

LS-OPT[®] TRAINING CLASS

OPTIMIZATION AND ROBUST DESIGN

TUTORIAL PROBLEMS

LS-OPT Version 5.1

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INTRODUCTION

This tutorial problem set allows LS-OPT users to exercise aspects of mathematical optimization, design optimization and robust design. LS-OPTui is used to create or modify the input.

A first part of the problem set attempts to simulate the design process for examples that are typical for the LS-DYNA[®] user. Detours have been introduced to investigate features related to a particular design step in more detail. The examples are

- Crashworthiness optimization of a vehicle
- Mode tracking
- Multidisciplinary Design Optimization
- Material parameter identification

Another example has an explicit algebraic formulation. The purpose is to introduce the user to the mathematical aspects of approximations, accuracy and convergence. The example is

• Nonlinear explicit problem

The final part of the problem set teaches the user how to assess reliability of a design, investigate the sources of variability on the FE model and incorporate the effect of uncertainties during design. The categories are:

- Reliability
- Outlier Analysis
- Reliability-based design optimization
- Robust design

The run times for the examples vary between a few seconds (simple explicit problems) and ~ 10 min. (3GHz) (Iterative optimization using LS-DYNA for crash optimization). The longest DYNA simulation time is about 15s.

The GUI allows easy navigation amongst examples by simply using the *New* or *Open* options in the File menu (menu bar, top left). New(ctrl+N) lists existing projects while *Open* (ctrl+O) allows the definition of new projects.

1.1 Software tools

The following tools are used in this tutorial:

- LS-OPT together with LS-OPT*ui* and Viewer (<u>Requires Ver. 5.0 or</u> <u>later</u>)
- LS-DYNA (Requires Ver. 971 *Revision R4.2.1* or later). Both the Single and Double Precision versions are required.
- LS-PrePost (included in the LS-OPT distribution)

1.2 General procedure for problem solution

- 1. Run the command file. This can be done using
 - LS-OPTui or
 - batch mode.
- 2. Use the Viewer to interpret the results. Guidelines for result interpretation are given at the end of this chapter.

1.3 Using LS-OPTui for input

The graphical user interface LS-OPTui can be used to prepare a command file for LS-OPT. The interface allows definition of the pre-processing and simulation tools, formulation of the design problem, definition of the LS-DYNA response variables and monitoring and control of the analysis runs.

LS-OPTui allows the creation of a command file as well as to read an existing command file.

1.4 Standard files contained in all directories

Some standard files are commonly used for directory management:

• **clean** Script file executed by LS-OPT to automatically clear the **run** directories after each iteration and while LS-OPT is running. The user must use UNIX commands, e.g.:

rm -rf d3plot*

The baseline and optimum results are not cleared.

• **xxxx.lsopt** Command input file for LS-OPT. To be created or modified by the user. The tool LS-OPTui is used to create/edit the file.

<u>1.5 Output files</u>

lsopt_input	Echo of the input data. (View→Input)
lsopt_output	Log of all the internal steps taken to solve each
	example. The interim and final results are given
	in this file. (View→Output)
lsopt_report	A short summary of the results. Optimization
	problems only. (View→Summary Report)

<u>1.6 Execution of LS-OPT</u>

Graphical User Interface

Type: lsoptui xxx.lsopt

Batch mode

Type: lsopt xxx.lsopt

where **xxx**.lsopt is the name of the command file.

Remarks:

- A typical restart only requires the selection of Normal Run in the menu bar or the lsopt <command_file_name> to be typed. If many or radical changes have been made to the input file, when a run is repeated, inconsistencies may develop and incorrect results may be computed. In this case, restart the run by clearing the work directory using the Clean option under Tools.
- LS-OPTui features a **Repair** option under **Tools** that enables the user to make changes in the design data and rerun the individual steps. Several Repair options are also available by right-clicking on individual steps such as *Optimization* or *Sampling*..

1.7 Using LS-OPTui for post-processing

Type **viewer xxxx.lsopt** in the working directory or select the **Viewer** button from the GUI.

<u>1.8 Result interpretation</u>

1. Simulation Statistics

a. Correlation Matrix

Matrix of correlation values, scatter plots and histograms of all variables and simulation results.

b. Scatter Plots

2D or 3D scatter plots of simulation results.

c. Parallel Coordinate Plot

d. Histories

Show time history curves of simulations as well as filebased curves.

e. Statistical Tools

Interactive tools for histograms, mean, standard deviation and probability of exceeding constraints

f. Correlation Bars

Correlation bar charts

2. Metamodel Plots

a. Surface Plots

- i. Rotatable metamodel surfaces with isolines, constraint contours, feasible regions.
- ii. Points with point list, links to value spreadsheet and LS-PrePost.
- iii. Constraints and feasible regions.

b. 2D Interpolator

Matrix of 2D metamodel surface plots

c. Metamodeling Accuracy

- i. The comparison between the <u>predicted</u> and <u>computed</u> results.
- ii. Errors. Metamodeling error measures.

d. Sensitivity

The magnitude and sign of the individual variable sensitivities and the associated 95% confidence interval of their significance can be visualized. Global sensitivity analysis.

e. Virtual Histories

Predicted history anywhere in the design space

3. Optimization

a. Optimization History

- i. The optimization **history** of the variables and responses. Computed vs. predicted responses, composites, constraints and objectives.
- ii. The RMS/Max. error, R^2 history of the responses.
- iii. The upper and lower bound (move limit or sub-region bound) history of the variables.
- iv. Movement of the design variables relative to the bounds of the design space.
- b. Variables

Optimal variable values. Confidence intervals for parameter identification.

4. Pareto Optimal Solutions

a. Tradeoff

2D or 3D scatter plots to visualize the Pareto-optimal front for multi-objective problems. 4D visualization is enabled using colors.

b. Parallel Coordinates

Exploration and elimination of optimal designs from the Pareto set by interactively moving constraints

c. Hyper-Radial Visualization

The exploration of Pareto Optimal designs by interactively adjusting the importance of each objective.

d. Self-Organizing Maps

Postprocessing of simulations using LS-PREPOST: Click on or near points on graphs in LS-OPTui. The variable data will be presented in tabular form. LS-PrePost can be selected to post-process a selected design

1. **Viewing printed results:** Use **View** *Input*, *Output* or *Summary Report* (top left). The Summary Report is the most convenient way of viewing details of results in tabular form.

<u>1.9 Reference documents</u>

The principal reference documents are:

- 1. LS-OPT User's Manual, Version 5.0, *Livermore Software Technology Corporation, Livermore, CA, 2013.* (access by selecting "Help" in the GUI)
- 2. Class Presentation notes, Livermore Software Technology Corporation, Livermore, CA, 2013.

SIMPLE OPTIMIZATION AND VIEWING RESULTS

Problem description

The problem is of a simplified vehicle moving at a constant velocity and crashing into a pole. The figures show the deformed vehicle after 50ms and the part numbers.



Objectives of this example

The problem illustrates the following features:

- Formulating the optimization problem
- Viewer functionality. Interpretation of results.

Design criteria

The criteria of interest are the following:

- Head injury criterion (HIC) of a selected point (15ms)
- Component Mass of the structural components (bumper, front, hood and underside)
- Intrusion computed using the relative motion of two points

Units are in *mm* and *sec*.

Design variables



The design variables are the following gauges:

- Hood, front and underside (thood)
- Bumper (tbumper)

Note: Parts 3, 4 and 5 are grouped under a single design variable thood while part 2 is identified as tbumper.

Post-processing study using the Viewer

Directory name: **DESIGN_OPTIMIZATION/SIMPLE/VIEWER**

Starting file: simple.start.lsopt

The files in the directory have the following meanings:

main.k	Main	(root)	file	with	parameter
	specifi	cation			
car5.k	Include	e file spo	ecified	l in ma	in.k
rigid2	Include	e file spo	ecified	l in ca	r5.k
simple.correct.lsopt	Final d	lesign co	omma	nd file	(modified
	using t	the .start	file)		

Design formulation

The design formulation is as follows:

Minimize

	HIC (15ms) at node 432	
subject to	Intrusion (50ms) < 550mm	

The intrusion is measured as the distance between nodes 167 and 432.

Setup:

- 1. Open the file simple.start.lsopt using the LS-OPT GUI.
- 2. Select View file→Other File in the menu bar to view the following input files:
 - a. View the parameter (*PARAMETER) definition in the file *main.k.* Note the inclusion of the file *car5.k.*
 - b. View the parameter use (e.g. &thood) in the file *car5.k*.
- 3. Inspect the flowchart to study the flow of information, starting with setup and ending with the problem solution.

- 4. Inspect each of the components in the GUI flowchart to see the input specification fields. Confirm that you will be running a Single Iteration metamodel-based optimization with 20 design points.
- 5. Now, formulate the design problem using the **Optimization** component of the flowchart as follows:
 - a. Select HIC as the objective function to minimize by selecting "HIC" in the **Objectives** tab.
 - b. In the **Constraints** tab, select Intrusion as the constraint function and set the upper bound to 550mm.
- 6. This option (single iteration) runs one iteration.
- 7. Run the example by selecting **Run Normal**.

Exercises:

Open the Viewer and select the following plot options:

1. Scatter plot:

- 1.1 Find the baseline design (Design 1.1) and display the Finite Element mesh using LS-PrePost. Find nodes 432 and 167.
- 1.2 Verify that there are 5 infeasible designs (Iteration 1).
- 1.3 Select the infeasible points to display them in a table. Verify in the table that they all have constraint violations.
- 1.4 Select Intrusion as the fourth (or color) variable.
- 1.5 Select "No entity" on the *z*-axis in order to view the sampling scheme arrangement of the points (Space Filling).

2. Parallel Coordinate Plot:

- 2.1 Display the Variables, Constraints and Objectives.
- 2.2 Find a feasible point with the lowest HIC value. Verify that tbumper = 2.3, thood = 2.0, Intrusion = 542, HIC = 196 (approximately).
- 2.3 Find a feasible point with the lowest Intrusion value. Verify that tbumper = 5, thood = 5, Intrusion = 455 and HIC = 352 (approx.).
- 2.4 Slide the upper bound of the Intrusion to 520mm and find the feasible point with the lowest HIC value. Verify that tbumper = 5, thood = 3.2, Intrusion = 505 and HIC = 290.

3. Histories

3.1 Display all the Acceleration histories and determine which ones represent feasible designs.

3.2 Display the Acceleration histories for designs 11, 16 and 20 (Select under the Options tab of the History plot display).

4. Metamodel Surface

- 4.1 Display the metamodel surface for the HIC function. Include all the simulation points.
- 4.2 Select *Isolines*, *Constraints* and *Predicted Value* for the Optimum. Switch off the *Gridline* display. Use the Ctrl+Left Button to rotate the 3D display.
- 4.3 Project all the points to the surface and select the *XY* view button to display a top view of the plot.

5. 2D Interpolator

- 5.1 Select both variables as well as HIC, Mass and Intrusion.
- 5.2 Select: Constraints, Predicted value, Transpose and Link ranges col/row.
- 5.3 Check whether the design (tbumper = 4, thood = 1) is predicted to be feasible. Verify that the predicted Intrusion value is approximately 575.

6. Metamodel Accuracy

- 6.1 Study and compare the PRESS values for HIC, Mass, Disp2 and Disp1.
- 6.2 Display the PRESS Statistics. Explain the difference between the PRESS Statistics display and the ordinary predicted response value display on the Accuracy plot.

7. Sensitivities

- 7.1 Using Linear ANOVA, which variable is the most important for influencing the HIC value?
- 7.2 Is it possible to state with confidence that thood is more important for Disp1 than tbumper?
- 7.3 In the GSA/Sobol plot, display the sensitivities for all the responses. Which variable seems to be the most important over all.
- 7.4 Display the Transpose and observe which response is the most sensitive to thood.

8. Predicted histories

- 8.1 Select the acceleration history and view its thood-sensitivity.
- 8.2 Plot the predicted acceleration at thood = 2.1, the the the the the second seco
- 8.3 In the Options tab, plot the design nearest to the predicted Acceleration history. Which design point does it represent.
- 8.4 Plot the maximum residual for the predicted Acceleration history.
- 8.5 Plot the maximum residual for the predicted Disp1 history.

9. **Optimization History**

- 9.1 View the HIC and Intrusion optimization histories on the same plot by selecting the "Split Vertical" icon on the menu bar.
- 9.2 Display the table with both the baseline and optimum values by clicking near Iteration 0 and then using the Shift key to also select Iteration 1.

10. Integrated plotting

10.1 Plot both the Parallel Coordinate Plot and the Scatter Plot in the same window by using the vertical split function. Select an infeasible point on the scatter plot. Then select + (for adding points) on the popup table and add all the other infeasible points by clicking the red points on the scatter plot.

11. File viewing

11.1 Return to the GUI and view the Summary Report using the "View" selection on the menu bar.

SETTING UP AN OPTIMIZATION RUN FROM SCRATCH

Directory name: **DESIGN_OPTIMIZATION/SIMPLE/SINGLESTAGE**

The files in the directory have the following meanings:

singlestage.corre	ect.lsopt Design command file (to be
	used for checking if needed).
main.k	Main (root) file with parameter specification
car5.k	Include file specified in main.k
rigid2	Include file specified in car5.k

Design formulation

The design formulation is as follows:

Minimize

	HIC (15ms) at node 432
subject to	
	Intrusion (50ms) < 550mm

The intrusion is measured as the distance between nodes 167 and 432.

Basic setup for a single iteration

1. Confirm that **main.k** has the following keyword information:

```
*PARAMETER
rtbumper,3.0,rthood,1.0
```

2. Confirm that, in **car5.k**, the element thicknesses are labeled, e.g. the **thood** parameter is labeled as follows:

```
*SECTION_SHELL
2,2,0.0,0.,0.
0.,0.,0.
&thood,&thood,&thood
```

thumper is defined in a similar fashion.

The values of the variables in the ***PARAMETER** statement will be substituted during the optimization process.

- 3. Open LS-OPT by clicking the lsoptui executable. Set the working directory as DESIGN_OPTIMIZATION/SIMPLE/SINGLESTAGE.
- 4. Enter a file name, e.g. singlestage.setup and press the "Create" button. A file named singlestage.setup.lsopt will be created in the working directory and the LS-OPT GUI will open with a problem definition template.
- 5. Using the LS-OPT GUI, define the required optimization problem by visiting the various flowchart components; the changes will be reflected in the .lsopt file when you save.

Step	Remark
Task and strategy selection $(\bullet \bullet \bullet)$:	
Choose the task as Metamodel-based	
Optimization with single iteration	
strategy.	
Stage(s):	The input file variables will be
1. Specify the dyna executable	automatically detected and added
1s971_single and the input file	as constants under Setup.
main.k	
2. Define the responses associated	
with the LS-DYNA stage. These are	
the x-displacement of node 432	
(Disp2) and node 167 (Disp1),	
the HIC response evaluated at node	
432, and the combined Mass of parts	
2, 3, 4 and 5.	
Variable Setup: Switch the constants to	
continuous variables under Setup.	
Define the size of the design space as	
[1,5] for each of the thickness variables.	
Sampling: The metamodel is set to	These selections are defaulted. The
RBF network and the point selection	samples are selected in a space
scheme is set to Space Filling. The	with dimensions equal to the

number of points is 10.	number of <i>Active Variables</i> under Sampling .
Composites: The Intrusion	A standard or expression composite
constraint consists of the difference	is used to define the intrusion.
between two of the responses (Disp2	
and Disp1). Add a composite from the	
"Add" menu to define it.	
Optimization setup:	The "Strict" option can be ignored
1. Select the objective function.	for the constraint. This is only used
2. Select the constraint and set the	in special applications.
bounds	
Uncheck "Do verification run" from the	
task menu (or delete the "Verification"	
component of the flowchart)	
Save the file by any name in the	
directory	
DESIGN_OPTIMIZATION/SIMPLE/	
SINGLESTAGE.	
Run the project (Normal Run)	

Exercises:

- 1. <u>The accuracy of the responses.</u> Study the approximation error indicators and the plots of the computed vs. the predicted results (Accuracy plots).
 - 1.1 Fill in the approximation errors of the results. These quantities can be found in the **Accuracy** plot.

	Starting Value	Sqrt PRESS %	R^{2}
Mass	0.41	0	1
Displ	-161	2.1	.4
Disp2	-737	.7	.99
HIC	68	40	.6

- 1.2 Using the two quantities RMS error and R^2 , what conclusions, if any, can you make for each approximation about the level of 'noise' or modeling error?
- 2. Study the Sensitivity charts (linear ANOVA).
 - 2.1 Which variable appears to be the most important?
 - 2.2 How are the values (of the main bar) in the plot derived?
- 3. Study the Point selection scheme.
 - 3.1 Use the **Scatter Plot** option and switch to 2D.
 - 3.2 Select the point status as *Feasibility*.
 - 3.3 How many infeasible designs are there in the design set?
- 4. Verification run: Set "Do verification run" (*task menu*) or add a verification run using '+'. Select **Run** (Normal Run). A single run will be done as part of the 2^{nd} iteration (directory 2.1) to verify the predicted optimum.
 - Obtain the starting and final results of the optimization run from the Optimization History plot by clicking near Iteration 0 and Iteration 1 respectively.
 - A spread sheet format of the computed results of both the starting and optimum points can be obtained by selecting both (use Ctrl or Shift while clicking in the Point List at the extreme left column)

Study

- 4.1 The change in each of the variables and responses
- 4.2 The accuracy of the starting point and the optimum point after the first iteration. These results are tabulated below.

	Start		Optimum	
	Comp.	Approx.	Comp.	Approx.
tbumper	3		3.3	
thood	1		1.7	
Mass	0.41	0.41	0.58	0.58
Intrusion	576	572	550	550

HIC	68	35	156	154
Max. Constr. violation	26	22	0	0

5. Design Sensitivities:

5.1 Study the final design sensitivities in View file→Summary **Report.** Confirm the estimated change in each of the following quantities for a 0.1 mm change in the Hood thickness and Bumper thickness respectively.

	Hood	Bumper
Mass	0.02	0.006
Intrusion	-3	3
HIC	+16	+1.8

Add a constraint and repair the optimization run

Directory: **DESIGN_OPTIMIZATION/SIMPLE/SINGLESTAGE** (same as previous)

Starting file: Use the file created in the previous section.

The purpose of the example is to add a constraint to the design without rerunning the simulations. You should have a database of 10 runs generated previously. The run will be done in the same project directory.

Setup:

- 1. Add a Mass upper bound constraint of 0.5
 - 1.1 Repair the optimum using the Optimize repair option (right-click the Optimization box). Make sure that the first iteration is repaired and not the verification iteration 2.
 - 1.2 View the feasible region by using the *Constraints* option in the Metamodel surface plot. What do you observe in terms of the influence of the mass constraint?
 - 1.3 Clean from iteration $\underline{2}$ (under Tools) and run a metamodel-based optimization to produce a *new* verification run. Tabulate the results:

	Start		Optimum	
	Comp.	Approx.	Comp.	Approx.
tbumper	3		1.81	
thood	1		1.94	
Mass	0.41	0.41	0.55	0.55
Intrusion	576	572	543	550
HIC	68	35	242	208
Max. Constr. violation	26	22	0.05	0.05

FINDING A CONVERGED SOLUTION

Directory: **DESIGN_OPTIMIZATION/SIMPLE/ITERATE**

Starting file: iterate.start.lsopt

Design Formulation

Minimize

HIC (15ms) at node **432**

subject to

Mass < 0.5 Intrusion (50ms) < 550mm

The intrusion is measured as the distance between nodes 167 and 432.

Setting up the problem

- 1. In the **Task selection** menu, select the SRSM strategy.
- 2. Use the **Sampling** and/or **Metamodel Building** page to confirm that the linear polynomial metamodel and *D*-Optimality sampling criterion have been selected. *Select 5 points per iteration*.
- 3. Select the Hybrid ASA (ASA with switch to LFOP) as core **optimizer algorithm**. This is also the default solver.
- 4. For **Termination criteria**, select a tolerance of 0.001 to be satisfied by the design and objective changes.
- 5. Select 10 iterations and run the problem.

Exercise

- 1. **Convergence.** Study the **Optimization History** of the variables and responses.
 - 1.1 What happens to the move limits (= region of interest) (blue lines) of **thood** and **thumper**?
 - 1.2 What are the trends in **thood** and **thumper**?
 - 1.3 Comment on the convergence behavior of the HIC response. Does it seem converged?
 - 1.4 Is this also true for the Intrusion and Mass?
 - 1.5 What is the mass trend during optimization?

1.6 Compare the optimal result to the result obtained using 10 points for a Single Iteration run.

	Single Iteration (10 simulations)		SRSM (51 simulations)	
	Comp.	Approx.	Comp.	Approx.
tbumper	1.81		1.58	
thood	1.94		1.77	
Mass	0.55	0.55	0.5	0.5
Intrusion	543	550	550	550
HIC	242	208	239	241
Max. Constr. violation	0.05	0.05	0	0

2. Accuracy.

- 2.1 Study the **Optimization History**. Comment on the accuracy of the HIC response (on the **Value** plot of HIC).
- 2.2 What is the RMS error trend of HIC?
- 2.3 What is the R^2 trend of HIC?
- 2.4 In the Optimization History, observe the accuracy of the **Disp2** response.
- 3. Would it be possible to repair an optimization result by adding or modifying a constraint in this iterative run (i.e. without rerunning any simulations)? Why/why not?
- 4. Comment on the differences between Single Iteration and iterative solutions as far as utility and accuracy is concerned.

DISCRETE OPTIMIZATION

Single iteration

Directory: DESIGN_OPTIMIZATION/SIMPLE/DISCRETE

Starting file: discrete.start.lsopt

Design Formulation

Minimize

HIC (15ms) at node **432**

subject to

```
Intrusion (50ms) < 550mm
```

The intrusion is measured as the distance between nodes 167 and 432.

Setup:

- Modify the thood variable so that it has to be selected from the set {1, 2, 3, 4, 5}. This is done by changing the variable type from "Continuous" to "Discrete variable" and "Adding new values" 1,2,3,4,5 to define the set of possible values. Use 1 as a starting variable value.
- 2. Set the *Sampling Type* for the variable thood to **Discrete**.
- 3. Confirm that the only constraint is Intrusion < 550.
- 4. On the **Sampling** page, select 20 points.
- 5. Set the optimizer to Hybrid ASA (the default).
- 6. Conduct a Single Iteration run.

Exercise:

1. Compare the predicted results of the continuous (first example) and discrete analyses.

	Continuous	Discrete
tbumper	3.5	3.2
thood	1.57	2
HIC	133	196
Mass	0.57	0.65
Intrusion	550	538

- 2. Study a thumper-thood plot of the surface and points to get an impression of the *discrete space filling* point selection scheme.
- 3. In the metamodel surface plot, select HIC with the Constraints option to view the optimal design in the feasible region.

USER-DEFINED OPTIMIZATION PROBLEM

Directory: **DESIGN_OPTIMIZATION/USER_DEFINED**

Special topics: LS-OPT parameter type, Neural nets, Pareto optimality, dependent variables

Problem description:

The problem is of a simple two-bar truss. A linear analysis is conducted using the user written program below. The height of the structure = 1. The force components are: Fx = +24.8kN, Fy=198.4kN.

The criteria are weight and stress. The stresses are limited to an absolute value of 1.0. Three design variables are chosen, namely the cross-sectional area of the bars and the base measurement between the supports. The baseline design has the following values:

	Baseline	Lower Bound	Upper Bound
Base	0.8	0.1	1.6
AreaL	2	0.2	4
AreaR	2	0.2	4



```
#!/usr/bin/perl
#
# 2BAR truss
#
# Open output files
#
      Each response is placed in its own file
#
  open(WEIGHT,">Weight");
   open(STRESSL,">StressL");
   open(STRESSR,">StressR");
#
#--Compute the responses
#
  $length = sqrt(1 + <<Base>>*<<Base>>);
   $cos = <<Base>>/$length;
   $sin = 1/$length;
   $Weight = (<<AreaL>> + <<AreaR>>) * sqrt(1 + <<Base>>*<<Base>>) / 2;
   $StressL = ( 24.8/$cos + 198.4/$sin)/<<AreaL>>/200;
   $StressR = (-24.8/$cos + 198.4/$sin)/<<AreaR>>/200;
#
  print WEIGHT $Weight,"\n";
  print STRESSL $StressL,"\n";
  print STRESSR $StressR,"\n";
#
#
  Signal normal termination
#
  print "N o r m a l\n";
#
```

Note the labeling of the variables using the double angular brackets **<<name>>.** These will be replaced by numbers.

The purpose of the example is to illustrate the following:

- How to define a user-defined problem
- The definition of dependent variables in the user interface.
- The application of neural nets.

Sequential optimization with domain reduction

Directory: **DESIGN_OPTIMIZATION/USER_DEFINED/LINEAR**

Setup:

Create a command file as follows:

- 1. Open the LS-OPT GUI, set the working directory, select names for the file, sampling and stage, and click Create.
- 2. *Stage Setup:* Select the **User-defined** solver option under stage setup. Enter the command as **per1**. Browse for the input file name: **2bar**.
- 3. *Setup:* Enter the variable data. Select the lower and upper bounds (Base:[0.1,1.6]; AreaL:[0.2 4]; AreaR:[0.2,4]).
- 4. Stage Responses: Enter the responses as USER-DEFINED. The solver dumps the results into individual files: Weight, StressL, StressR, therefore the response command must write the value in the file to standard output, e.g. cat Weight (Linux) or type Weight (Windows).
- 5. *Optimization*: Minimize the Weight. Bound the stresses from above and below as [-1;1] in both bars.

Exercises:

- 1. *Strategy:* Set the **Strategy** (under Task selection) to *SRSM* and do a baseline run only.
- 2. *Run:* Report the stresses associated with the baseline design by using the Scatter Plot or Parallel Coordinate plot.

StressL	0.73
StressR	0.54
Weight	2.6

3. Run 10 iterations using a linear approximation and the *D*-Optimality criterion for point selection and tabulate the optimal variables and responses:

	Predicted	Computed
Base	0.18	-
AreaL	1.7	-
AreaR	0.29	-
StressL	1	0.99
StressR	1	1.02
Weight	1.02	1.02

Reducing the number of variables by constraining the bar areas

Starting file: userdef.constrained.start.lsopt

Directory:

```
DESIGN_OPTIMIZATION/USER_DEFINED/
CONSTRAINED_VARS_LINEAR
```

Setup:

- 1. Choose the SRSM strategy.
- 2. Remove the range values so that the problem starts running from the full design space.
- 3. Change AreaR to a Dependent Variable with definition AreaR = AreaL/2.0. (Just type in AreaL/2.0 in the box opposite Dependent).
- 4. Save the modified data under any name.
- 5. Run 5 iterations.

Exercises:

1. Tabulate the optimal variables.

	Computed	Predicted
AreaL	1.4	
AreaR	0.7	
Base	0.42	
StressL	0.97	1.0
StressR	1.0	0.95
Weight	1.17	1.19

2. Do you think the solution has converged?

IMPORTING ANALYSIS RESULTS

The purpose of this example is to import a user-defined table of results into the GUI and to enable an optimization to be conducted using these results. A description of the steps can also be found in the User's Manual Section 8.5.3.

Directory: DESIGN_OPTIMIZATION/IMPORT_RESULTS

Starting file: A text file with comma separated variables **AnalysisResults.csv**. There is no input command file.

Setting up the problem

The steps for importing user-defined analysis result files using the GUI are as follows:

1. Add a second header line to the given "AnalysisResults.csv" file using "dv" for design variables *thumper* and *thood* and "rs" for responses *Disp2*, *Disp1*, *Acc_max*, *Mass* and *HIC*. This header line is just below the *name* header.

Start lsoptui:

- 2. Specify a project directory, file, sampling and stage name and click Create.
- 3. *Task selection menu:* Choose Metamodel-based Optimization task Single Iteration strategy.
- 4. *Sampling:* Browse for the "AnalysisResults.csv" file using the "Import user results" option under Sampling Features. Select the metamodel as RBF network.
- 5. *Variables and Responses setup*. Check the variables (under setup) and responses (under stage(s)).
- 6. Adjust the variable bounds to [1,5].

- 7. *Menu bar*. Click Tools→Repair→Import Results. You can also rightclick on Sampling and then Repair→Import Results.
- 8. View the Summary Report.
- 9. Optimization:
 - a. Define HIC as the objective.
 - b. Use a Composite-Expression to define the constraint:

Intrusion = Disp1 - Disp2 < 550mm.

10. In the Task selection menu, uncheck "Do verification run" (or simply delete the Verification box). Run the project (Normal Run). An optimization history is created.

Exercise

- 1. Display the simulation design points on the Parallel Coordinate plot:
 - a. What is the HIC value of the design with the smallest intrusion? (340)
 - b. What are the HIC and Intrusion values for the design with the lowest Max. Acceleration? (412,484)
- 2. Using the Parallel Coordinate Plot, compare the best simulated design (i.e. from the imported table) with the predicted optimum.

	Simulation	Predicted
		Optimum
tbumper	3.7	3.9
thood	1.7	1.6
HIC	168	166
Mass	0.61	.60
Intrusion	548	550

DIRECT OPTIMIZATION

Directory: **DESIGN_OPTIMIZATION/DIRECT/SIMPLE**

Starting file: direct.start.lsopt

The example is the same as the small car pole crash.

Design Formulation

Minimize

HIC (15ms) at node **432**

subject to

Mass < 0.5 Intrusion (50ms) < 550mm

The intrusion is measured as the distance between nodes 167 and 432.

Setting up the problem

- 1. Open **direct.start.lsopt** in the GUI and change the task to Direct Simulation→Optimization.
- 2. Verify that the Objectives and Constraints are set correctly.
- 3. In the **Optimization**→**Algorithms** page, set the population size of the Genetic Algorithm (GA) to 20 and the number of generations to 20. The changes will be reflected in Sampling and Termination Criteria.
- 4. Save the input to a new file name.
- 5. Run the direct optimization.

Exercise

1. Compare the results of metamodel-based (iterative) and direct methods.

	SRSM (51 simulations)		<i>Direct</i> (400 simulations)	
	Comp. Approx.		Comp.	Approx.
Tbumper	1.58		1.13	
Thood	1.77		1.75	
Mass	0.5	0.5	0.47	
Intrusion	550	550	550	
HIC	239	241	174	
Max. Constr. violation	0	0	0	

MATERIAL PARAMETER IDENTIFICATION

Directory: **PARAMETER_IDENTIFICATION**

Special topics: Point-based and history-based parameter identification



Problem description

The material parameters of a foam material must be determined from experimental results, namely the resultant reaction force exerted by a cubic sample on a rigid base. The problem is addressed by minimizing the residual resultant reaction force (**rcforc** binary database) with the material parameters Young's modulus E (**YMod**) and Yield stress Y (**Yield**) as unknown variables. The Mean Squared Error is computed using the formula below:

$$\varepsilon = \frac{1}{P} \sum_{p=1}^{P} W_p \left(\frac{f_p(\boldsymbol{x}) - G_p}{s_p} \right)^2 = \frac{1}{P} \sum_{p=1}^{P} W_p \left(\frac{e_p(\boldsymbol{x})}{s_p} \right)^2$$

The "experimental" resultant forces are shown below. The results were generated from an LS-DYNA run with the parameters ($E=10^6$, $Y=10^3$). Samples are taken at times 2, 4, 6 and 8 ms:


New Points illustrated by this example:

- How to define a history.
- How to do parameter identification.
 - using a history-based Mean Squared Error composite function.
 - using a point-based Mean Squared Error composite function.
- How to construct crossplots.
- Using multiple simulation models in the same optimization problem (multi-case).

Ordinate-based MSE

Directory: **PARAMETER_IDENTIFICATION/MSE_HISTORY/SINGLECASE**

Problem description:

The following files are provided:

- Test1.txt
- foam1.k

Measured data of Exp. 1 Model representing Exp. 1

The experimental results are:

Displacement	Force Resultant
0.36168	10162
0.72562	12964
1.0903	14840
1.4538	17672

Note that the abscissa is not time but displacement.

Setup:

- 1. The example must be set up from scratch.
- 2. Select the SRSM strategy.
- 3. Specify **foam1.k** as the input file.
- 4. Specify the parameter bounds as [5e5,2e6] for the Young's modulus and [5e2,2e3] for the yield stress.
- 5. Go to the "Histories" panel under Stage:
 - a. Create **Disp1** as the *z*-displacement at node 296 (nodout).
 - b. Create **Force1** as the *z*-slave reaction force at interface 1 (rcforc).
 - c. Create a Crossplot **F_vs_d** using **-Disp1** and **Force1**. Note Disp1 is *negative*.
- 6. Add an ordinate-based Curve Matching composite called **MSE**. Select the algorithm as Mean Square Error.

- Using "add new file history", assign Test1 as the target curve. Assign F_vs_d as the computed curve.
- 8. Select **MSE** as the objective.
- 9. Run the example with an iteration limit of 3.

Exercises:

- 1. View **Optimization**→**History** and the **MSE** composite (multiobjective).
- 2. View the optimal curve matching by selecting **Histories** under **Simulations** and then selecting **F_vs_d** and **Test1**.
- 3. Also view all the histories by selecting **All** in the iteration control window. Use *Iteration* color coding.
- 4. View the "Mean Squared Error Residuals" table at the end of View→Summary Report. Also view **Optimization→Variables** for the 95% Confidence interval.
- 5. Confirm the confidence intervals for the two parameters from the lower-most table. Comment on the significance of the confidence intervals.
- 6. In **Metamodel**→**Histories** study the sensitivity of F_vs_d to the Young modulus and Yield stress variables.

Doromator nomo	Value	95% Confidence Interval		
	v aluc	Lower	Upper	
YMod	7e5	-13e6	14e6	
Yield	1010	830	1200	

Ordinate-based MSE: multiple cases

Directory:

PARAMETER_IDENTIFICATION/MSE_HISTORY/MULTICASE

Starting file: msehistory.multi.start.lsopt

Setup:

The previous example shows that the Young's modulus cannot be confidently identified by test points in the plastic range. Therefore a second test file (Test2) has been added which consists of test points in the linear range of force vs. deformation. Modify the starting file as follows:

- 1. Add a stage Stage2 with input file foam2.k under the same sampling. This can be done by cloning the existing stage and modifying the new stage.
- 2. Stage2 Histories tab:
 - a. Change the name to Disp2, the *z*-displacement at node 288
 - b. Change the name to Force2, the *z*-reaction slave force at interface 1
 - c. Add the crossplot of these values as F2_vs_d2 (-Disp2 vs. Force2)
 - d. Add Test2 as an imported file history from Test2.txt

Because both stages have similar histories, one can clone Stage1 while creating Stage2 to reduce the effort.

- 3. Add a mean square error curve matching composite MSE2 using Test2 and F2_vs_d2
- 4. Add MSE2 as an objective
- 5. Run the example with an iteration limit of 4.

Exercises:

- 1. Study the Optimization History.
- 2. View F1_vs_d1 vs. Test1 using the Simulations→Histories selection.
- 3. View F2_vs_d2 vs. Test2. These can be viewed together with the histories of Stage 1 using the "Multi" option.

4. Note down the optimal values and confidence intervals for the two parameters (**View**→**Summary Report**, scroll to the bottom):

Doromotor nomo	Valua	95% Confidence Interval		
Parameter name	value	Lower	Upper	
YMod	1.04e6	7.68e5	1.32e6	
Yield	1008	929	1088	

5. Compare the confidence intervals to those of the single case.

Point-based Mean Squared Error (optional)

Directory:

PARAMETER_IDENTIFICATION/MSE_POINT/SINGLECASE

Setup:

1. Parameterize the material data in the LS-DYNA keyword file as:

1,.001,&YMod,.3,&Yield,10.,0.

- 2. Open LS-OPT GUI with any name for the file, sampling and stage.
- 3. *Task selection menu*: Select Metamodel-based Optimization with the SRSM strategy.
- 4. *Sampling or Metamodel Building*: Use the default settings linear polynomial approximations.
- 5. *Stage setup*: Use the single precision LS-DYNA solver ls971_single with foam1.k as the input file.
- 6. *Setup*: Use the starting values of (E=700,000; Y=1,500). Use [5e5; 2e6] and [5e2; 2e3] as bounds on the variables.
- 7. Stage histories and responses: Extract the Z-slave force history Force from RCFORC. The interface ID = 1. Use response-function expressions to compute the forces, e.g. Force(0.002).
- 8. *Composite*: Add an MSE composite called **MSE** from the table above. (The composite to be selected is the "standard" type in which Target values can be defined, not a Composite-Expression).
- 9. Optimization: Select MSE as the objective function to minimize.
- 10. Set the number of iterations to 5 and **Run**.

Exercise:

- 1. Accuracy:
 - 1.1 Study the accuracy of the response forces at the various times. Use the **Accuracy** option as well as the **Optimization History** option in which the error history can be viewed.

2. Convergence:

2.1 Confirm the optimal parameters and MSE value:

	Value
YMod	1.15e6

Yield	992
MSE	2.6e5

- 2.2 Study the MSE history.
- 2.3 Comment on the nature of the optimization history of the Yield stress vs. that of the Young's Modulus. Try to find a reason for the differences in the convergence behavior of the two variables by studying the Global Sensitivity bar chart for MSE.

3. Confidence Intervals:

3.1 Study the table of 95% Confidence Intervals of **YMod** and **Yield** using the View \rightarrow Summary Report option (scroll to the bottom). The confidence intervals can also be viewed using the "Variables" selection under "Optimization" (main plot selector). Click on a selected bar in the bar chart.

	Value	Lower bound	Upper bound
YMod	1.15e6	-7.1e6	9.4e6
Yield	992	816	1169

3.2 Comment on the confidence levels of the individual parameters.

Parameter identification with hysteretic response: multiple cases

Directory:

PARAMETER_IDENTIFICATION/CURVE_MAPPING

The Bauschinger effect is significant for automotive sheet steels. The phenomenon is observed under cyclic loading which results in a hysteretic stress-strain curve. The nature of the hysteretic curve complicates the curve matching required to identify the material parameters and therefore an approach which is more sophisticated than the ordinate-based matching is required. For this purpose, a Curve Mapping algorithm is used.

The following example consists of three load cases, each representing a different cyclic loading range as illustrated in the stress-strain diagram in the figure below. The material is defined by 9 parameters.



Starting file: mat125.calibration.start.lsopt

Setup:

Modify the starting file as follows:

- 1. Histories tab of each stage: Study the definitions of the stress and strain histories.
- 2. Composites: Change each of the Composite Functions Residual2, Residual6 and Residual10 to *Curve Mapping* types instead of *Mean Square Error* types.
- 3. Sampling: Confirm that all the stages *share the same sampling or have identical samplings*.
- 4. Optimization: Construct an objective by adding the residual components together with equal weights.
- 5. Select deletion of d3* files in all run directories (Stage \rightarrow File Operations \rightarrow Add \rightarrow Delete). The d3plot and other database files will be deleted as a consequence.
- 6. Run the example with an iteration limit of 3.

Exercises:

- 1. Study the Optimization History of the total residual. Also look at the individual residual components.
- 2. In the **Simulations** \rightarrow **Histories** plot selection, select the *Multi* option to view all the stress-strain crossplots as well as test results simultaneously. Select the *Neutral* color option (4th column in the control panel, very last option) in order to distinguish between the load cases.
- 3. Under the **Options** tab in the control panel, select *Only Optimal* and compare the results of Iteration 1 and Iteration 4. *Hint: Select* All *at the top and use* Iteration *as color option*.
- 4. Select *Compute Global Sensitivities* in the Sampling panel of the GUI and run the example again. *Note:* To prevent rerunning of the simulations, do not run a clean start!
- 5. Select the **Sensitivity** option in the Viewer (under **Metamodel**). Choose the *Multi* option to display all the residuals. Which parameter appears to dominate the matching ability?

MODAL ANALYSIS AND TRACKING

Directory: **DESIGN_OPTIMIZATION/MODAL_ANALYSIS**

Special topics: Mode tracking

Problem description

This example illustrates the following new features:

- Running an LS-DYNA implicit (double precision) solver.
- Mode tracking done for an optimization problem with frequency criteria

The figure shows a modification of the geometry of the crashworthiness optimization problem. Rails have been added, and the combined bumperhood section is separated into a grill, hood and bumper. The mass of the affected components in the initial design is 1.149 units while the torsional mode frequency is 1.775Hz. This corresponds to mode number 10.



The optimization problem is defined as follows:

	Minimize Mass (x) of the parts 2, 3, 4, 5, 6 & 7.
subject to	1.7 Hz < Torsional mode frequency(x) < 1.9 Hz
	Bounds on design variables: $x \in [1,6]$

Other data:

- Input file: car6_NVH.k
- Solver: ls971_double

Identifying the mode

Directory: **DESIGN_OPTIMIZATION/MODAL_ANALYSIS/DOE**

Setup:

Identifying the Torsional mode:

- 1. In the stage setup, use the double precision version of LS-DYNA (ls971_double). Add the mass response.
- 2. Set the bounds of the design variables in **Setup**.
- 3. Select 1 as the "Baseline Mode Number" for the frequency extraction under the **Responses** tab of the stage definition. We have yet to identify the Torsional mode number, so "1" is as good a number as any.
- 4. Set up the design optimization problem as defined above.
- 5. Using the DOE Study task, run the baseline case. Save the file under any name.
- 6. Manually inspect the mode shapes. The mode can be visualized by clicking on the single point in the scatter plot (Viewer) and selecting LS-PrePost to visualize the FE model and animation. For the baseline run, identify a *pronounced* twisting mode with the lowest mode number.

DOE task:

- 1. Enter the previously identified mode number as the "Baseline Mode Number" for the frequency response.
- 2. Add the **New Mode Number** and **MAC** as two additional responses in addition to Mass and Frequency. Visualization of the mode tracking is aided by selecting these responses.
- 3. Use a linear approximation with default settings. Save the work under any name.
- 4. Clean the existing results using the **Tools** menu. *This is important since responses have been added which changes the design problem.*
- 5. **Run** the project.

Exercise:

1. Which mode numbers are found when the twisting mode is tracked for the 10 different designs. (7, 10 and 11)

- 2. What is the lowest value of MAC found for the 10 different designs and for which mode (0.73; 11).
- 3. What is the highest value of MAC found for the 10 different designs and for which mode (1; 10).

Optimization

Directory: DESIGN_OPTIMIZATION/MODAL_ANALYSIS/ITERATE

Starting file: frequency.iterate.start.lsopt

Setup:

- 1. Set the strategy to SRSM and check the Sampling for the default settings of the metamodel (lin. polynomial) and point selection (D-optimal).
- 2. Set the limit on the number of iterations to 5 (or more if time is available)
- 3. Run the optimization.

Exercise:

- 1. Study the optimization history of the objective and constraints.
- 2. Study the optimization history of the mode number. The variation of the mode number due to tracking can also be viewed in the Scatter plot.
- 3. Record the optimal values of the mass and frequency.
- 4. What is the new mode number?
- 5. What is the MAC value?

	Value
tbumper	3.9
troof	1
trailb	1.2
trailf	1
tgrill	1
Mass	0.74
Frequency	1.7
Mode	11
MAC	0.99

MULTIDISCIPLINARY OPTIMIZATION

Directory: **DESIGN_OPTIMIZATION/MDO**

Problem description

This example has the following new features:

- LS-DYNA is used for both explicit crash and implicit NVH simulations.
- Multidisciplinary design optimization (MDO) is illustrated with a simple example.
- Scaling of the constraints is performed to ensure that the optimizer treats their violations equally.



The figure shows a modification of the geometry of the crash example attempted previously. Rails are added, and the combined bumper-hood section is separated into a grill, hood and bumper. The mass of the affected components in the initial design is 1.328 units while the torsional mode frequency is 1.775Hz. This corresponds to mode number 10. The Head Injury Criterion (HIC) based on a 15ms interval is initially 17350. The initial intrusion of the bumper is 536mm.

The optimization problem is defined as follows:

Minimize Mass (\boldsymbol{x}_{crash}) subject toHIC $(\boldsymbol{x}_{crash}) < 900$ Intrusion $(\boldsymbol{x}_{crash}) < 500$ mmTorsional mode frequency $(\boldsymbol{x}_{NVH}) = 1.8$ Hz

Nodes 184 and 432 are used for the intrusion calculation and node 432 for HIC. Both a crash analysis and modal analysis need to be conducted. Scale all 3 constraints by the respective bound.

The purpose of the example is as follows:

- 1. Select the important variables for each discipline using *Sensitivities*.
- 2. Optimize the design with the limited number of partially shared variables.
- 3. Use the frequency constraints and mode tracking.
- 4. Solve a problem with an infeasible solution.

Variable screening: First iteration with all variables

Directory: **DESIGN_OPTIMIZATION/MDO/ITERATE**

Starting file: mdo.iterate.start.lsopt

Setup:

- 1. Use the GUI to open the **mdo.iterate.start.lsopt** file.
- 2. Check the availability of parameters from the input files by clicking "Stage Matrix" and "Sampling Matrix" under **Setup**, "Active variables" under **Sampling** and "Parameters" under the **Stages**.
- 3. Use all variables, except tgrill. (Deselect tgrill for both cases). *Note:* tgrill can also be set to a constant in the Setup dialog.
- 4. Constraints:
 - a. Set the frequency constraint as an *equality* constraint of 1.8 by setting both the lower and upper bounds to 1.8.
 - b. Set the internal constraint scaling (check box in the Constraints tab). Normalization is done to avoid conditioning problems when choosing both large and small constraints. A constraint with a large number will inflate its importance in the problem; hence constraints with significantly smaller numbers tend to be ignored.
- 5. Use '+' in the top menu bar to add the Global Sensitivities calculation.
- 6. Change the task selection to Metamodel-based optimization with SRSM strategy, set the termination criteria to one iteration and Run.

Exercise:

1. *Viewer:* Using the *Global Sensitivities* selection, estimate the 3 most important variables of the CRASH discipline. Use all the available variables for NVH.

	CRASH	NVH
tbumper		\checkmark
troof		\checkmark
trailb		\checkmark
trailf		\checkmark
thood		n/a

Iterative optimization using screened variables

Directory: **DESIGN_OPTIMIZATION/MDO/ITERATE**

Starting file: mdo.iterate.correct.lsopt

Setup:

- 1. Identify the 3 most important variables of the crash discipline from the previous LS-OPT run of one iteration. Note that the LS-OPT input file of the previous run can be modified to continue optimization with the screened variables.
- 2. Sampling: Using the Sampling Matrix in Setup, select the 3 most important variables of the CRASH discipline (recorded in the previous section) as active variables for the crash sampling by deactivating the insignificant variables.
- 3. Set the number of iterations to 5 (or more, time allowing) and continue the optimization process with the screened variables.

Exercise:

- 1. *Viewer:* Study the feasibility of the solution. Which response has the largest normalized constraint violation (violation divided by bound value)?
- 2. Use the 2D Interpolator to study the sensitivity of all functions to a variable which is only present in the NVH case. What do you see?

MULTI-OBJECTIVE OPTIMIZATION

This example illustrates two approaches to the computation of the Pareto Optimal Frontier. The first approach uses *direct* optimization while the second approach is *metamodel*-based. The example uses the finite element model of the vehicle impacting a pole as was used for single objective optimization (see page 11).

Pole crash problem using Direct GA

Minimize Mass Minimize Intrusion (50ms)

subject to

HIC (15ms) < 250

The parameters are the same two variables as before, namely the theorem and thood.

Special topics: Multi-objective optimization, Pareto optimality

Directory: DESIGN_OPTIMIZATION/MULTIOBJECTIVE/SIMPLE/DIRECT

Starting file: direct.moo.start.lsopt

Setting up the problem

- 1. Select Mass and Intrusion as objectives for defining a two-objective optimization problem. De-select all other responses.
- 2. Set a HIC upper bound constraint of 250. De-select all other constraints.
- 3. Select the task as *Direct Simulation->Optimization* and check the box "Create Pareto Optimal Front". The Pareto Optimal option can also be turned on from the objective tab under Optimization. *Note that the* "Create Pareto Optimal Front" option appears only if multiple objectives are defined.

- 4. On the **Optimization** \rightarrow **Algorithms** page, set the population size to 20 and the number of generations to 20. Set the termination criterion to *Hypervolume change*.
- 5. Run.

Exercise

- 1. Display the Tradeoff plot for iteration 20.
- 2. How is the Utopian point defined? Determine the objective function values of the Utopian point.

Intrusion	Mass
521	0.29

- 3. Add the Parallel Coordinate (<u>Pareto</u>) plot by splitting the screen vertically. Check "Select from active points" on the Parallel Coordinate plot and slide the upper bounds of the *Mass* and *Intrusion* functions down to about 0.65 and 560 resp. leaving a limited number of Pareto candidate points. What do you observe on the Tradeoff plot?
- 4. Add the SOM plot by splitting the screen again and choose a cell representing a set of designs with the lowest mass. Observe the Parallel Coordinate plot and Tradeoff plot as well as the table representing the point data. Also click on some of the adjacent cells on the SOM plot and observe the parallel plot. *Note:* (i) Points can be selected with '=', added with '+' or subtracted with '-'. (ii) "Active" points can be totally unset by selecting the '-' button on the table and then "rubberbanding" the entire set of points in the Tradeoff plot.
- 5. *HRV*: Select the HRV plot. Unselect "Scale weights". Slide the weights of the objective functions to [0;1] and [1;0] and observe what happens to the Pareto Front and the point closest to the Utopian point (colored in purple).
- 6. Document the point closest to the Utopian point for the following weight selections. *Hint:* Use the text box option in the HRV control window to set the weights.

W _{Mass}	W Intrusion	tbumper	thood	Mass	Intrusion
0	1	2.7	2.5	.73	521
1	1	1.1	1.8	.49	544
1	0	1.0	1.0	.29	583

- 7. Using the Optimization History (MOO Performance Metrics) feature, tabulate the following:
 - a. Archive size at 10 iterations
 - b. Archive size at 20 iterations
 - c. The Dominated Hypervolume of the Pareto Frontier at 20 iterations.
 - d. What happens to the Spread of the Pareto Frontier during the optimization?

"Exact" optimization result using a population of 50 for 125 generations





Pole crash problem using Metamodel-Based optimization

Directory:

DESIGN_OPTIMIZATION/MULTIOBJECTIVE/SIMPLE/METAMODEL

Starting file: metamodel.moo.start.lsopt

Setting up the problem

- 1. *Optimization*. Select Mass and Intrusion as objectives. De-select all other. Set a HIC upper bound constraint of 250.
- 2. *Task Selection*. Select the task as *Metamodel-based Optimization*. Select *Sequential Optimization* strategy with Create Pareto Optimal Frontier option.
- 3. *Sampling*. Confirm that RBF and Space Filling are selected.
- 4. *Optimization* \rightarrow *Algorithms*. Set the termination criterion to *Hypervolume change*.
- 5. Termination criteria. Set the iteration limit to 10.
- 6. *Run*

Exercise

- 1. Display the Tradeoff plot for iteration 10.
- 2. Determine the objective function values of the Utopian point.

Intrusion	Mass
522	0.29

- 3. Add the Pareto Parallel Coordinate plot by splitting the screen vertically. Check "Select from active points" on the Parallel Coordinate plot and slide the upper bounds of the *Mass* and *Intrusion* functions down to about 0.65 and 560 resp. leaving a limited number of Pareto candidate points. Check that the HIC upper bound is set correctly at 250. What do you observe on the Tradeoff plot?
- 4. Add the Pareto SOM plot by splitting the screen again and choose a few cells representing a set of designs with the lowest mass. Observe the Parallel Coordinate plot and Tradeoff plot as well as the table representing the point data.
- 5. *HRV:* Select the HRV plot. Unselect "Scale weights". Slide the weights of the objective functions to [0;1] and [1;0] and observe what happens to

the Pareto Front and the point closest to the Utopian point (colored in purple).

6. Document the point closest to the Utopian point for the following weight selections. *Hint:* Use the text box option in the HRV control window to set the weights.

W _{Mass}	W Intrusion	tbumper	thood	Mass	Intrusion
0	1	2.9	2.5	.76	522
1	1	1.3	1.9	.50	549
1	0	1.0	1.0	.29	582

- 7. When comparing the direct with the metamodel-based optimization, what are the possible reasons for differences between the results?
- 8. Extend the metamodel-based optimization to 20 iterations (by changing the number on the Termination Criteria dialog) and compare the results again. You may have to set a lower response surface accuracy tolerance for stopping, e.g. 0.0001.

W _{Mass}	W _{Intrusion}	tbumper	thood	Mass	Intrusion
0	1	3.0	2.8	.82	510
1	1	1.2	1.9	.51	543
1	0	1.0	1.0	.29	582

- 9. Select 20 verification runs and extend the run (do not select a clean start). LS-OPT will simulate 20 Pareto designs from the last iteration.
 - a. Plot Intrusion vs. Mass using the Scatter Plot selection in the Viewer. Use "Max Constr. Violation" to color code the design points. This will provide an impression of the feasibility of the computed Pareto designs.
 - b. Tabulate the Utopian design of the simulation results.

Intrusion	Mass
509	0.29

MULTI-LEVEL OPTIMIZATION

This example demonstrates the approach for setting up a multi-level optimization in LS-OPT using nested optimization framework. An initial LS-OPT input file is treated as the outer loop of the setup with an LS-OPT stage consisting of another LS-OPT input file considered as the inner loop of the setup. The outer loop design variables are transferred as constants to the inner loop which could have its own design variables and an optimization setup. The optimum responses of the inner loop are extracted and defined as responses of the outer loop.

Two-level pole crash problem

Problem description

This example is a two level optimization of a simple pole crash analysis with both levels consisting of head injury criteria (HIC) and intrusion distance as the design objective and constraint, respectively. The inner loop optimization is based on thickness of a few selected parts whereas; the material parameters are considered as design variables of the outer loop optimization.

Directory: DESIGN_OPTIMIZATION/MULTILEVEL/OuterMat_InnerThickn ess

Starting files: Outer.start.lsopt, inner.start.lsopt

Setting up the problem

Inner loop

- 1. Open the file **inner.start.lsopt** using the LS-OPT GUI.
- 2. Inspect the *Stage* component of the flowchart and make sure the LS-DYNA command and input file are defined.
- 3. Inspect the *Setup* component of the main GUI to assign the design variables of the inner loop optimization. Change the *Parameter* type of the thickness variables *tbumper* and *thood* to *Continuous* and assign a lower and upper bound of 1 and 5, respectively. The material variables SIGY and YM are the outer loop design variables which are transferred

to the inner loop. Therefore, *Transfer variable* should be selected as the parameter type for the outer loop variables.

- 4. Assign a population size of 10 in the *Sampling* component.
- 5. Inspect the optimization component and confirm that HIC and intrusion distance are selected as objective and design constraint, respectively.
- 6. Inspect the termination criteria component and make sure you will be running four generations. Save the LS-OPT input file as inner.correct.lsopt.

Outer loop

- 1. Open the file **outer.start.lsopt** using the LS-OPT GUI.
- 2. *Stage Setup*: Select the **LS-OPT** solver option under stage setup. Enter the full path of the *lsopt* executable in the command section (default path can be selected by checking the option '*use default command*'), select **inner.correct.lsopt** as the input file and click OK.
- 3. The variables defined in **inner.correct.lsopt** as transfer variables are now listed in the *Setup* component. Change the parameter type to *Continuous* and assign the following lower and upper bounds for the outer loop variables.

Variable	Starting value	Lower bound	Upper bound
SIGY	400	3500	450
YM	200000	150000	250000

- 4. *Sampling*: Enter the 20 as the number of simulation points for the space filling sampling technique. Make sure *Radial Basis Function Network* is selected as the metamodel type.
- 5. *Stage Responses*: Define the outer loop responses using LS-OPT option listed under *Stage specific* response options. The LS-OPT response option lists all the responses, composites, objectives and constraints defined in **inner.correct.lsopt** file. Define the outer loop LS-OPT responses for head injury criteria and intrusion distance by selecting the corresponding component and make sure that the last iteration value is extracted.
- 6. *Optimization:* Select the LS-OPT response for *HIC* as the objective and LS-OPT response for *Intrusion* as the design constraints with a value of 550 as the upper bound.

7. Save the outer loop setup and use *Normal Run* option to run the two-level optimization example.

Exercise

- 1. Open the *Viewer* and inspect the simulation, metamodel and optimization history plots.
- 2. Report the optimum values of the objective, constraint and all the design variables. Note: You need to check the inner loop results of the verification run to obtain the optimum values of the inner loop variables. However, to avoid this step, you can define the inner loop variables as responses of the outer loop setup while setting up the example.

	Start	Optimum
SIGY	400	450
YM	200000	150000
tbumper	3	4.80
thood	1	1
HIC	67.21	47.25
Intrusion	287.65	307.21

- 3. Define the inner loop variables *SIGY* and *YM* as responses of the outer loop and extract the optimum values using the *Repair* tool.
- 4. Can metamodel-based optimization techniques be used in the inner loop instead of direct optimization? Comment on the simulation cost vs. metamodel accuracy associated with this approach.

RELIABILITY ANALYSIS

Reliability analysis is used to compute the probabilities of events.

This example demonstrates:

- Monte Carlo Analysis, and
- Metamodel-based Monte Carlo Analysis.

Problem description

This example is a Monte Carlo analysis of a steel tube being crushed. The effect of both a variation in material thickness and a variation in the plastic stress-strain curve is investigated. The geometry is shown in the figure in its original and partially deformed state. The z-displacement of the upper tube boundary is also shown below as a history. The minimum value of the z-displacement is used as the response variable, and the response is compared to a crush distance of the selected nominal design.





A scale factor (SIGY) is used to modify the plastic stress-strain curve. The binary LSDA LS-DYNA database is used for the extraction of the maximum displacement (largest negative value given the direction of the z-axis, hence the MIN selection) response.

Monte Carlo Analysis

Setting up the problem

- 1. Open the file monte_carlo.start.lsopt in the directory PROBABILISTIC/RELIABILITY/MONTE_CARLO.
- 2. Change the task to Direct Monte Carlo Analysis.
- 3. Change the T1 constant to be a noise variable with a variation around the nominal value described by a *normal* distribution with a mean of 1 and a standard deviation of 0.05. Note that you have to change the task, change the variable type, and create the distribution before you can assign the distribution.
- 4. Also change SIGY to have a variation around the nominal value described by a *normal* distribution with a mean of 1 and a standard deviation of 0.05.
- 5. A Latin Hypercube Sample (stratified Monte Carlo) experimental design should be used to reduce the cost of the stochastic simulation. Use 20 experiments to allow the simulation to finish in reasonable time.

- 6. Constrain the displacement constraint to be more than -230 (a lower bound therefore).
- 7. Save your work under any name.
- 8. Run the Monte Carlo Analysis.

Viewer

- 1. View the variables and response using a Correlation Matrix plot.
- 2. Create a Scatter Plot of TOP_DISP on the y-axis and the T1 variables respectively on the x-axis. Hint: you can get this plot by double clicking on the corresponding small plot in the correlation matrix plot.
- 3. View the statistics of TOP_DISP response using the Statistics functionality or by double clicking in the Correlation Matrix plot on the corresponding histogram plot. Use the Summary and Bounds options to:
 - a. Verify that the mean is -227 and standard deviation is 6.0
 - b. Verify that the probability of the response being larger than -220 is 0.1.
 - c. Verify that the probability of the response being less than -230 is 0.4.
 - d. Verify that the probability of the response being less than -235 is 0.05.
- 4. Identify, if possible, the variable contributing the most to the variation of the crush distance using a Correlation plot. Is it possible to select the most influential variable given the confidence intervals?

DYNA Stats

Use lsoptui Dynastats panel to display statistics in LS-PREPOST.

- 1. Create as fringe plots:
 - a. The mean of the z_displacement.
 - b. Standard deviation of the z_displacement.
 - c. Correlation of the z_displacement and the TOP_DISP response.
- 2. Generate and display the three fringe plots.
- 3. Create as history plots:
 - a. Mean and standard deviation of the TOP_DISP_HIST history.
 - b. Individual histories from each LS-DYNA run of the TOP_DISP_HIST history.

- 4. Generate and display the two history plots.
- 5. Create and display a fringe plot showing the probability of the *z_displacement* being less than -230.

Metamodel-based Monte Carlo Analysis

Setting up the problem

- 1. Open the file metamodel.start.lsopt in the directory PROBABILISTIC/RELIABILITY/METAMODEL.
- 2. Change the task to Metamodel-based Monte Carlo Analysis.
- 3. Change the T1 constant to be a noise variable with a variation around the nominal value described by a *normal* distribution with a mean of 1 and a standard deviation of 0.05. Note that you have to change the task, change the variable type, and create the distribution before you can assign the distribution.
- 4. Also change SIGY to have a variation around the nominal value described by a *normal* distribution with a mean of 1 and a standard deviation of 0.05.
- 5. Keep the default value of 2 standard deviations for the noise variable subregion size.
- 6. Verify that the metamodel is a quadratic surface.
- 7. Use full factorial design with 3 points per variable.
- 8. Constrain the displacement constraint to be more than -230 (a lower bound therefore).
- 9. Save your work under any name.
- 10. Run the Metamodel-based Monte Carlo Analysis.

Viewer

- 1. View the response values using the Metamodel Surface plot. Note that you have to select Points, Iterations = All to view the actual response values.
- 2. Considering the TOP_DISP response in the Statistical Tools:
 - a. Verify that the metamodel is selected to compute the statistics.

- b. Verify that the mean is -228 and standard deviation is 7.3 using the Summary Plot type.
- c. Verify that the probability of the response being larger than -220 is 0.15 using the Bounds plot type.
- d. Verify that the probability of the response being less than -230 is 0.39.
- e. Verify that the probability of the response being less than -235 is 0.15.
- 3. Identify the variable contributing the most to the variation of the crush distance using the Stochastic Contribution plot.

DYNA Stats

Use lsoptui Dynastats panel to display statistics in LS-PREPOST. Always use a quadratic response surface to compute the results.

- 1. Create as fringe plots:
 - a. The mean of the z_displacement.
 - b. Standard deviation of the z_displacement.
- 2. Verify that a quadratic response surface is used to compute the results.
- 3. Generate and display the two fringe plots.
- 4. Create, generate, and display the following history plots:
 - a. The statistics of the TOP_DISP_HIST history.
 - b. Individual histories from each LS-DYNA run of the TOP_DISP_HIST history.
- 5. Using single variable mode (contribution analysis)
 - a. View as a fringe plot:
 - a. The standard deviation of the z_displacement due to the SIGY variable.
 - b. A plot of the index of the variable contributing the most to the z_displacement.
 - b. View as a history plot:
 - a. The standard deviation of the TOP_DISP_HIST due to each of the variables.

RELIABILITY BASED DESIGN OPTIMIZATION (RBDO)

Reliability Based Design Optimization (RBDO) includes the variation of the design variables into the design problem.

This example demonstrates:

- Reliability Based Design Optimization (RBDO)
- Creating statistical distributions and assigning them to design variables.
- Probabilistic constraints.

Problem description

This is the two-bar as considered previously.



The two-bar truss problem. The problem has two variables: the thickness of the bars and the leg width as shown. Both the thickness and the leg width have uncertainties associated with them. The weight of the structure is minimized and the probability of the maximum stress in the bars exceeding the failure stress is constrained.

A value of the base variable and area variable must be obtained that minimizes mass while respecting a probability of not exceeding the allowable stress value.

Setting up the problem

- 1. Open the file 2bar.rbdo.start.lsopt in the working directory PROBABILISTIC/RBDO.
- 2. Change the area variable to have a variation around the nominal value described by a *normal* distribution with a standard deviation of 0.1. Note that you have to change the task to RBDO/Robust Parameter Design to assign the distribution.
- 3. Change the base variable to have a variation around the nominal value described by a *uniform* distribution with a range of 0.2.
- 4. Verify that the metamodel is a quadratic surface and that the experimental design is suitable.
- 5. Set the objective to be the weight of the structure.
- 6. Change the constraint such that the probability of exceeding the upper bound on the stress constraint does not exceed 0.05.
- 7. Save your work under any name.
- 8. Run the RBDO job.

Viewer

- 1. Verify that the optimum value of the area variable is computed as 1.6. This can be done using the Opt History functionality.
- 2. Verify that the optimum value of the base variable is computed as 0.4.
- 3. Verify that the probability of exceeding the upper bound of the constraint has converged to 0.05 using the Optimization History functionality.
- 4. Using the Stochastic Contribution functionality, verify that:
 - a. The standard deviation of the stress due to all the variables is 0.06.
 - b. And that almost all of the variation of the stress is caused by the area variable.

ROBUST PARAMETER DESIGN

Robust parameter design selects designs insensitive to the variation of given parameters.

This example demonstrates:

• Robust Parameter Design

Problem description

This is the two-bar as considered previously.



The two-bar truss problem. The problem has two variables: the thickness of the bars and the leg widths as shown. The bar thicknesses are noise variables while the leg widths are adjusted (control variables) to minimize the effect of the variation of the bar thicknesses. The maximum stress in the structure is monitored.

A value of the base variable must be obtained that makes the stress response insensitive to variation of the area variable.

Setting up the problem

1. Open the file 2bar.robust.start.lsopt in the directory PROBABILISTIC/ROBUST_PARAMETER_DESIGN.

- 2. Change the area variable to be a noise variable described by a normal distribution with a mean of 2.0 and standard deviation of 0.1. Note that you have to change the task to RBDO to assign the distribution.
- 3. The base variable should be left unchanged. Verify that it is a control variable with a starting value of 0.8, allowable minimum of 0.1, and allowable maximum of 1.6.
- 4. Change the metamodel and experimental design to consider interaction between the variables.
- 5. Set the objective to be the standard deviation of the existing stress response. Note that you have to create a composite that is the standard deviation of the existing stress response in order to do this.
- 6. Save your work under any name.
- 7. Run the robust parameter design job.

Viewer

- 1. Verify that the value of the area noise variable remains unchanged. This can be done using the Optimization History functionality.
- 2. Verify that the optimum value of the base control variable is computed as 0.5.
- 3. Verify that the standard deviation composite has converged.
- 4. Use the Metamodel facility to investigate how the value of the stress standard deviation changes with the variables.
BIFURCATION/OUTLIER ANALYSIS

Bifurcation analysis investigates scatter in the results, with the goal of understanding bifurcations in the results.

This example demonstrates:

- Monte Carlo analysis
- Identification of different buckling modes in the structure

This example is also presented in the LS-OPT User's Manual.

Problem description

The plate as shown has two buckling modes. Buckling in the positive zdirection occurs with a probability of 80% while buckling in the negative zdirection occurs with a probability of 20%. Assigning a distribution (in this case uniform) to an imperfection at tip nodes allows control of the probability of buckling.



Buckling Mode II (20% probability)

A Latin hypercube experimental design is used for the Monte Carlo analysis. We analyze only five points. Given the probability of 20% of buckling in the negative z-direction and a Latin hypercube experimental design, one run will buckle in the negative z-direction. The next section will demonstrate how to find out which run contains the different buckling mode.

Setting up the problem

1. Open the file outlier.lsopt in the directory PROBABILISTIC/OUTLIER.

2. Run the Monte Carlo job.

Viewer

- 1. Use Viewer to determine the minimum and maximum displacements of the tip by plotting the tip_z vs. the tip tip_x response using a Scatter plot.
- 2. Identify the LS-DYNA jobs associated with the maximum and minimum values of the tip_z response.

DYNA Stats

Use the lsoptui Dynastats panel to display the bifurcations in LS-PREPOST.

- 1. Create, generate, and display a fringe plot of the standard deviation of the *z*-*displacement*.
- 2. Create a bifurcation plot of the plot created in the previous step.
 - a. Select to overlay the FE model of the job with the maximum value. Also overlay the FE model of the job with the minimum value.
 - b. Select the maximum and minimum overall values by considering the whole model.
 - c. Display this plot. You should see three FE models with the bifurcation clearly visible.
- 3. Create another bifurcation plot considering the z_displacement values at a node:
 - a. Determine the node in the structure where the maximum variation of the z-tip displacements occurs by plotting the range of the z_displacement.
 - b. Overlay the FE model of the job with the maximum value at this node. Also overlay the FE model of the job with the minimum value at this node.
- 4. Using the history statistics of the z-tip displacement (NHist_Z):
 - a. At what analysis time did bifurcation start?
 - b. During which analysis time interval can the bifurcation be viewed?
 - c. Identify the LS-DYNA jobs associated with the maximum and minimum values.

ROBUSTNESS OF METAL FORMING (OPTIONAL)

Metal forming requires the analysis of adaptive results at specific coordinates. The results can then be compared even though the node locations and numbers differ between FE models.

This example demonstrates:

- Robustness of metal forming,
- Mapping results from adaptive meshes, and
- Using a stochastic field described with a sinusoidal perturbation.

Problem description

The structure shown is a simple metal forming problem. Part 1, modeled as adaptive, is the work piece being deformed.



A Monte Carlo analysis is done to estimate the scatter that can occur in practice. The variables are:

- YIELD, the yield strength of the material used in the work piece;
- FS1, the scaling of the contact force between the work piece and the punch;
- FS2, the scaling of the contact force between the work piece and the die;
- FS3, the scaling of the contact force between the work piece and the blank holder; and
- POFF, the offset of the stochastic field.

Setting up the problem

The results from the Monte Carlo analysis should already exist in your directory PROBABILISTIC/METALFORMING. If not, run the file metal_MC.lsopt.

Viewer

- 1. Identify the most important variable for the maximum thickness reduction by viewing the correlation of the maximum percent thickness reduction (*prc_thick_red_max*) with the variables.
- 2. Verify the variable identified in 1 using Scatter plots or a Correlation Matrix plot. Plot the response (*prc_thick_red_max*) against the various variables.

DYNA Stats

- 1. Set the metal forming options to map the results of part 1 (follow the coordinates instead of the nodes).
- 2. Plot the variation of the sheet thickness. The standard deviation should have a maximum value of order 0.03 0.05.
- 3. Set the FLD options to use the curve 90 in the LS-DYNA input file. Plot "*maxima flc-eps1*".