Multidisciplinary System Design Optimization applied to a Space Shuttle External Fuel Tank

Anonymous MIT students

Agenda

- Introduction
- Problem Statement
- Model Implementation and Validation
- Design of Experiment
- Single Objective Optimization
- Sensitivity Analysis
- Multi objective Optimization
- Conclusions

Agenda

- ✓ Introduction
- Problem Statement
- Model Implementation and Validation
- Design of Experiment
- Single Objective Optimization
- Sensitivity Analysis
- Multi objective Optimization
- Conclusions

Problem Statement

Maximize the **Return On Investment (ROI)** by changing the physical Space Shuttle External Fuel Tank design variables while satisfying the given mechanical requirements (Volume, Stress, Vibrations) at a fixed specific Payload.

Problem Statement (cont')

ROI =

Tank Weight

$$\frac{\text{Revenue}_{\text{(tax payers)}} - (\text{Launch Fixed Costs} + \text{Tank Cost})}{(\text{Launch Fixed Costs} + \text{Tank Cost})}$$

Agenda

- ✓ Introduction
- ✓ Problem Statement
- Model Implementation and Validation
- Design of Experiment
- Single Objective Optimization
- Sensitivity Analysis
- Multi objective Optimization
- Conclusions

Model implementation and validation

Objectives (7)

- Total surface of the tank
- Tank weight
- Total seam cost
- Delta payload
- Payload launched
- ROI

Design Variables (6)

- Nose cone height
- Radius of the hemisphere
- Length of the cylindrical body
- Nose cone thickness
- Cylinder thickness
- Hemisphere thickness
- Aspect ratio of cone

Constraint (5)

- Volume
- Stress (cylinder nose, hemisphere, nose cone)
- Vibration

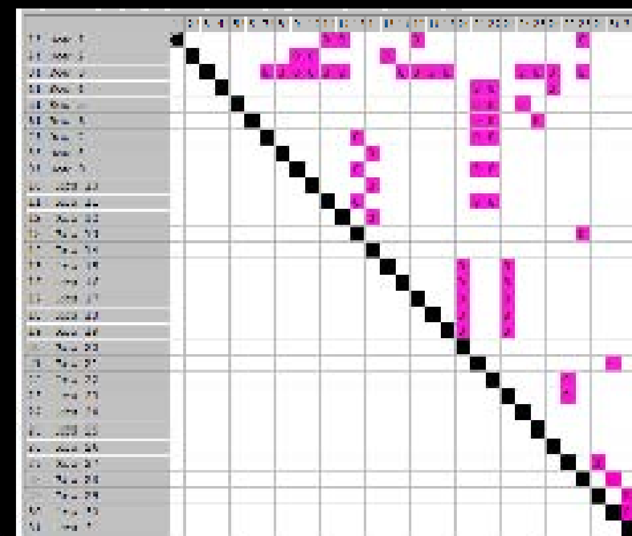
Parameters (10)

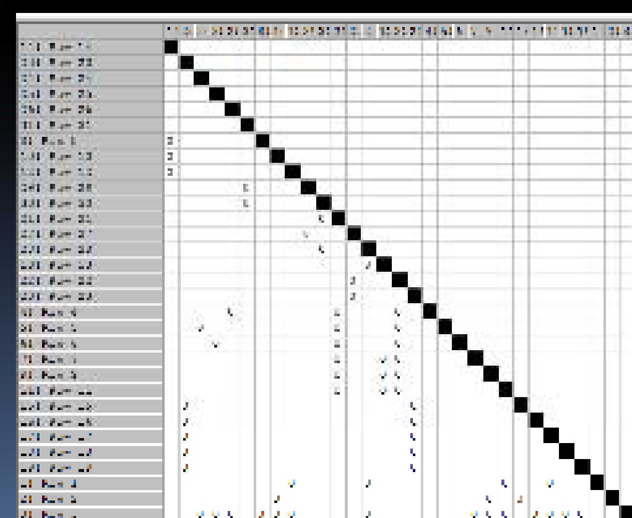
- Cost of material/unit
- Cost Seam/unit
- Material weight/unit
- Liquid fuel pressure
- Payload 1
- Payload 2
- Nominal Payload
- Profit ratio
- Vibration constant
- Fixed launch cost per weight
- Charge to customer for launching payload per unit weight

Model implementation and validation (cont')

		Description	Symbol	Unit of measurement	Inputs	Outputs
Design Vector	1	Nose cone height	H	cm		11, 12, 17, 28
	2	Length of center cylindrical body	L	cm		9, 10, 15
	3	Radius of hemisphere	R	cm		7,8,9,10,11,12,16, 17, 18, 19, 24, 25, 26, 28, 32
	4	Nose cone thickness	T_{cone}	cm		21, 22, 26
	5	Cylinder thickness	$T_{cylinder}$	cm		21, 22, 24
	6	Hemisphere thickness	$T_{hemisphere}$	cm		21, 22, 25
Surfaces and Volumes	7	Hemisphere Surface	HS	cm^2	3	13, 21, 22
	8	Hemisphere Volume	HV	cm^3	3	14
	9	Cylinder Surface	CS	cm^2	2,3	13, 21, 22
	10	Cylinder Volume	CV	cm^3	2,3	14
	11	Cone Surface	CnS	cm^2	1,3	13, 21, 22
	12	Cone Volume	CnV	cm^3	1,3	14
	13	Tank surface	TS	cm^2	7, 9, 11	28
	14	Tank volume	TV	cm^3	8, 10, 12	36
Seams length	15	Seam length in Cylinder	S1	cm	2	20, 23
	16	Seam length in Hemisphere	S2	cm	3	20, 23
	17	Seam length in Cone	S3	cm	1, 3	20, 23
	18	Seam length cylinder & hemisph	S4	cm	3	20, 23
	19	Seam length cylinder & cone	S5	cm	3	20, 23
	20	Total Seam length	St	cm	15-19	
Weight and material cost	21	Tank weight	TW	kg	9,5,7,6,11,4	30, 32
	22	Tank material cost	$C_{material}$	dollar	9,5,7,6,11,4	27
Seam Cost	23	Cost of seams	C_{seam}	dollar	15-19	27
Stress	24	Cylinder Eq. stress	E	N/cm sq	3, 5	34
	25	Sphere Eq. stress	SE	N/cm sq	3, 6	35
	26	Cone Eq. stress	CE	N/cm sq	3, 4	33
Total cost	27	Total Cost	TC	dollar	22, 23	27

PSM32





Model implementation and validation (cont')

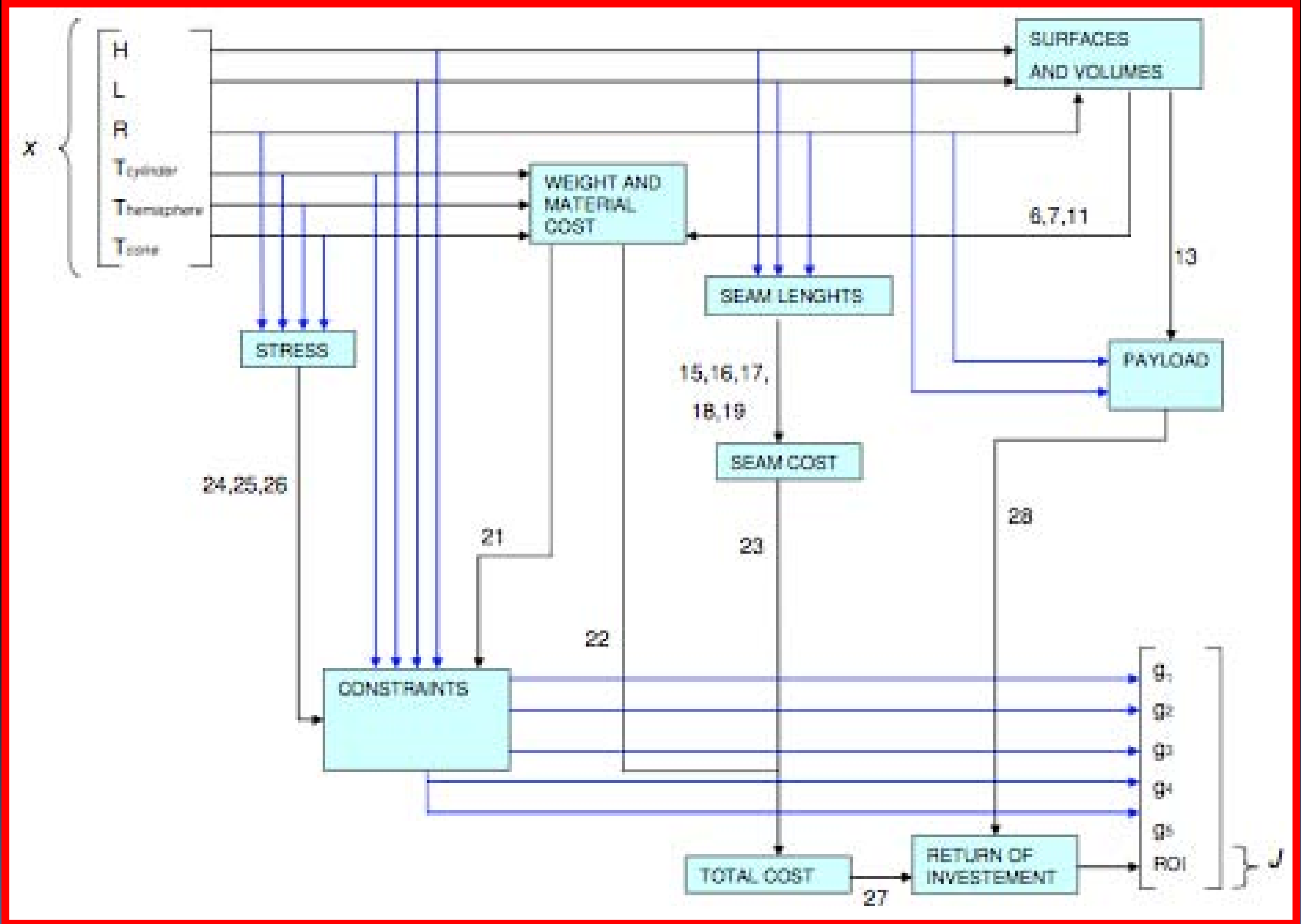
N2 Matrix

Modules

Design Vector	Surfaces and Volumes	Seam lengths	Weight and material costs	Seam cost	Stress	Total Cost	Payload	Retun of investment	Constraints
Design Vector	1, 2, 3	1, 2, 3	4, 5, 6		3, 4, 5, 6		1, 3		1, 2, 3, 4
	Surfaces and Volumes		6, 7, 11				13		
		Seam lengths		15, 16, 17, 18, 19					
			Weight and material costs			22			21
				Seam cost		23			
					Stress				24, 25, 26
						Total Cost		27	
							Payload	28	
								Retun of investment	
									Constraints

Model implementation and validation (cont')

Block Diagram



Model implementation and validation (cont')

Model Validation

- The given nominal values of the real External Tank were used in the model formulas
- Outputs verified the model as valid, but with low fidelity

E.g.: Nominal Tank Weight = 27,737.79 [Kg]
Model Tank Weight = 21,254.46 [Kg]

Agenda

- ✓ Introduction
- ✓ Problem Statement
- ✓ Model Implementation and Validation
- Design of Experiment
- Single Objective Optimization
- Sensitivity Analysis
- Multi objective Optimization
- Conclusions

Design of Experiment

DOE factors and levels

Factors	Level 1	Level 2	Level 3
HR2	1	2	3
L	4600	4800	5000
R	420	435	450
TCO	0.66	0.75	0.84
TCY	0.66	0.7	0.74
TH	0.76	0.86	0.96

$$X_0 = \begin{bmatrix} 1 \\ 4600 \\ 435 \\ 0.84 \\ 0.74 \\ 0.86 \end{bmatrix}$$

$$ROI_0 = 0.0903$$

18-Orthogonal array

Exp	HR2	L	R	TCO	TCY	TH
1	1	4600	420	0.66	0.66	0.76
2	1	4800	435	0.75	0.7	0.86
3	1	5000	450	0.84	0.74	0.96
4	2	4600	420	0.75	0.7	0.86
5	2	4800	435	0.84	0.74	0.76
6	2	5000	450	0.66	0.66	0.86
7	3	4600	435	0.66	0.74	0.86
8	3	4800	450	0.75	0.66	0.96
9	3	5000	420	0.84	0.7	0.76
10	1	4600	450	0.84	0.7	0.86
11	1	4800	420	0.84	0.74	0.96
12	1	5000	435	0.75	0.66	0.76
13	2	4600	435	0.84	0.66	0.96
14	2	4800	450	0.66	0.7	0.76
15	2	5000	420	0.75	0.74	0.86
16	3	4600	450	0.75	0.74	0.76
17	3	4800	420	0.84	0.66	0.86
18	3	5000	435	0.66	0.7	0.96

Main effects

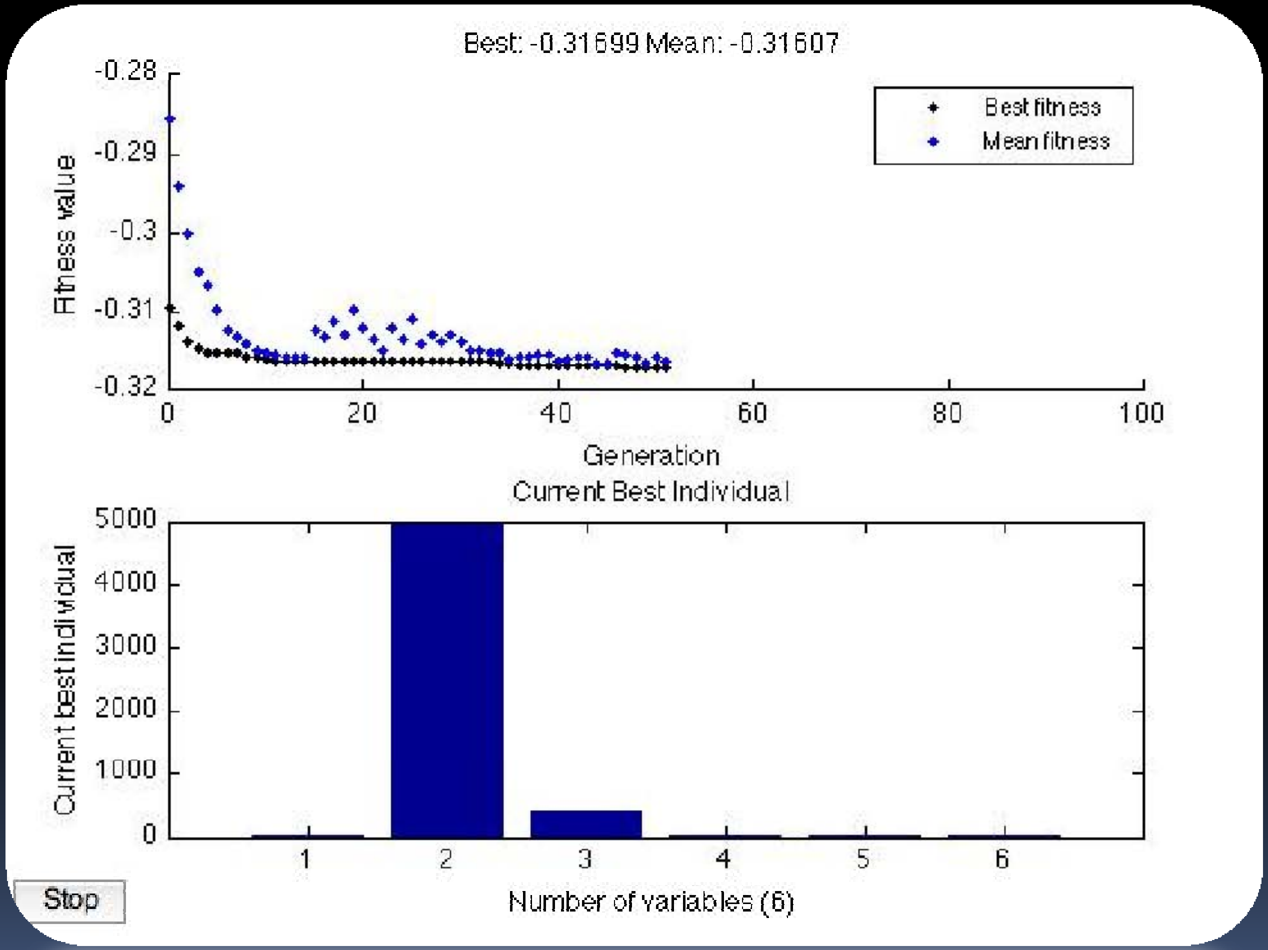
Variable	Level	Factor	Mean	Main Effect
HR2	1	1	-0.2455	0.2555
	2	2	-0.4377	0.0633
	3	3	-0.8197	-0.3187
L	1	4600	-0.3959	0.1050
	2	4800	-0.6122	-0.1112
	3	5000	-0.4948	0.0062
R	1	420	-0.6945	-0.1936
	2	435	-0.1060	0.3950
	3	450	-0.7024	-0.2014
TCO	1	0.66	-0.7426	-0.2416
	2	0.75	-0.4401	0.0609
	3	0.84	-0.3806	0.1204
TCY	1	0.66	-0.5596	-0.0586
	2	0.7	-0.6043	-0.1034
	3	0.74	-0.3390	0.1620
TH	1	0.76	-0.5986	-0.0976
	2	0.86	-0.3494	0.1515
	3	0.96	-0.5959	-0.0950

Agenda

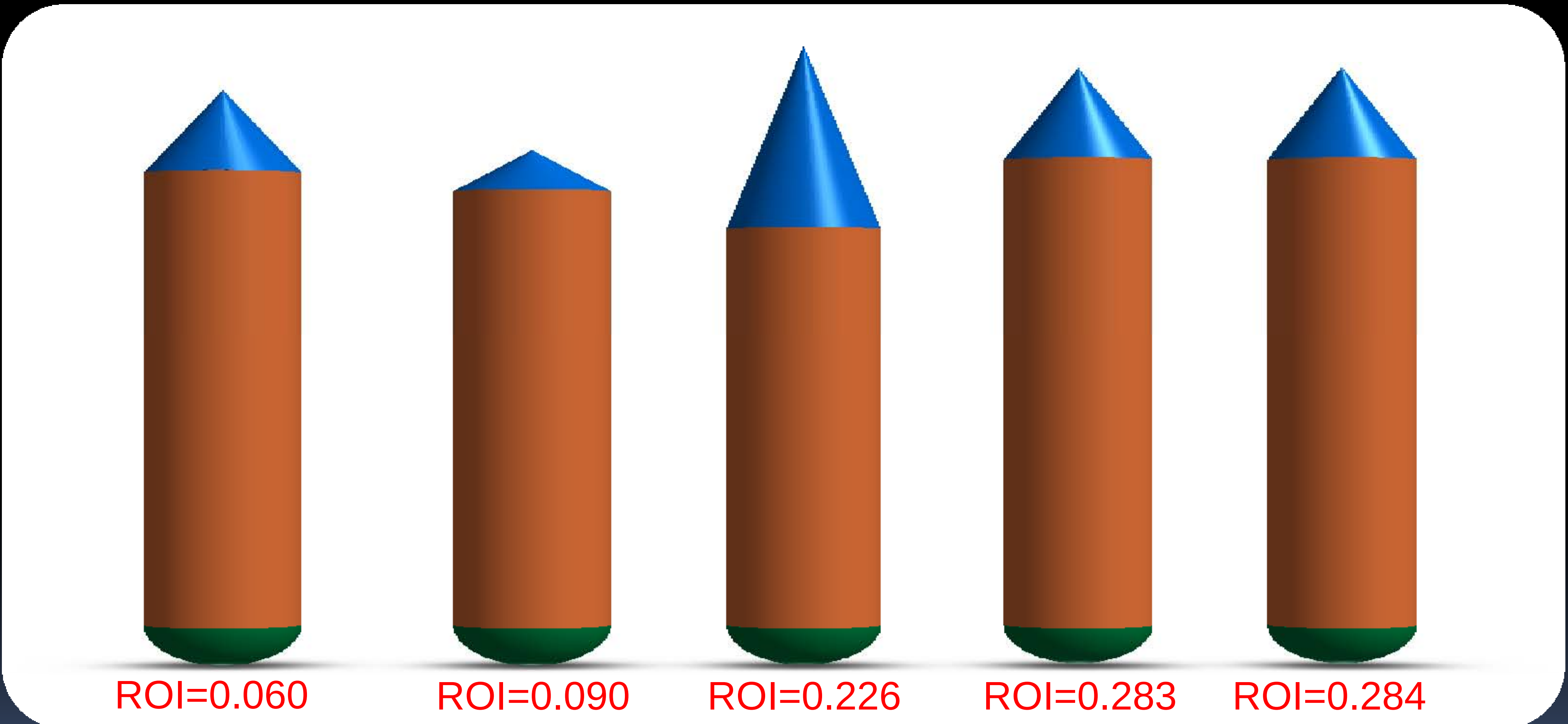
✓ Introduction
✓ Problem Statement
✓ Model Implementation and Validation
✓ Design of Experiment
- Single Objective Optimization
- Sensitivity Analysis
- Multi objective Optimization
- Conclusions

Single Objective Optimization

Best solution by Genetic Algorithm



Single Objective Optimization

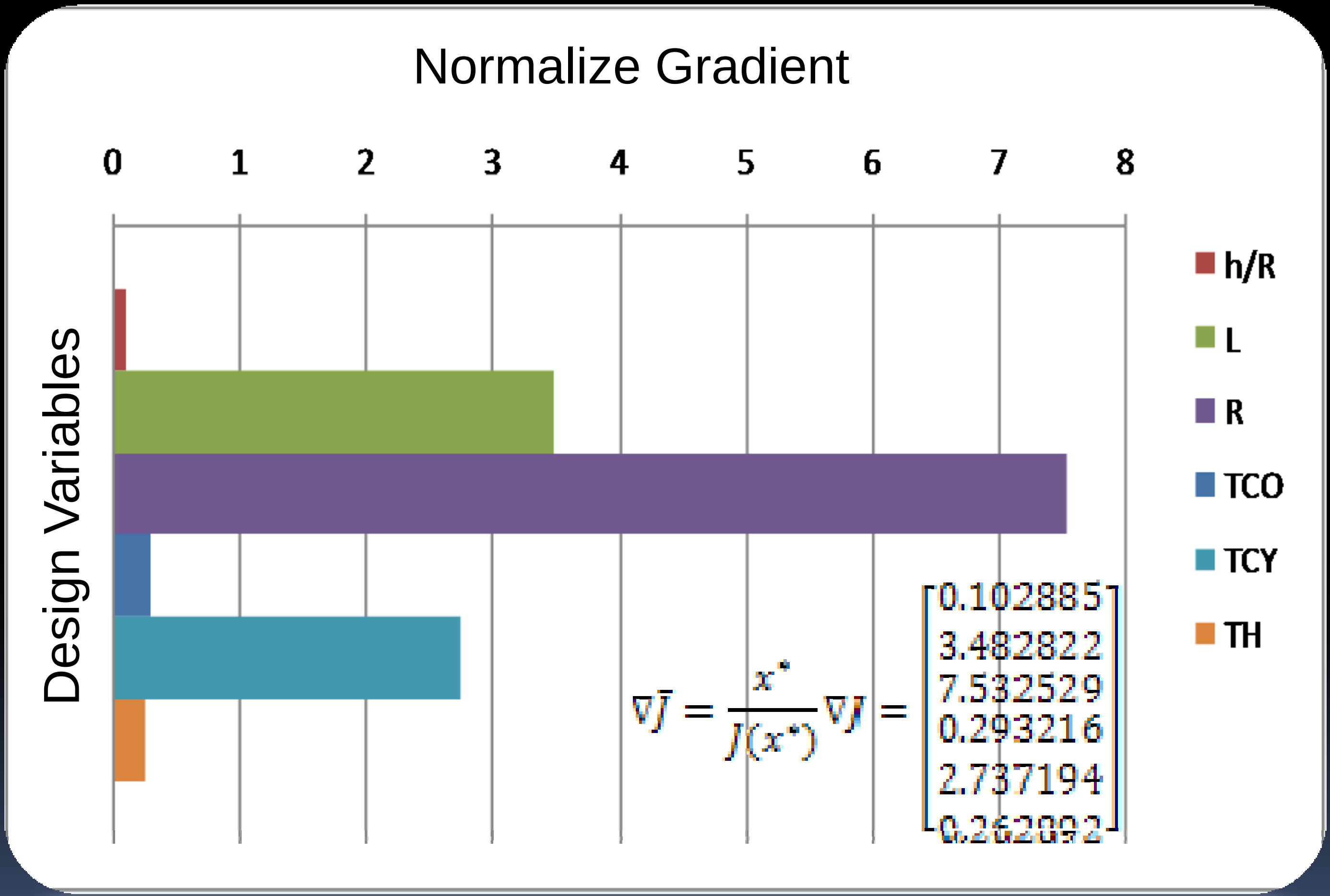


Pre-DOE DOE SQP SQP Scaling GA

Agenda

- ✓ Introduction
- ✓ Problem Statement
- ✓ Model Implementation and Validation
- ✓ Design of Experiment
- ✓ Single Objective Optimization
- Sensitivity Analysis
- Multi objective Optimization
- Conclusions

Sensitivity Analysis



Sensitivity Analysis

$$\frac{d(x)}{d(C)} = \begin{bmatrix} \frac{dHR2}{dC} \\ \frac{dL}{dC} \\ \frac{dR}{dC} \\ \frac{dTCO}{dC} \\ \frac{dTCY}{dC} \\ \frac{dTH}{dC} \end{bmatrix} = \begin{bmatrix} -0.02576 \\ \sim 0 \\ \sim 0 \\ -0.00413 \\ \sim 0 \\ \sim 0 \end{bmatrix}$$

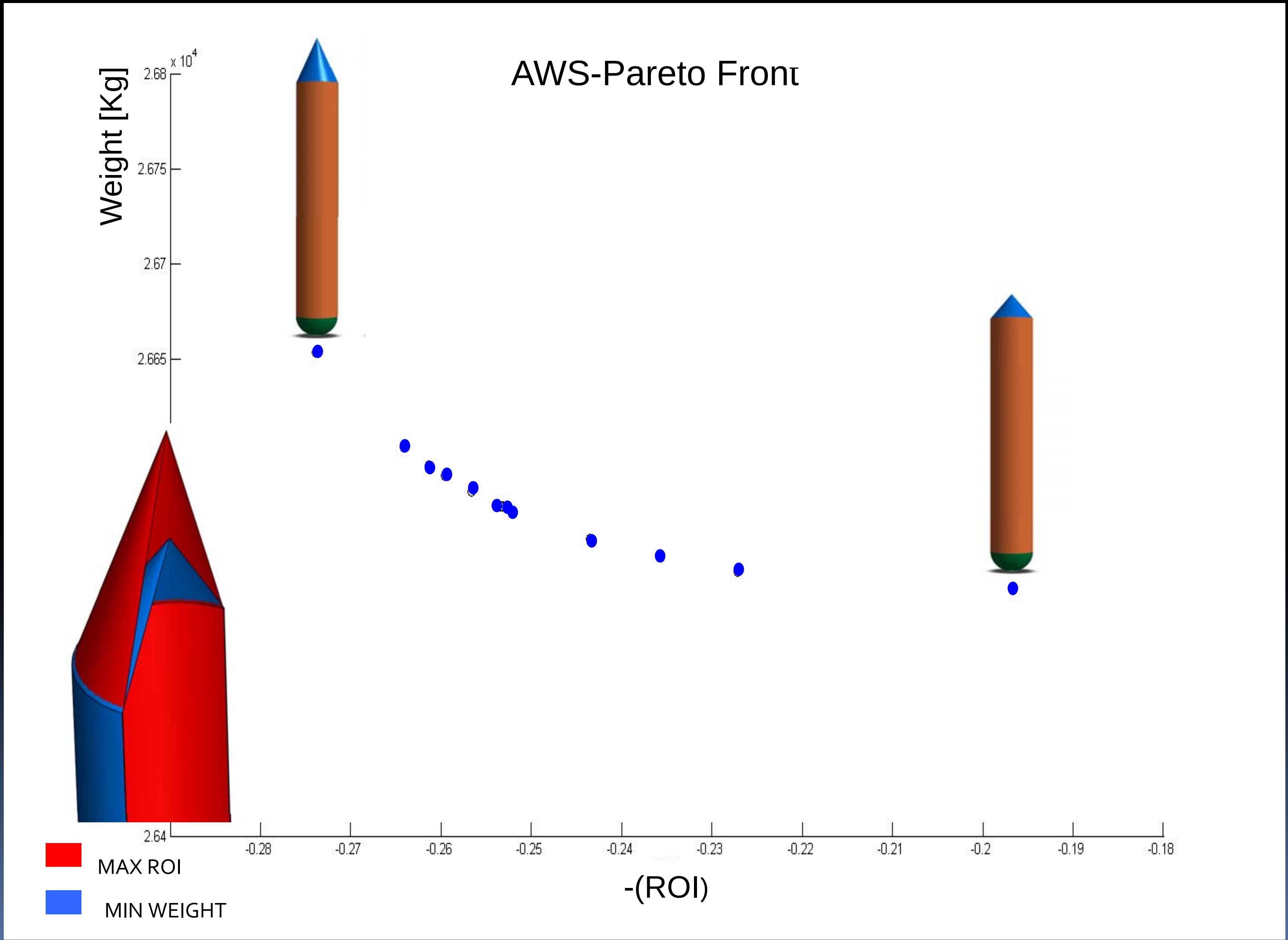
$$\frac{d(x)}{d(FL)} = \begin{bmatrix} \frac{dHR2}{dFL} \\ \frac{dL}{dFL} \\ \frac{dR}{dFL} \\ \frac{dTCO}{dFL} \\ \frac{dTCY}{dFL} \\ \frac{dTH}{dFL} \end{bmatrix} = \begin{bmatrix} -1.993 * 10^{-5} \\ \sim 0 \\ 3.164 * 10^{-6} \\ -5.155 * 10^{-6} \\ -2.206 * 10^{-8} \\ -9.482 * 10^{-8} \end{bmatrix}$$

Constraint	Form	Value at x*	Active?
Vibration constraint	1-VF/VFallowed ≤0	~ 0	Yes
Volume constraint	1-Vtank/Vnominal ≤0	~ 0	Yes
Eq. Cylinder stress constraint	Scyl/Sallowed-1≤0	~ 0	Yes
Eq. Hemisphere stress constraint	Shem/Sallowed-1≤0	~ 0	Yes
Eq. Cone stress constraint	Scon/Sallowed-1≤0	~ 0	Yes

Agenda

- ✓ Introduction
- ✓ Problem Statement
- ✓ Model Implementation and Validation
- ✓ Design of Experiment
- ✓ Single Objective Optimization
- ✓ Sensitivity Analysis
- Multi objective Optimization
- Conclusions

Multi Objective Optimization



Agenda

- ✓ Introduction
- ✓ Problem Statement
- ✓ Model Implementation and Validation
- ✓ Design of Experiment
- ✓ Single Objective Optimization
- ✓ Sensitivity Analysis
- ✓ Multi objective Optimization
- Conclusions

Conclusions

- Single Objective Optimization
- Multi Objective Optimization

http://www.nasa.gov/topics/shuttle_station/index.html