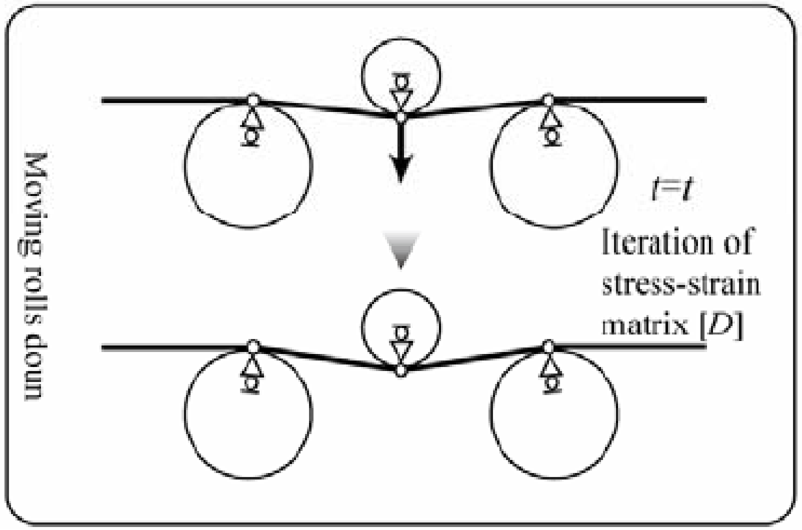
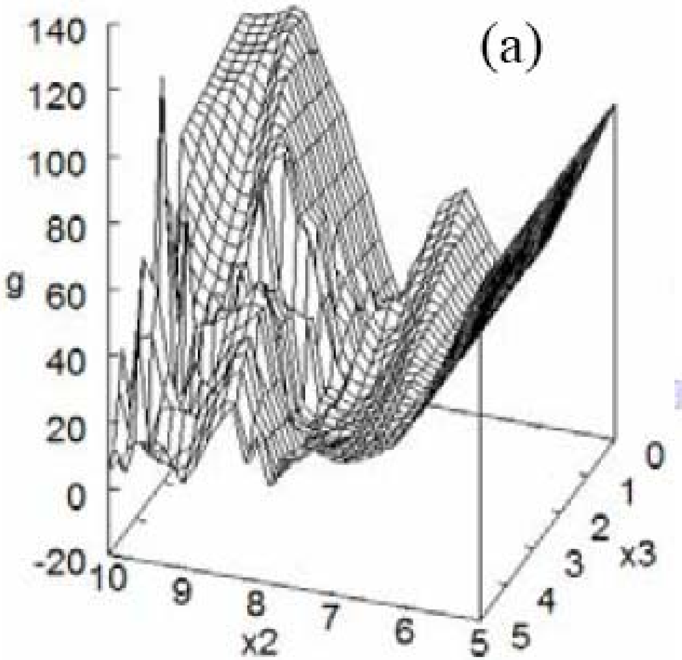
Common Problems of CAE- or FEA-Based Optimization

Numerical Noise/Local Minimum

- Example taken from : STOCHASTIC OPTIMIZATION OF TENSION LEVELING PROCESS FOR PRODUCTION OF FLAT METALLIC STRIPS, Dr. Hiroshi Hamasaki, Dr. Ryutaro Hino, Prof. Fusahito Yoshida(Hiroshima University, Japan), Prof. Vassili V. Toropov(University of Leeds, United Kingdom), WCSMO7, May 2007, South Korea.



Parametric Study by CAE Simulation



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Common Problems of CAE- or FEA-Based Optimization

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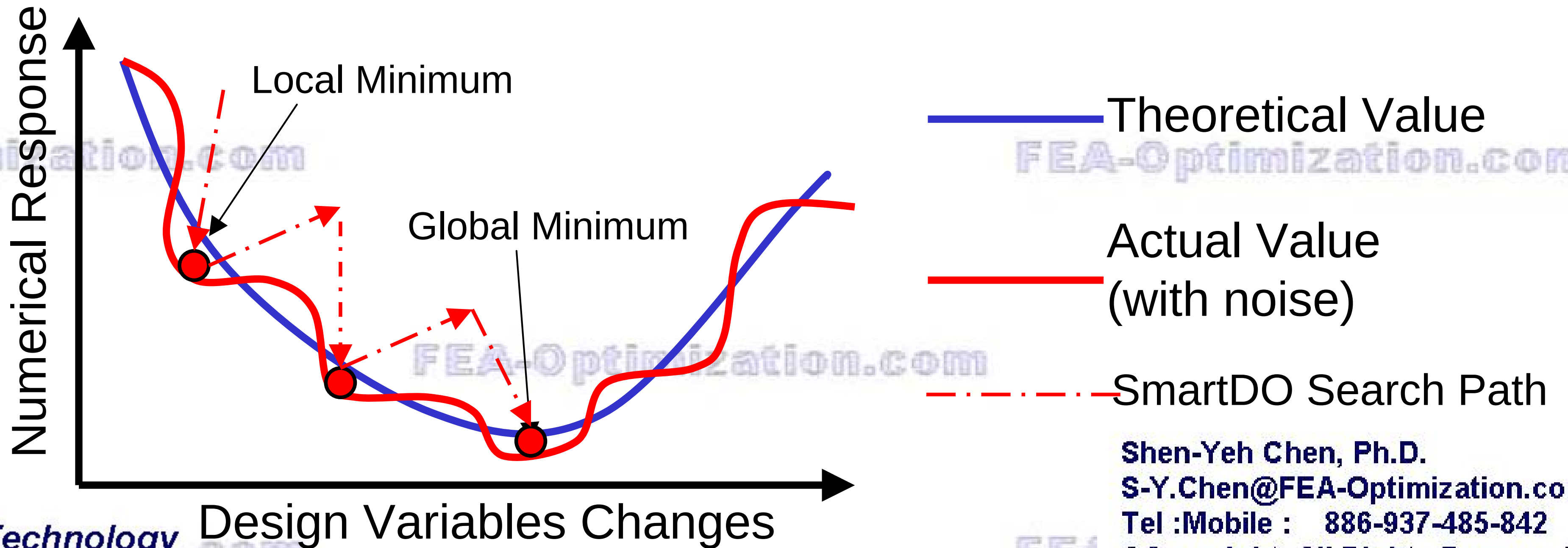
Numerical Noise/Local Minimum

- The Response Smoothing Technology by SmartDO
  - Gradient-Based Solver : Response Smoothing Technology
  - GA-Based : Adaptive Penalty Function and Association String with Absolute Descent Property



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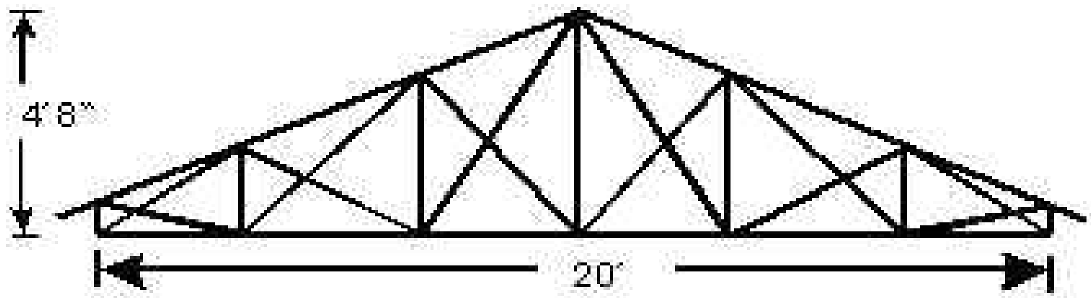
Applications (1)

Skeleton Supporting Structure (1995~1997)



- Design Variables
  - Cross-section of each member
  - Location of each joint
  - Topology of the structures
- Objective Function
  - Minimize the cost or weight of the structure
- Constraints
  - Structural response : stress, displacement, buckling and vibration
  - Easy to fabricate
  - Hardware test data/experience must be taken into account
- Results
  - The strength is increased by 20%
  - The cost reduced by 40%

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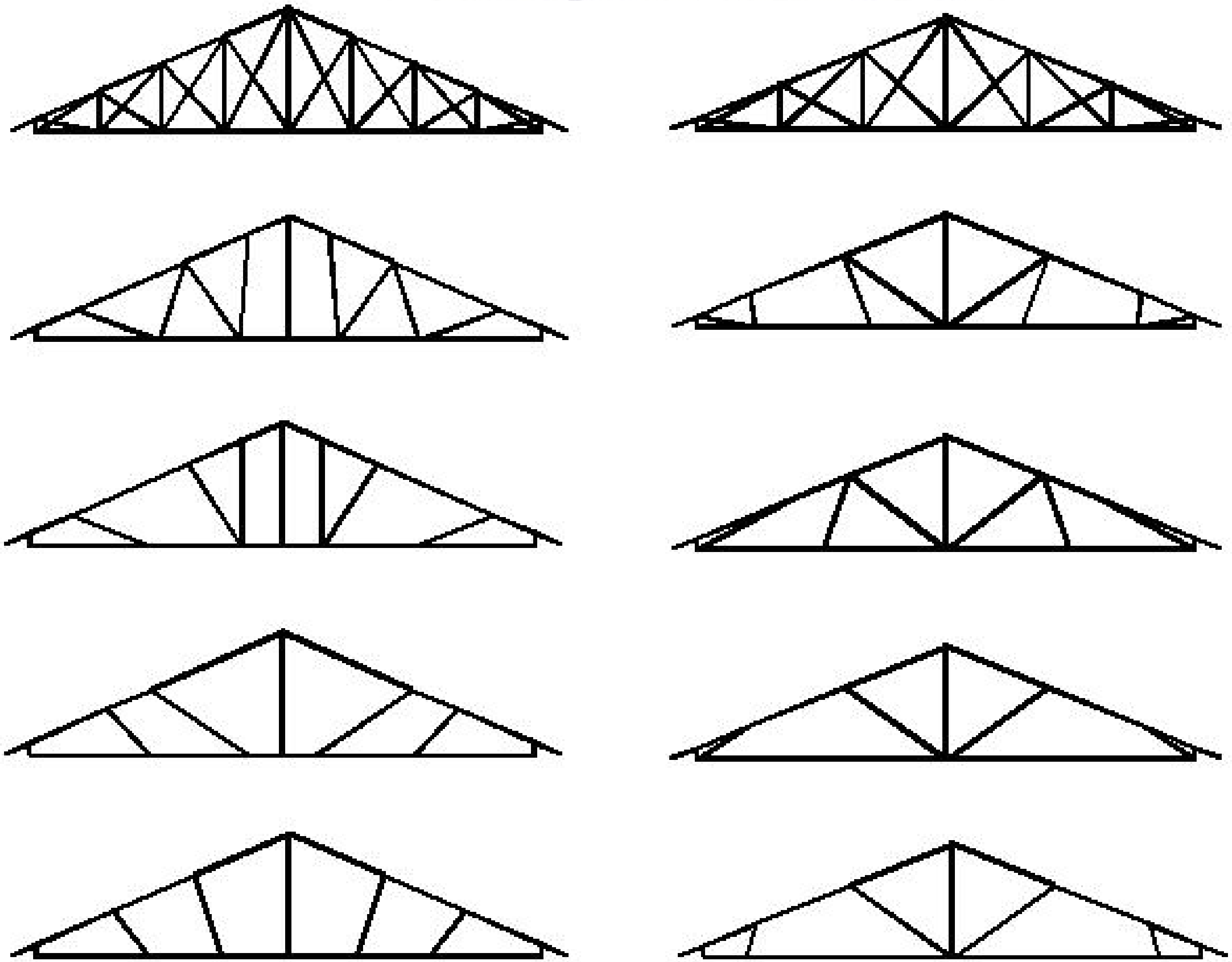
Applications (1)

Skeleton Supporting Structure (1995~1997)

Original Design → **Optimal Design**



Original Design → **Optimal Design**

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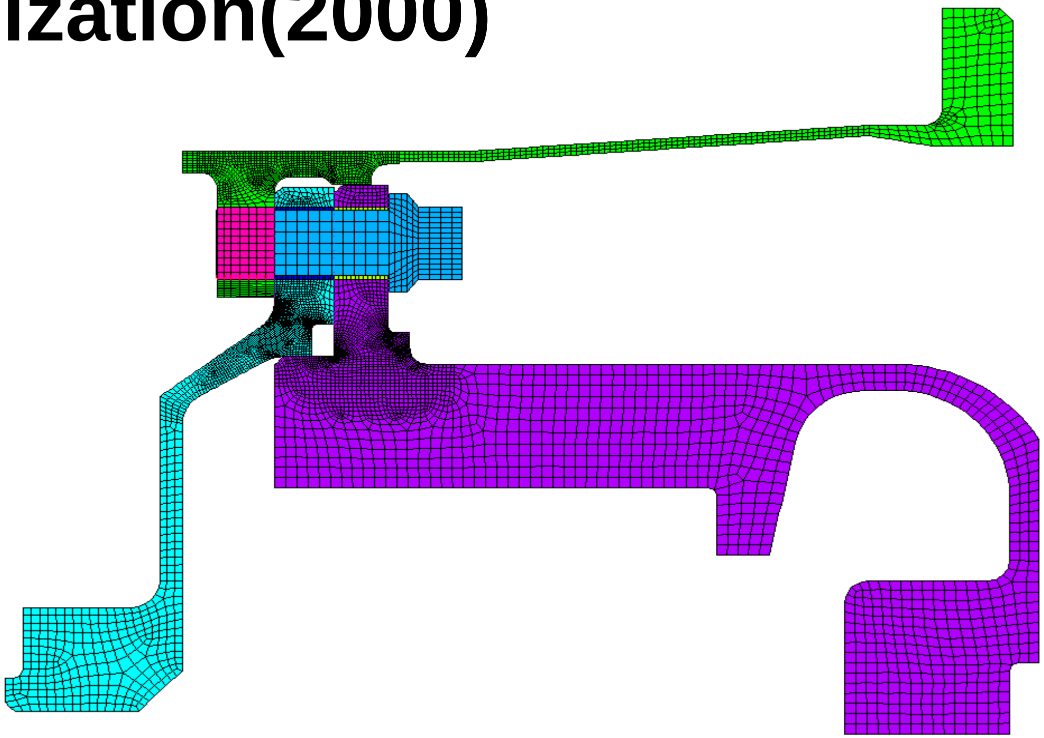
Applications (2)

Components/Assembly Optimization(2000)



- Design Variables
  - Parameters that decides the size and shape of the components
- Objective Function
  - Minimize the stress
- Constraints
  - Stress and Manufacturing limitations (minimum thickness, radius, etc)
  - Parallel shape variation on certain area
- Results
  - Stress reduced below targeted value
  - No weight increase
  - Optimum design without manufacturing difficulty

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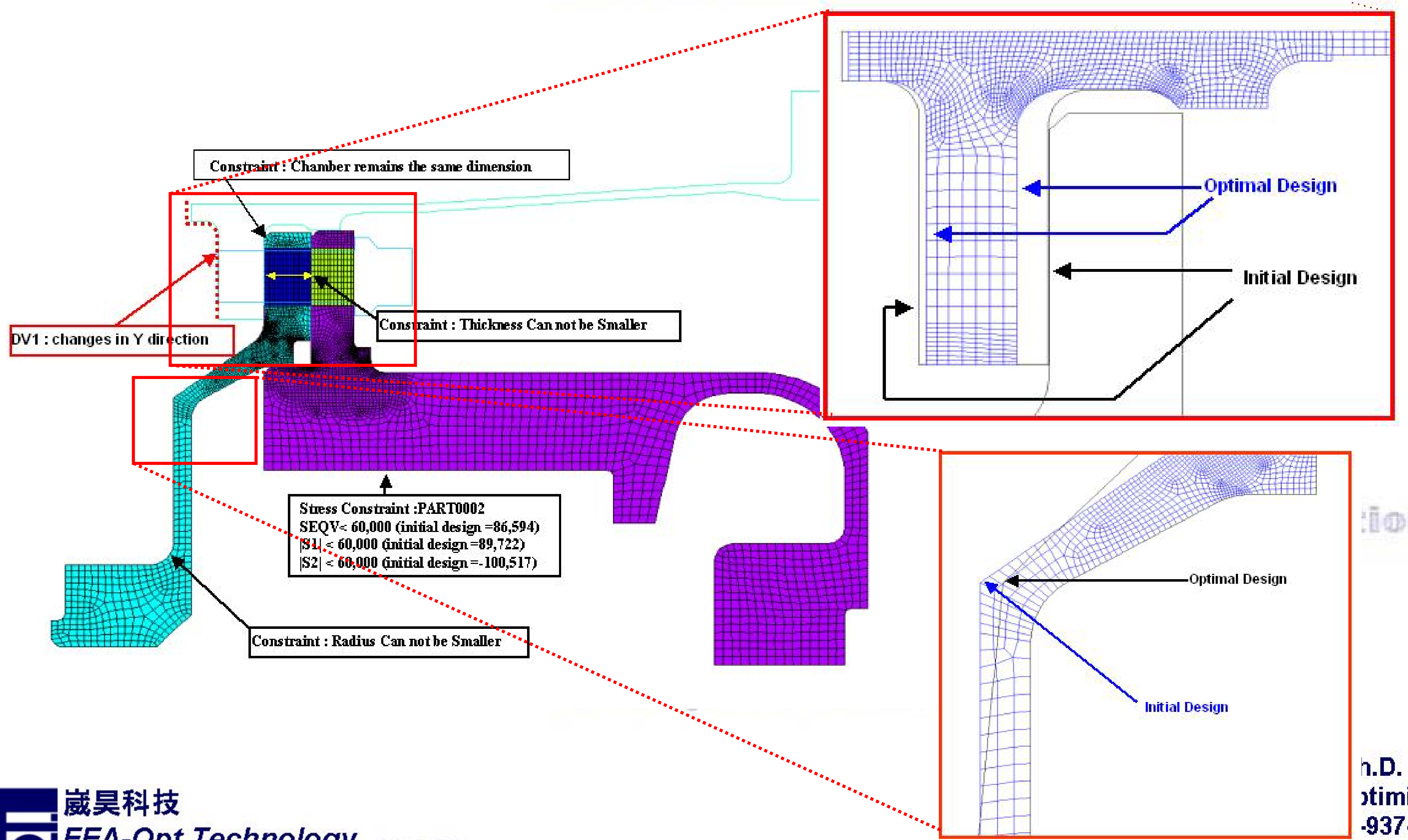
Applications (2)

Components/Assembly Optimization(2000)



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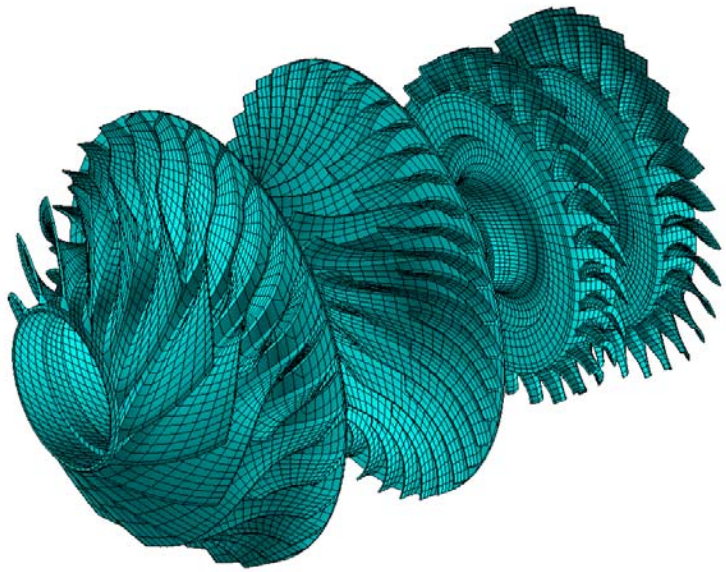
Applications (3)

Rotors/Wheels (2001)

- Design Variables
  - – Parameters that decide the shape of the rotor/wheel
- Objective Function
  - – Minimize the weight of the disk
- Constraints
  - – Stress
  - – Geometry consistency and feasibility
- Results
  - Strength increased by 5%
  - Weight reduced by 22%



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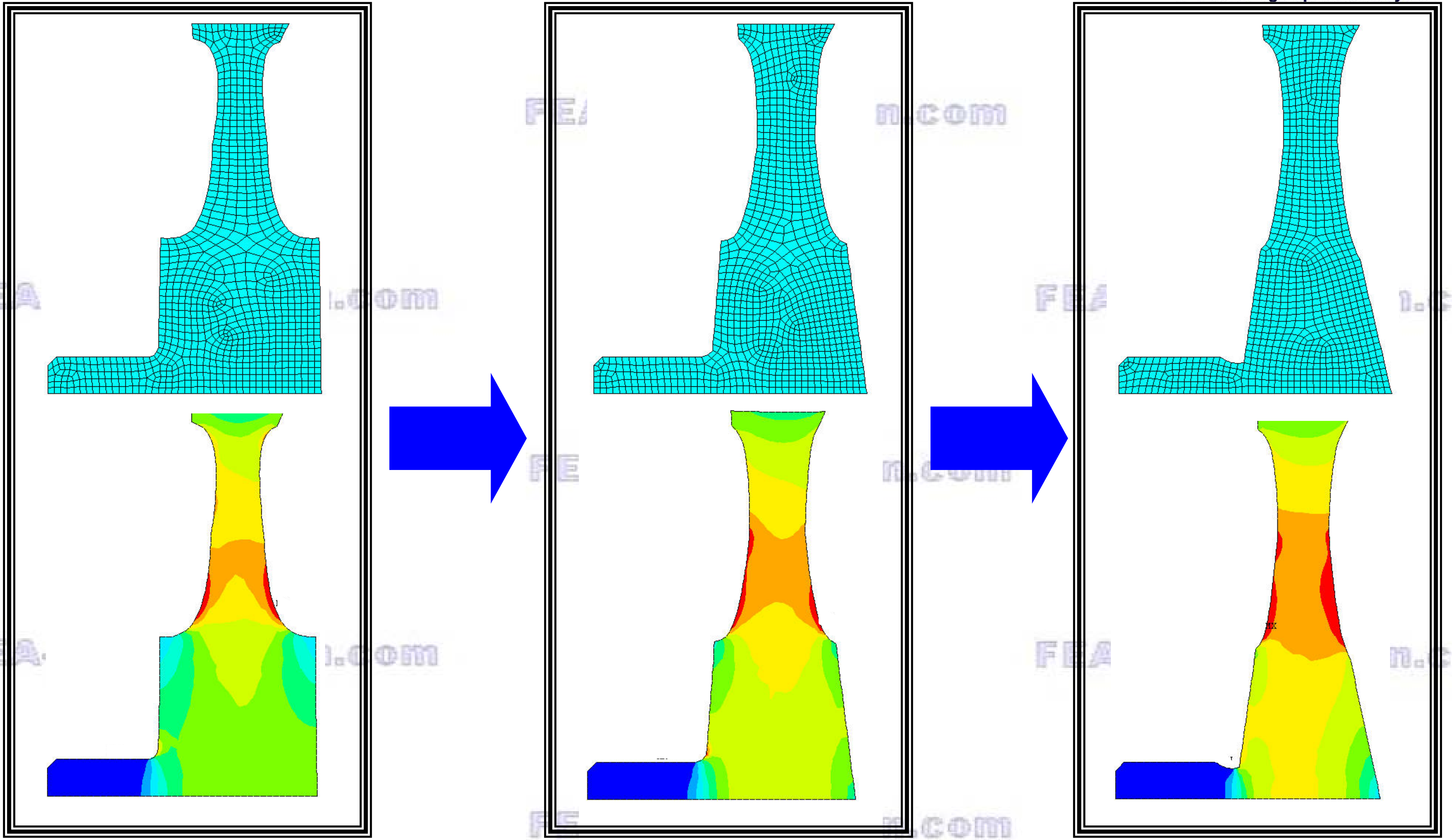

Original Design　　Interim Design　　Optimal Design

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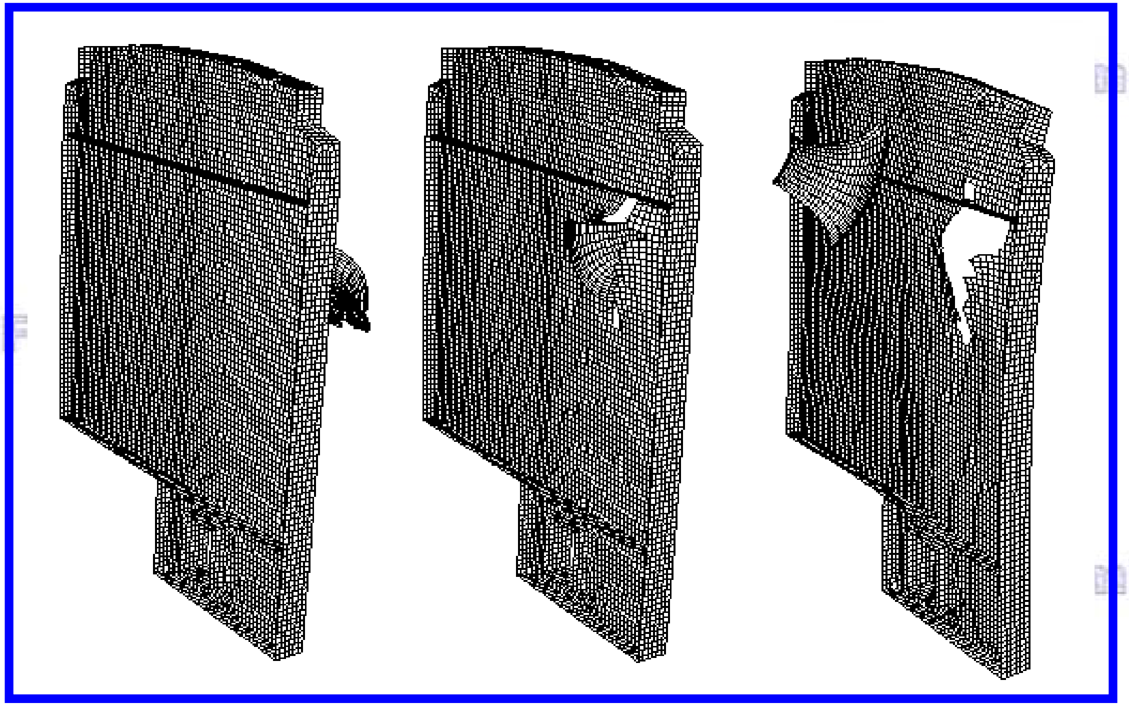
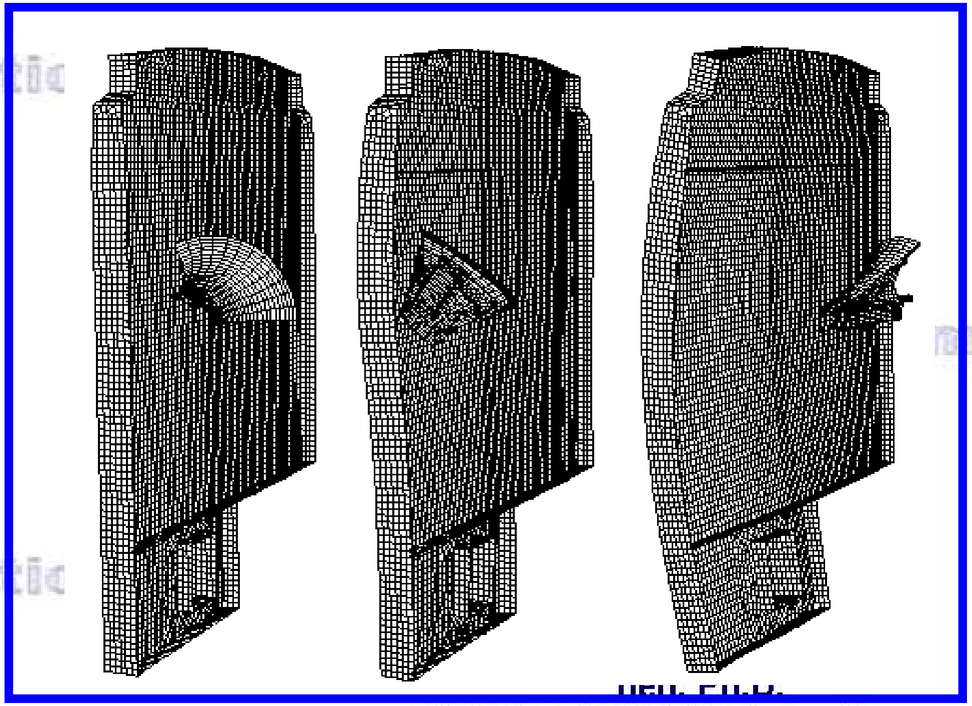
Applications (4)

Crashworthiness/Penetration (2001)

- Design Variables
  - Thickness of the shield
- Objective Function
  - Minimize the weight of the shield
- Constraints
  - Deformation
  - Penetration
  - Structural integrity
- Results : weight reduced by 40%



Original Design



Optimal Design

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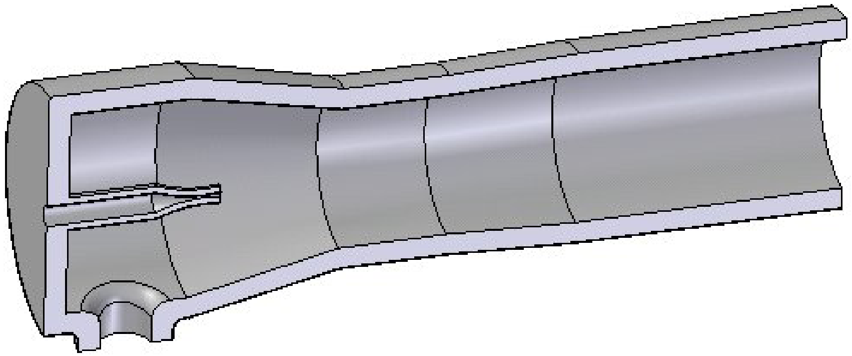
Applications (5)

Ejector (2005~2006)

- Design Variables
  - 3D dimensions of the ramjet system
- Objective Function
  - Maximize the performance
  - Evaluated by CFD codes
- Constraints
  - Overall length
  - Maximum and minimum dimension
  - Geometry consistency and feasibility
  - Environmental condition



- Results
  - The first ejector design automation system on earth.
  - The performance is usually increased to 2 to 4 times.

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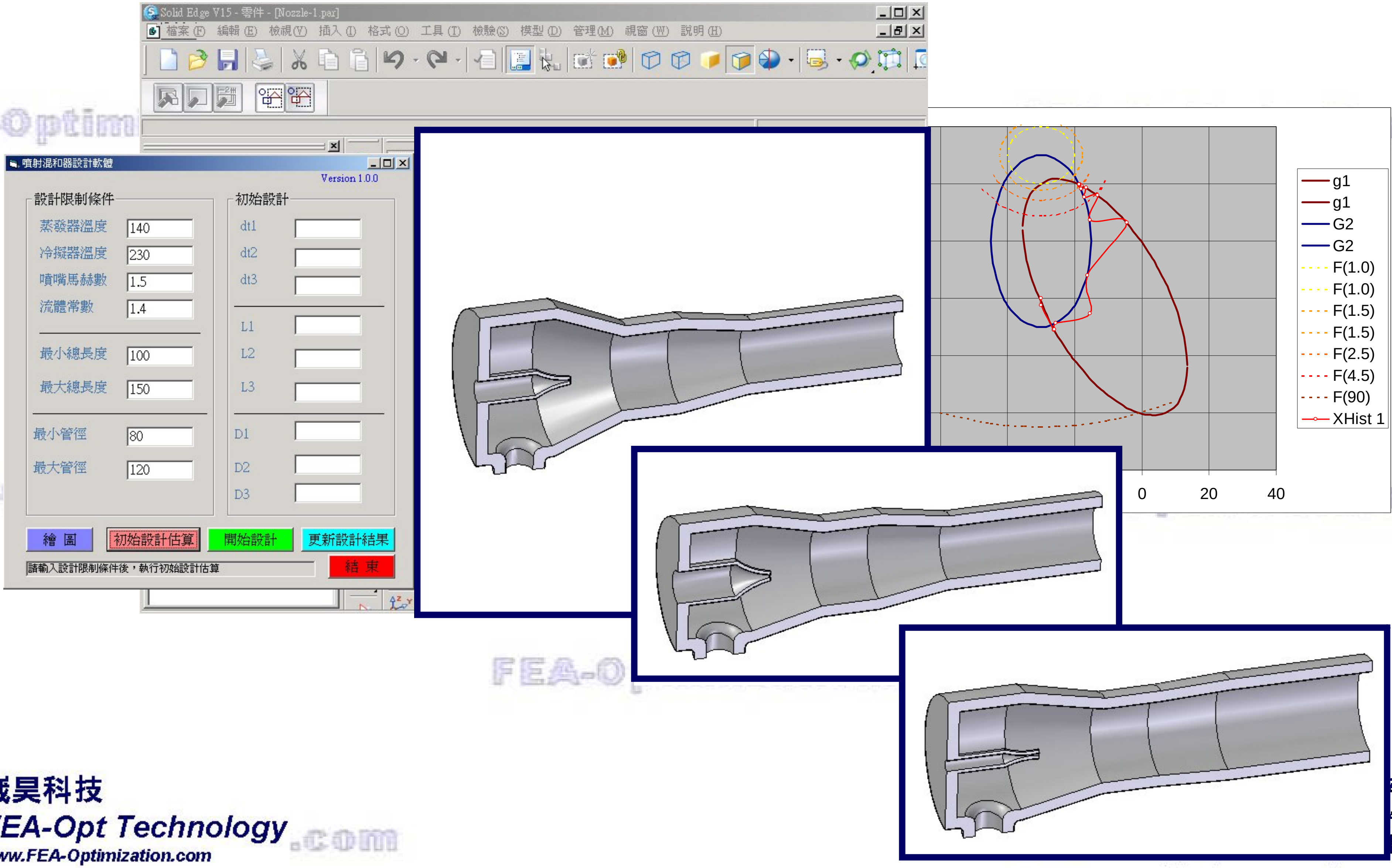
Applications (5)

Ejector (2005~2006)



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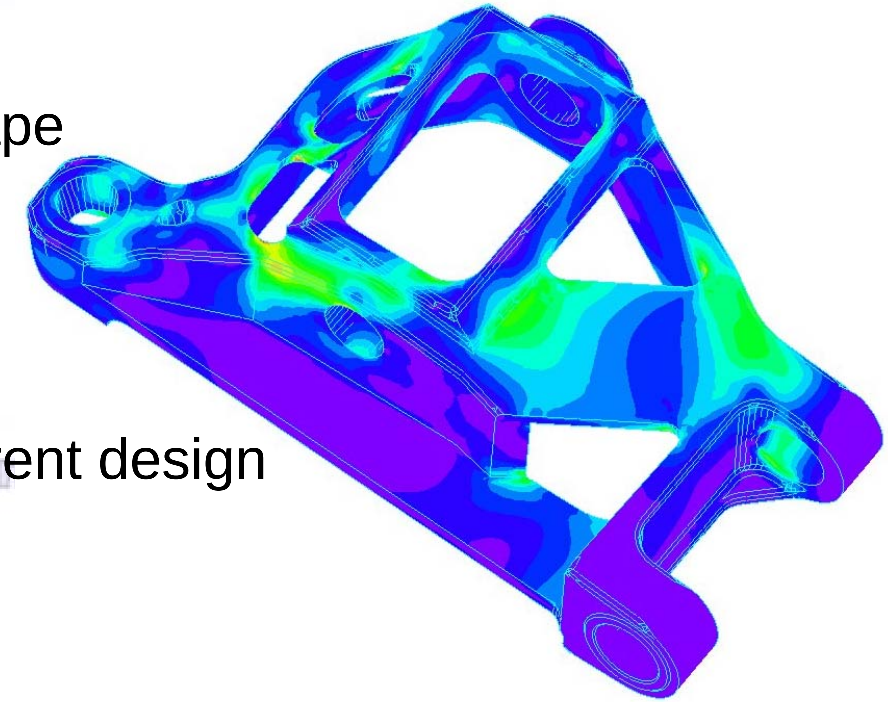
Applications (6)

A-Arm Wight Reduction (2005~2006)



- Design Variables
  - Material distribution (topology) and local shape
- Objective Function
  - Minimize the weight
- Constraints
  - Stress must be little than or equal to the current design
  - Interference with other components
  - Take the hardware test result into account
- Results
  - Weight reduced by 30%
  - Stress reduced by 20%~40%

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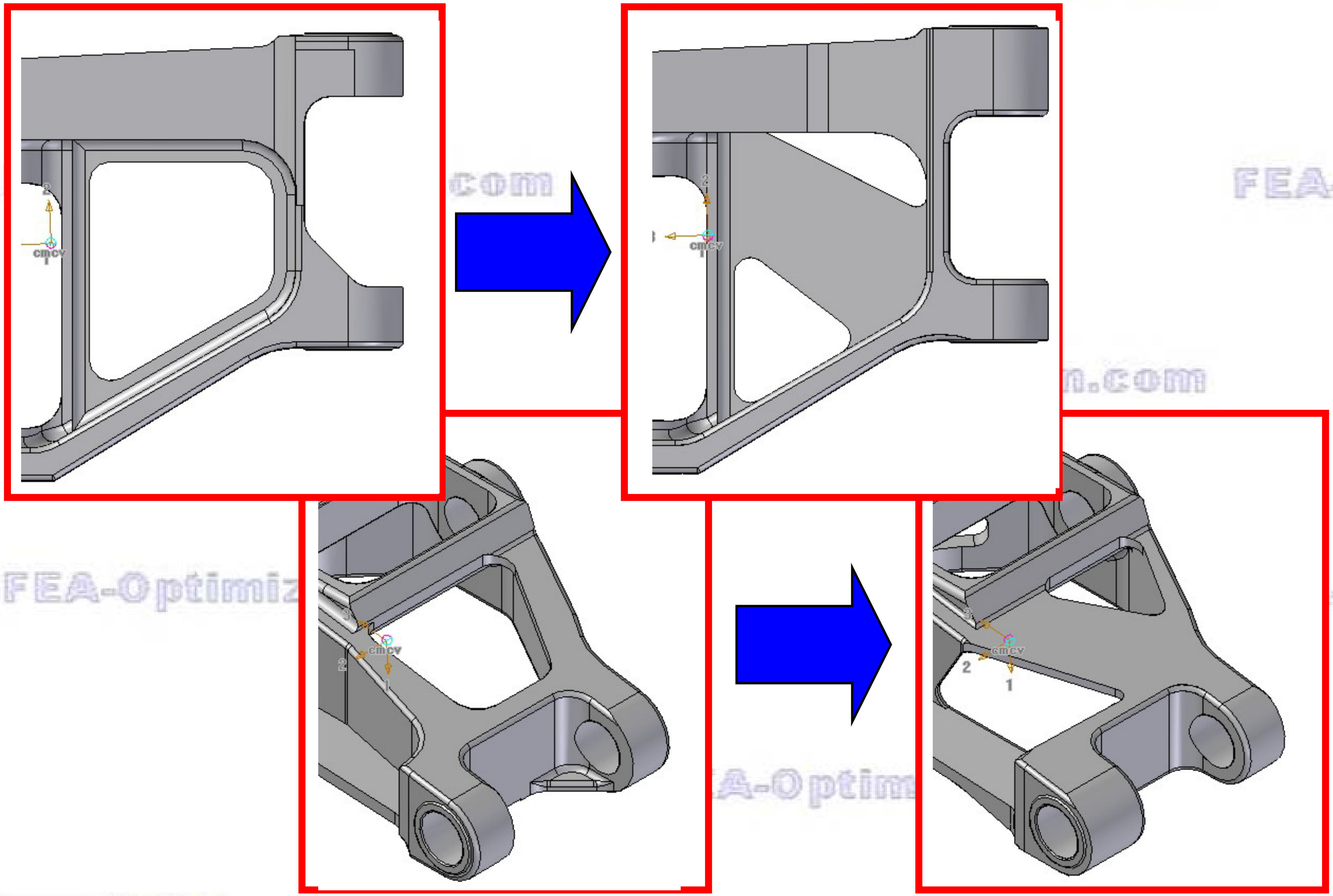
Applications (6)

A-Arm Wight Reduction (2005~2006)



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2000~2002

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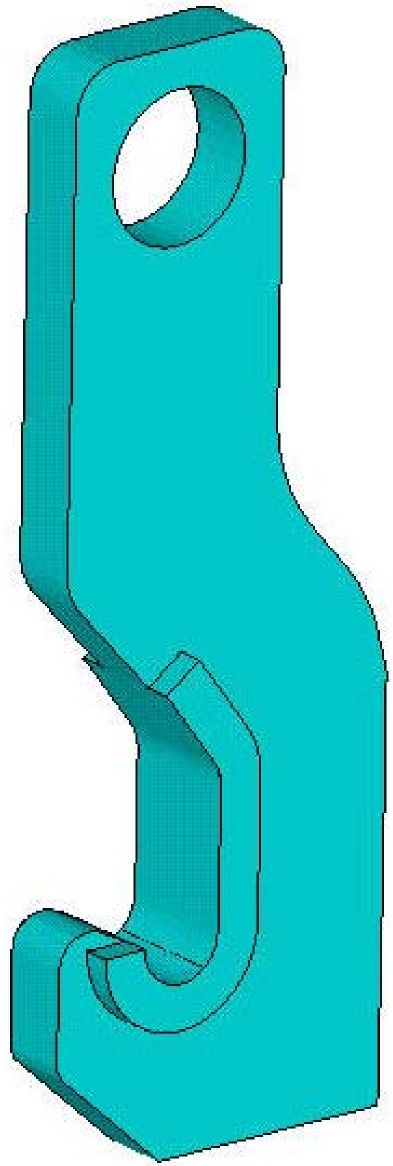
Applications (7)

Linking Rod Wright Reduction(2006)

- Design Variables
  - Parameters that decides the shape of the york
- Objective Function
  - Minimize the weight. The strength can not be reduce.
- Constraints
  - Space is confined and limited
  - Strength is subjected to code check
- Results
  - Weight reduced by 20%
  - Stress is slightly reduced



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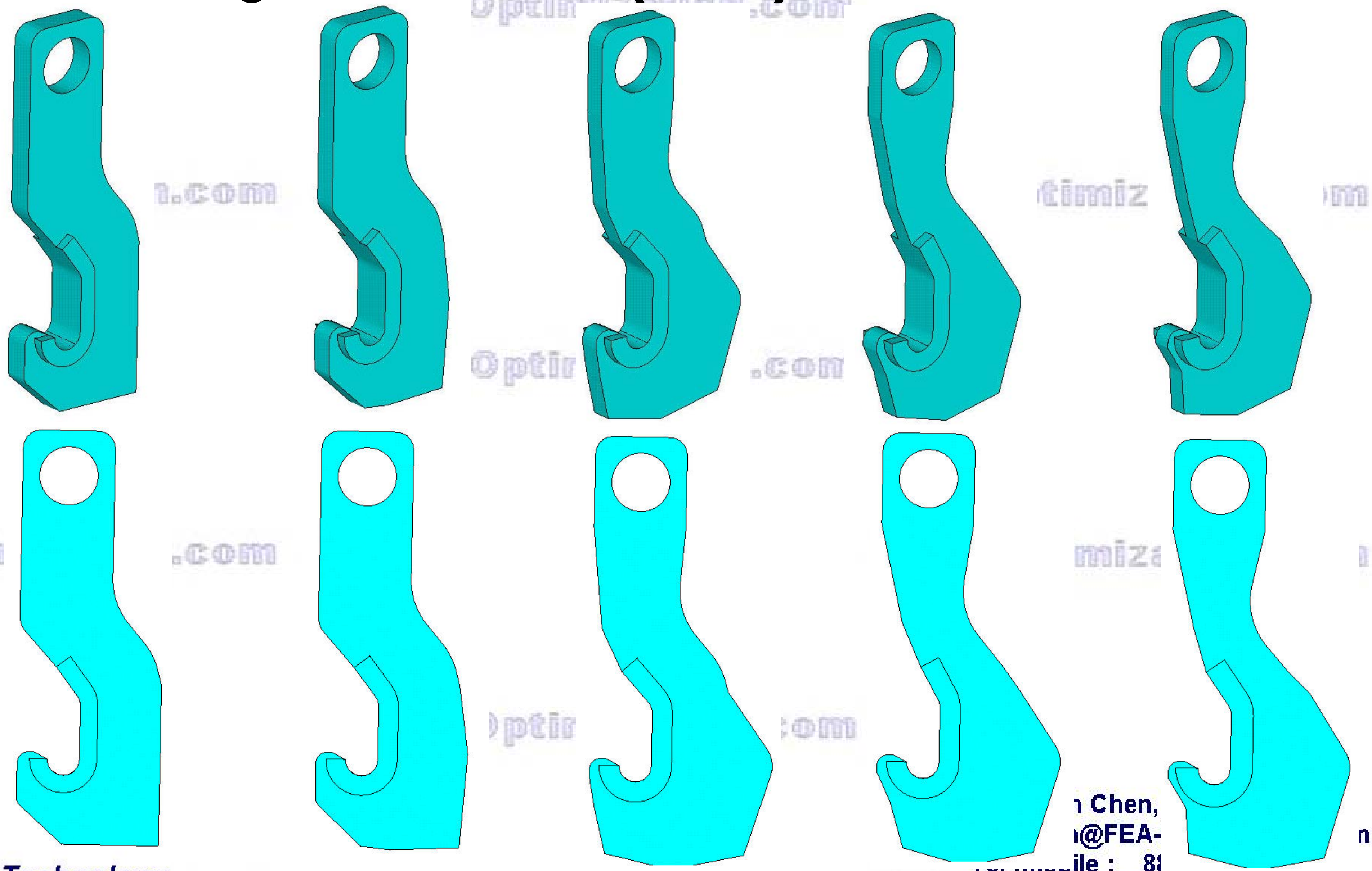
Applications (7)

Linking Rod Wright Reduction(2006)



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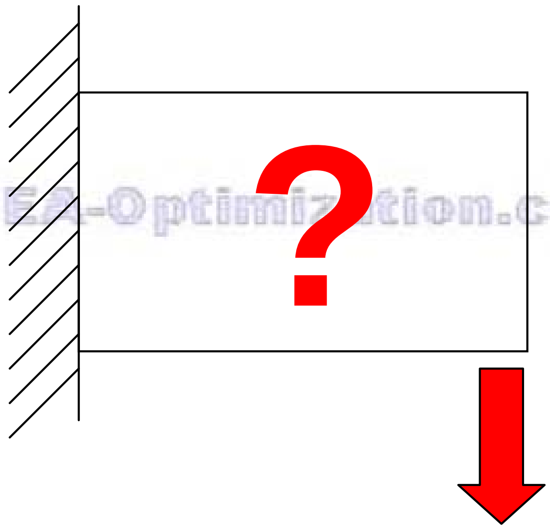
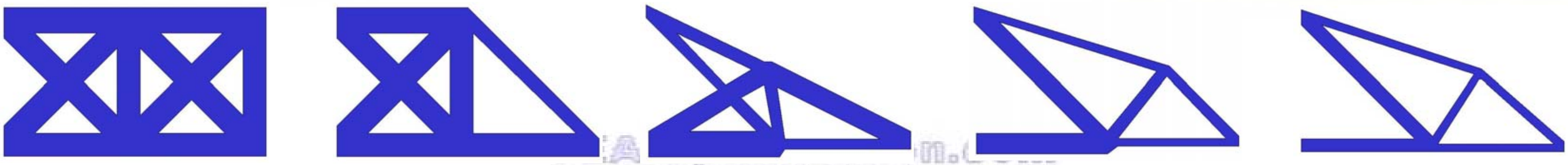
Applications (7)

Cantilever Supporting Structure (2005~2007)

- Design Variables
  - Concurrent Sizing, Shaping and Topology
- Objective Function
  - Minimize the weight
- Constraints
  - Structural response : stress and displacement
- Results
  - Weight reduced by 50%





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Thank You for Your Participation

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