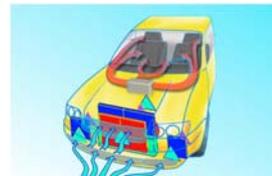




MultiObjective Optimization in Commercial Vehicle Cooling Layout

Using Genetic Algorithms to Improve
Engine Cooling Performance

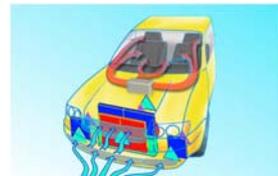
Nader Fateh
Esteco North America





Agenda

- Optimization Software – **modeFRONTIER**
- Optimization – single- and multi-objective
- Genetic Algorithms
- Test Case
- TRUCK Model





Software Overview

modeFRONTIER is a **multi-objective optimization and design environment**, featuring:

- Process Integration (easily coupled to almost any CAE tool)
- Complete Collection of Algorithms for:
 - Design of Experiments
 - Robust Design
 - State of the art Optimization (Single- and Multiobjective)
 - Response Surface Methods
 - Data Modelling
 - Data Mining & Statistics
 - Decision Support Methods
- Java Source Enables Portability: Unix and Windows
- Network Operation (Homogeneous and Heterogeneous)





Optimization

Single-objective vs Multi-objective

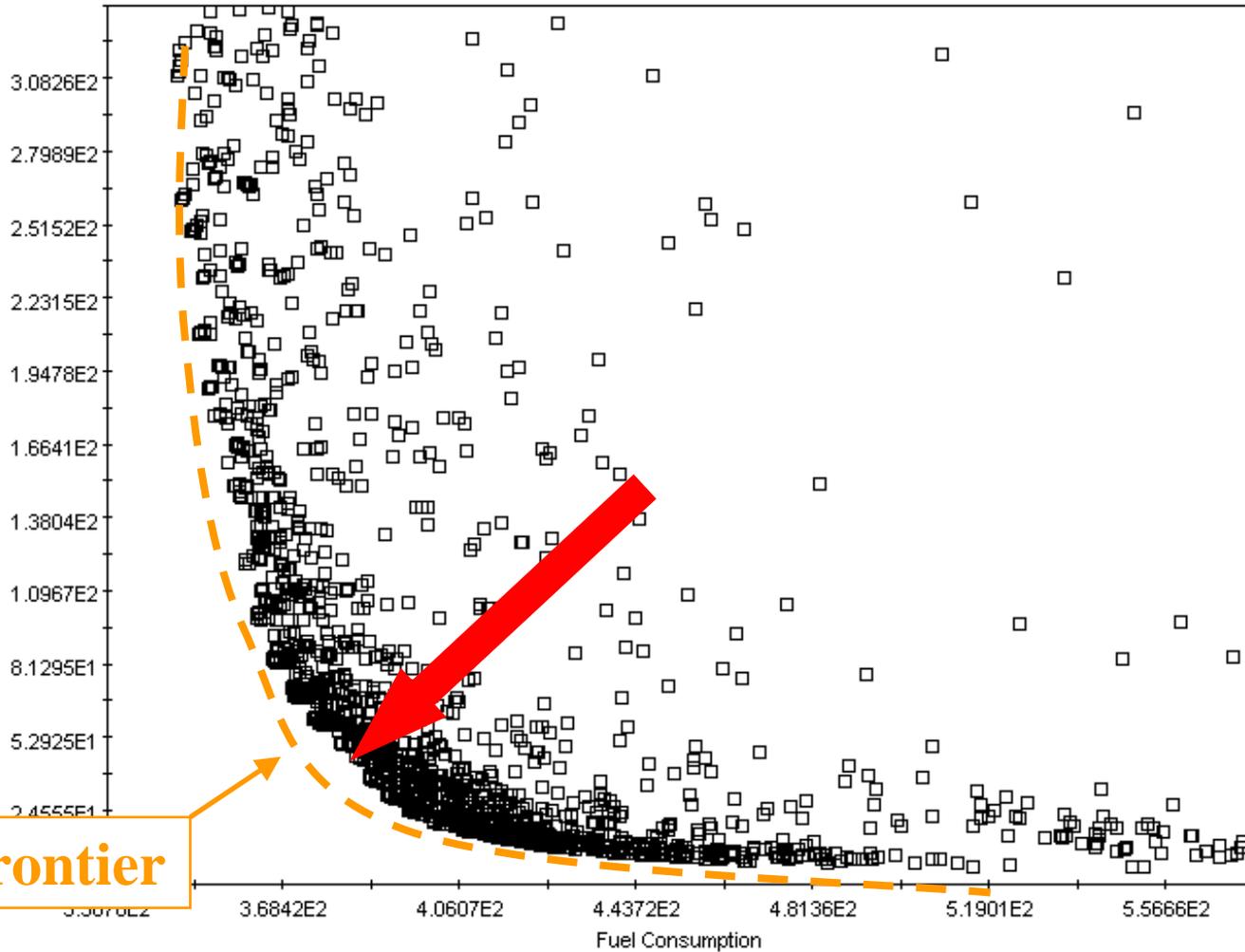
SO	MO
Typically use gradients to maximize (or minimize) a single objective function	Allows multiple objectives
Continuous Variables	Discrete variables (including “Catalog Data”)
May converge to local optimum	Finds global optimum
Produces single optimum point	Produces <i>Pareto Frontier</i> , or <i>Trade-Off Curve</i>
Computationally more efficient	Requires more data points





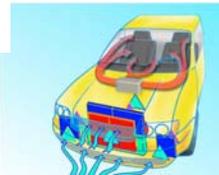
Pareto Frontier (Trade-Off Curve)

NOX



Pareto Frontier

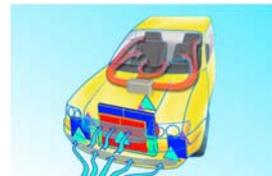
Fuel Consumption





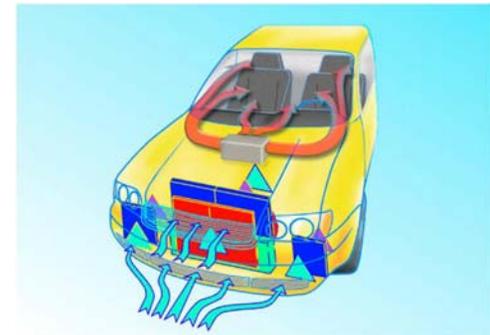
Genetic Algorithms

These mimic natural evolution, where a biological population evolves over generations to adapt to an environment through processes of selection, crossover (“reproduction”) and mutation of genes.





Coupling KULI with modeFRONTIER

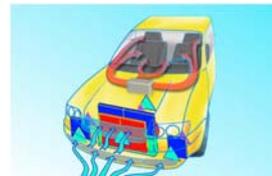


KULI 5.2



Coupling **modeFRONTIER** and **KULI**

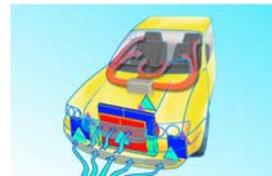
- **KULI** can be run through Excel, using VB macros and COM objects
- **modeFRONTIER** has a direct interface to Excel, so that it can directly enter the input parameters into the Excel file, run macros, and extract the output data
- Not all variables can be modified through the COM objects - **modeFRONTIER** sets these by modifying **KULI**'s **.scs** file directly





Coupling **modeFRONTIER** and **KULI** through Excel

- Simple Example:
 - Simple system with radiator and fan
 - 3 variables: fan diameter, radiator width and radiator height
 - Objective: minimize radiator entry temperature
 - As we only have one objective, we use a gradient-based algorithm (Simplex)
 - Clearly, the program should converge to a system where all 3 variables take their maximum values





KULI Inner Circuit

KULI - System generation [Fan-Rad-Opt.scs]*

File Library Insert Output Graphics mode Extras Windows / Toolbars Help

General data Inner circuit Air side Simul. param. Variables

COM

1.COM object

COM-ID

Diameter

Input Output

Unit mm

Ok Cancel

1. Water circuit

In Out

CF

1.RAD [!]

In Out

Width

Height

Entry temperature IM

COM

COM

COM

1.MFan

Out

Diameter

COM

Simulation parameters

SP

Modified



KULI - Excel File

The screenshot shows a Microsoft Excel spreadsheet titled "Fan-Rad-Opt.xls". The spreadsheet is divided into sections for input parameters, output values, and file information. Annotations with arrows point to specific cells and text boxes explaining their roles.

Example Fan Radiator Optimization			
Ambient Temperature °C	20		
Relative Humidity %	50		
Fan Diameter	Radiator Width	Radiator Height	Radiator Entry Temp IM °C
600	600	800	

Location of KULI File to be run (points to Path: C:\Work\Kuli\NF-Fan-Rad-Opt)

Name of KULI File to be run (points to File: Fan-Rad-Opt.scs)

Output Value: This will be calculated by KULI and fed to modeFRONTIER (points to Radiator Entry Temp IM °C)

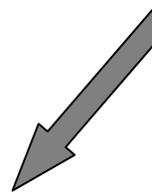
Input Values: These will be set by modeFRONTIER (points to Fan Diameter, Radiator Width, Radiator Height)



KULI - Excel VB Macro

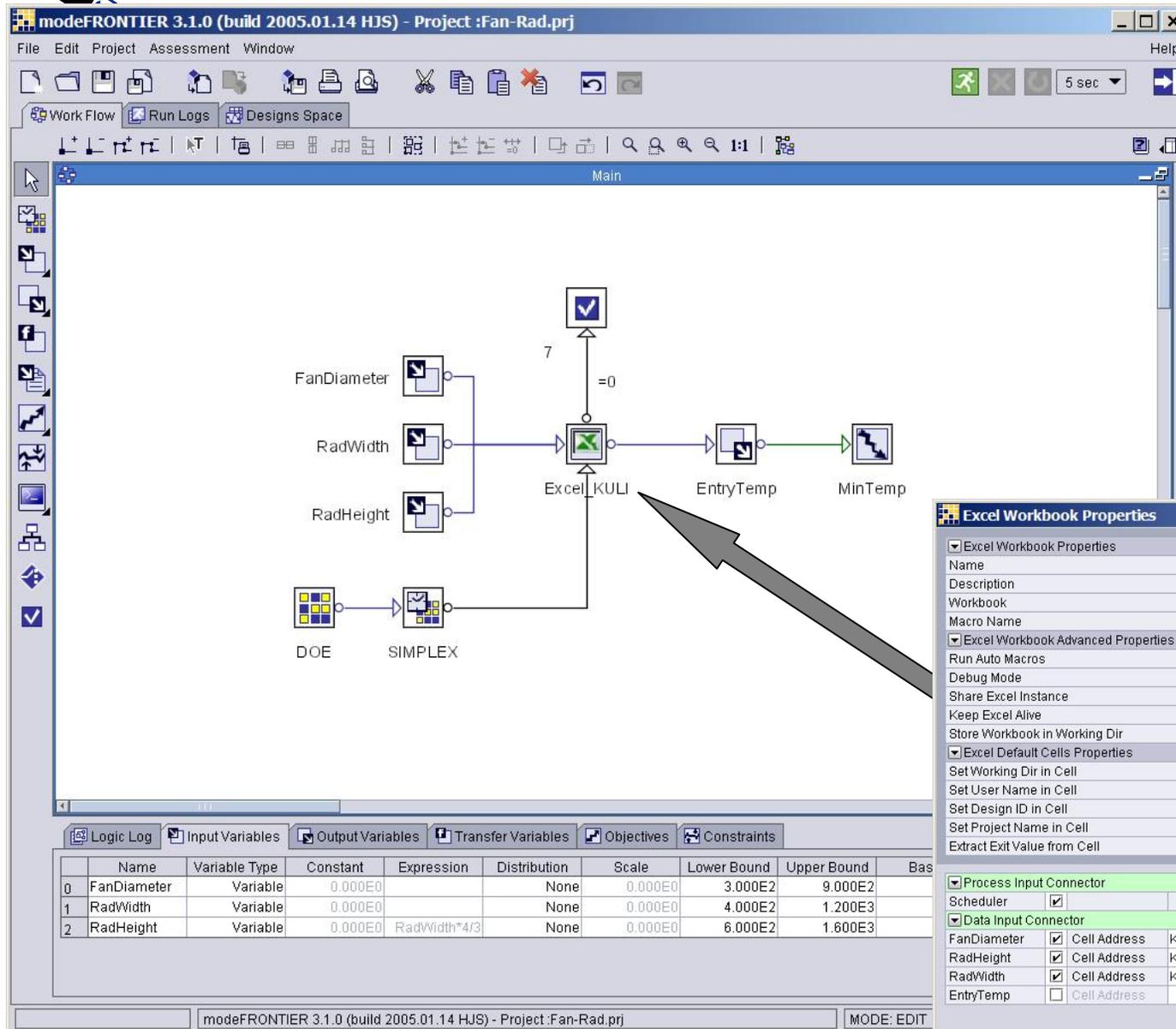
```
Sub KULIIF()  
    Dim calcOK As Boolean  
    Dim folder    As String  
    Dim fileKULI  As String  
    Dim Temp  
  
    'Getrennte Eingabe von Ordner und filename  
  
    folder = Cells(3, 8)  
    If Right(folder, 1) = "\" Or Right(folder, 1) = "/" Then folder = Left$(folder, Len(folder) - 1)  
    fileKULI = folder & "\" & Cells(4, 8)  
  
    If Dir(fileKULI, vbNormal) = "" Then ' File exists ?  
        MsgBox "File not found", , fileKULI ' no - Error  
        Exit Sub  
    End If  
  
    'set a new KULI-controller  
    Set KULI = New KuliAnalysisCtr2  
  
    'change directory name to your settings  
    KULI.KuliFileName = fileKULI  
  
    'initialize the cooling system  
    calcOK = KULI.Initialize()  
  
    calcOK = KULI.SetCOMValueByID("Diameter", Cells(8, 1))  
    calcOK = KULI.SetCOMValueByID("Width", Cells(8, 2))  
    calcOK = KULI.SetCOMValueByID("Height", Cells(8, 3))  
  
    'KULI calculates the values  
    KULI.SimulateOperatingPoint (1)  
    Cells(8, 4) = KULI.GetCOMValueByID("EntryTempIM")  
  
    'End KULI-analysis  
    KULI.CleanUp  
    Set KULI = Nothing  
End Sub
```

The name used in the macro
is the same as that in the
COM objects





modeFRONTIER Process Flow



Excel Workbook Properties

Excel Workbook Properties

Name: Excel_KULI

Description:

Workbook: C:\Work\Kul\INF-Fan-Rad-Opt\Fan-Ra...

Macro Name: Auto_Open

Excel Workbook Advanced Properties

Run Auto Macros:

Debug Mode:

Share Excel Instance:

Keep Excel Alive:

Store Workbook in Working Dir:

Excel Default Cells Properties

Set Working Dir in Cell:

Set User Name in Cell:

Set Design ID in Cell:

Set Project Name in Cell:

Extract Exit Value from Cell:

Process Input Connector

Scheduler:

Data Input Connector

FanDiameter: Cell Address: KULIA8

RadHeight: Cell Address: KULIB8

RadWidth: Cell Address: KULIC8

EntryTemp: Cell Address:

Process Output Connector

EndOK7: Condition: =0

Data Output Connector

EntryTemp: Cell Address: KULID8

OK Preview Cancel Help



modeFRONTIER - Excel Node

The screenshot shows the 'Excel Workbook Properties' dialog box. The 'Name' field is 'Excel_KULI', the 'Workbook' field is 'C:\Work\Kuli\NF-Fan-Rad-Opt\Fan-Ra...', and the 'Macro Name' is 'Auto_Open'. The 'Run Auto Macros' checkbox is checked. The 'Process Input Connector' section is expanded, showing 'FanDiameter', 'RadHeight', and 'RadWidth' with checked checkboxes and cell addresses 'KULIIA8', 'KULIIB8', and 'KULIIC8' respectively. The 'Process Output Connector' section is also expanded, showing 'EndOK7' with a checked checkbox and condition '=0', and 'EntryTemp' with a checked checkbox and cell address 'KULIID8'. Annotations include a red circle around the 'Name' and 'Workbook' fields with the text 'Name of Excel file', a red circle around the 'Process Input Connector' section with the text 'modeFRONTIER sets the values for the variables in the Excel worksheet', and a red circle around the 'Process Output Connector' section with the text 'modeFRONTIER extracts the value of the output parameter'. Arrows point from the text boxes to the corresponding fields in the dialog.

Excel Workbook Properties

Excel Workbook Properties

Name: Excel_KULI

Description:

Workbook: C:\Work\Kuli\NF-Fan-Rad-Opt\Fan-Ra...

Macro Name: Auto_Open

Excel Workbook Advanced Properties

Run Auto Macros:

Set User Name in Cell

Set Design ID in Cell

Set Project Name in Cell

Extract Exit Value from Cell

Process Input Connector

Scheduler:

Data Input Connector

FanDiameter	<input checked="" type="checkbox"/>	Cell Address	KULIIA8
RadHeight	<input checked="" type="checkbox"/>	Cell Address	KULIIB8
RadWidth	<input checked="" type="checkbox"/>	Cell Address	KULIIC8
EntryTemp	<input type="checkbox"/>	Cell Address	

Process Output Connector

EndOK7: Condition: =0

Data Output Connector

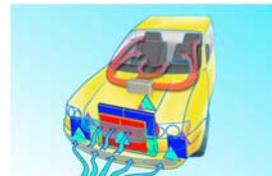
EntryTemp	<input checked="" type="checkbox"/>	Cell Address	KULIID8
-----------	-------------------------------------	--------------	---------

OK Preview Cancel Help

Name of Excel file

modeFRONTIER sets the values for the variables in the Excel worksheet

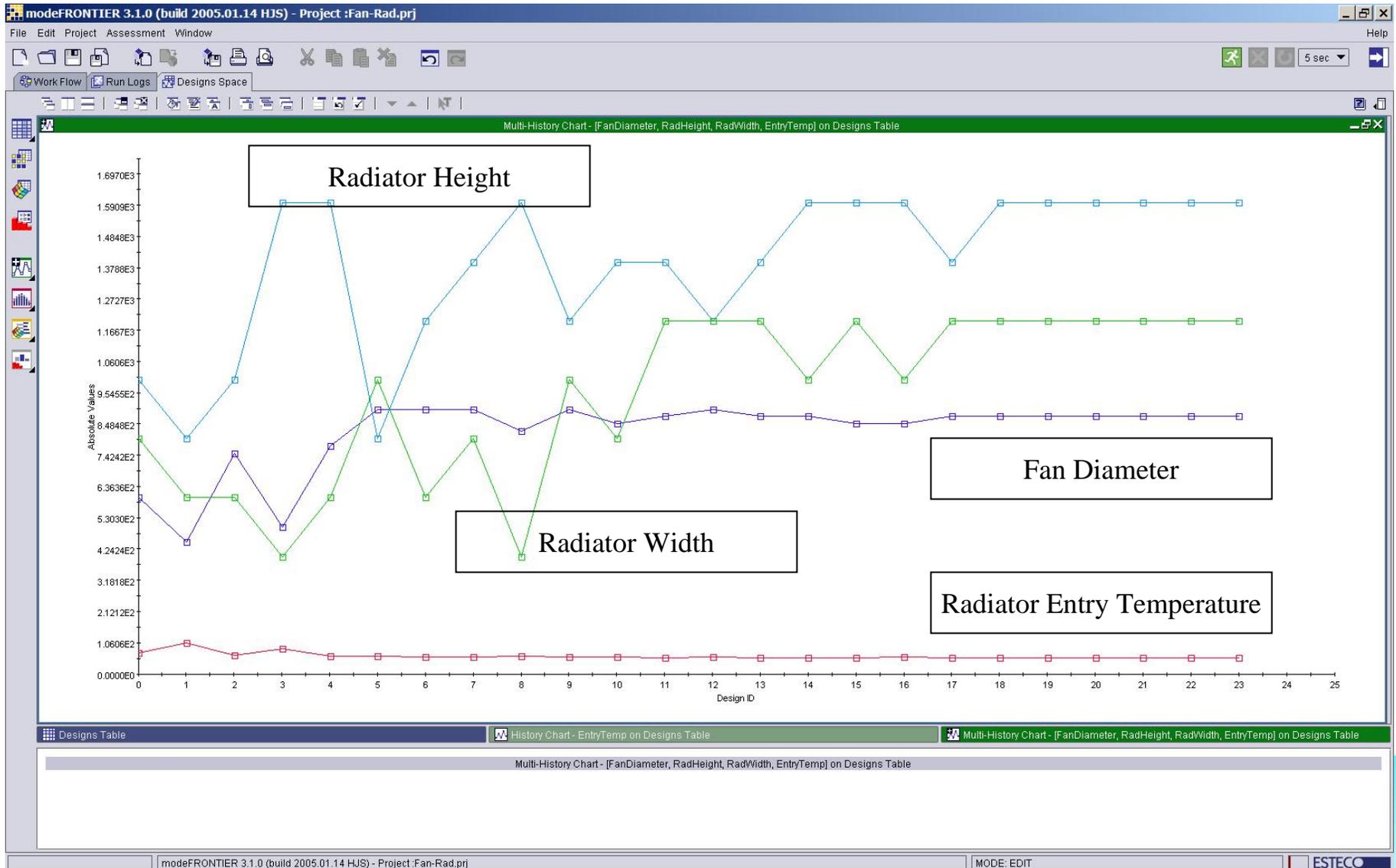
modeFRONTIER extracts the value of the output parameter





modeFRONTIER

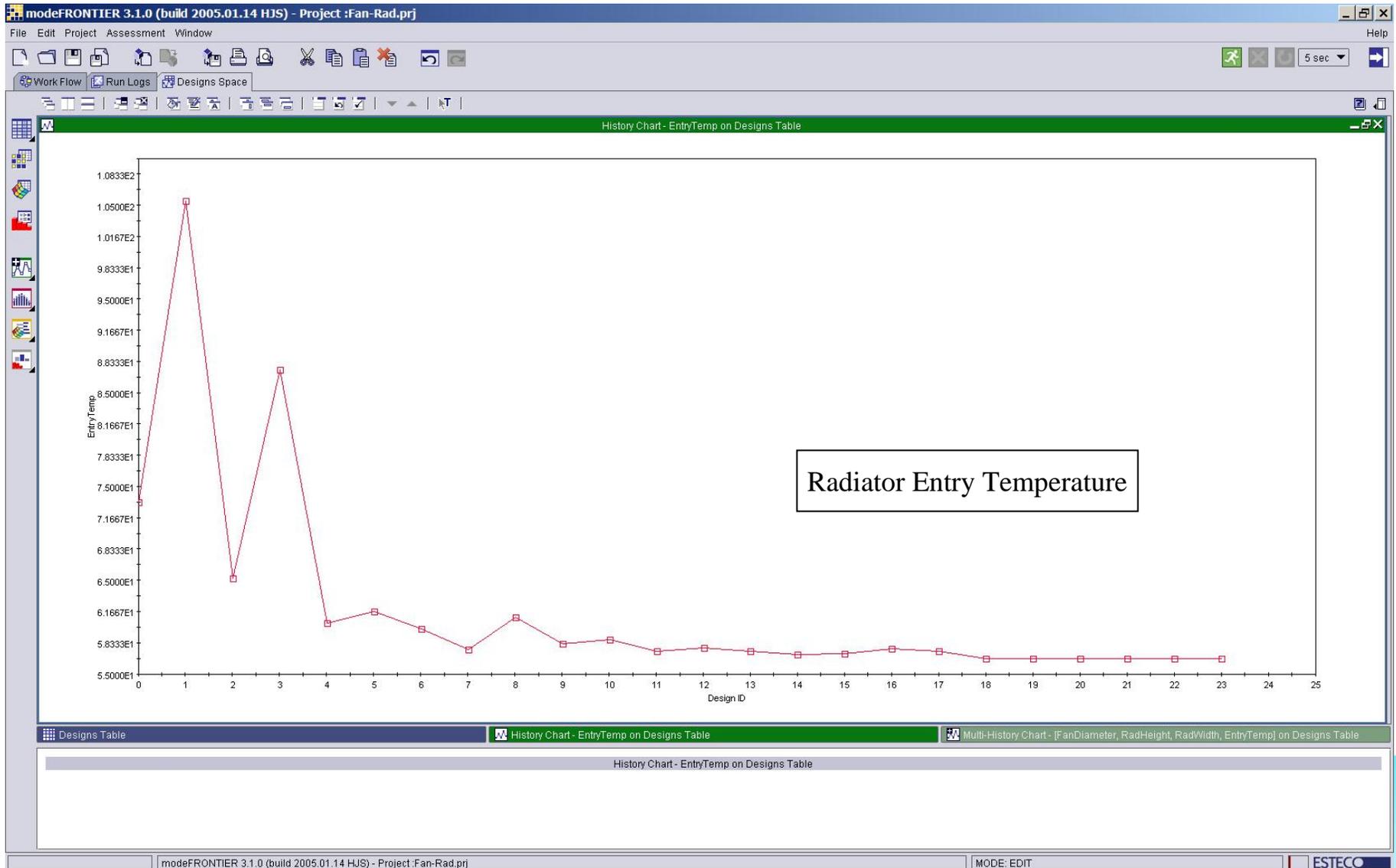
Solution Development





modeFRONTIER

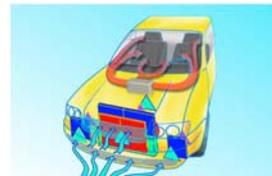
Radiator Entry Temperature





The TRUCK Model

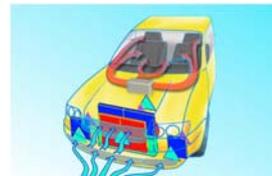
- Given three engine ratings, with 2 operating points (peak power and peak torque) each, the goal was to maximize cooling capacity of a heat exchanger package which would pass all 6 cases.
- For each case, there was a maximum allowable Radiator Exit Temperature, and CAC Entry Temperature, given by the Engine Manufacturer's Specifications. Therefore, one Design Iteration involved 6 KULI runs; at the end of which 6 radiator temperatures and 6 CAC temperatures were calculated. For a design to pass, all 12 calculated temperatures needed to be below the maximum allowable.





Inputs

- **modeFRONTIER** was allowed to modify the height and width of the radiator and charge air cooler, as well as the position of these components.
- Tank blockages were introduced, always with the correct position corresponding to their parent component.
- The input variables were constrained to ensure that all components remained within a predefined envelope.
- Constraints were also placed on the width and height of each component, to prevent searches in parts of design space which would clearly not produce solutions of interest.





The Objectives

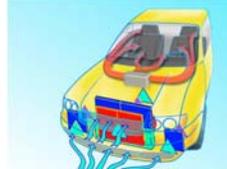
- In order to try to maximize the margin by which the 6 cases passed, two 2 quantities, $T_{R_{tot}}$ and $T_{CAC_{tot}}$ were calculated within **modeFRONTIER**:

$$T_{R_{tot}} = \sum_{n=1}^6 (T_{R_{nmax}} - T_{R_n})$$

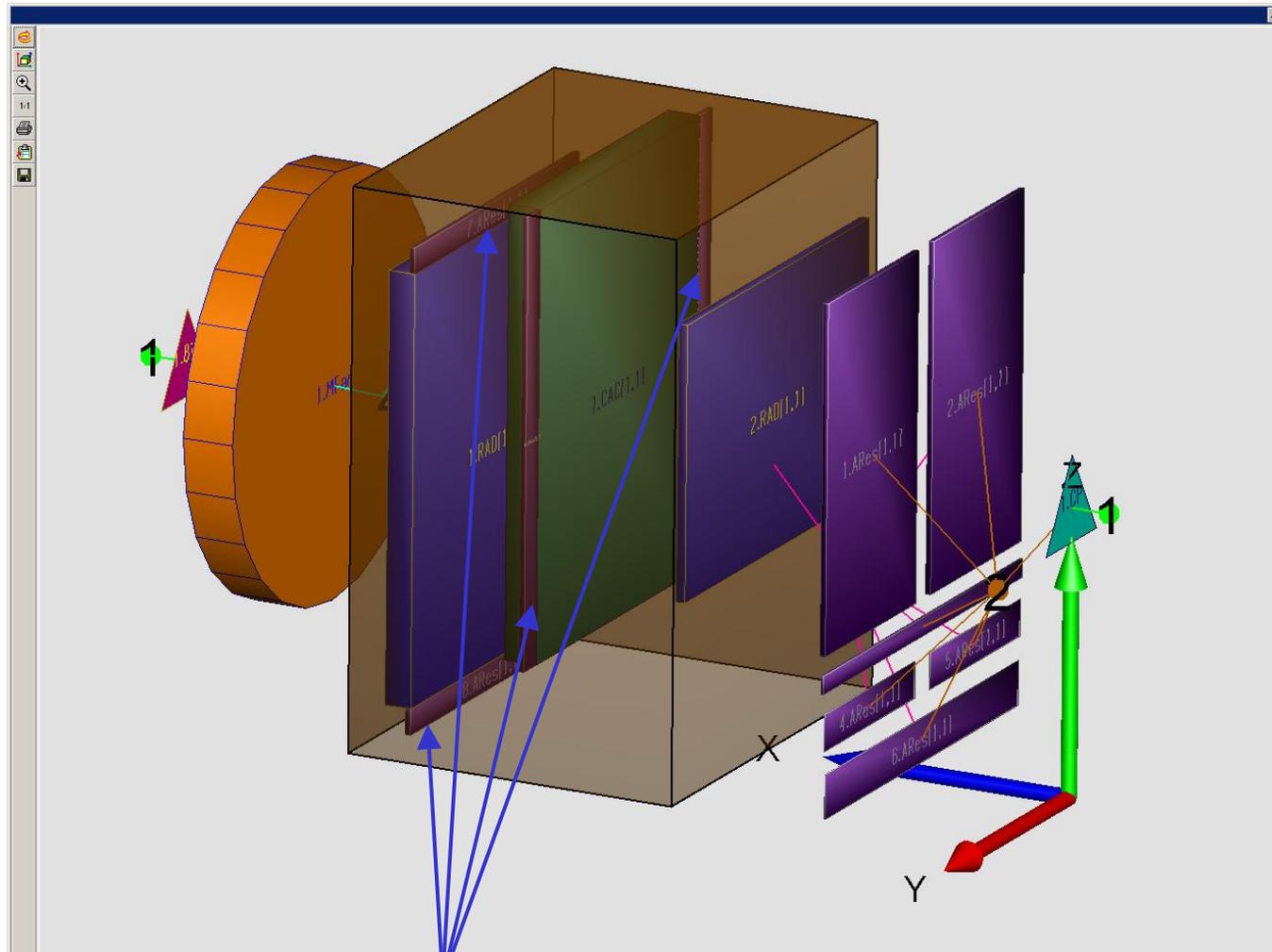
$$T_{CAC_{tot}} = \sum_{n=1}^6 (T_{CAC_{nmax}} - T_{CAC_n})$$

where $T_{R_{nmax}}$ and $T_{CAC_{nmax}}$ are the maximum allowable temperatures for radiator and CAC respectively, for case n.

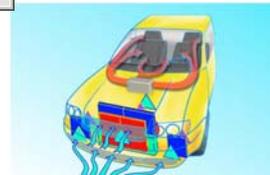
- Two objectives were defined: to maximize each of $T_{R_{tot}}$ and $T_{CAC_{tot}}$



KULI Model



Tank Blockages

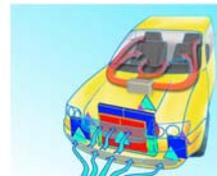




Optimization Parameters

8 Independent Variables:

Variable	Minimum	Maximum	Step (mm)
Radiator	$Y1_{\min}$	$Y1_{\max}$	5
Radiator	$Y2_{\min}$	$Y2_{\max}$	5
Radiator	$Z1_{\min}$	$Z1_{\max}$	5
Radiator	$Z2_{\min}$	$Z2_{\max}$	5
CAC	$Y1_{\min}$	$Y1_{\max}$	5
CAC	$Y2_{\min}$	$Y2_{\max}$	5
CAC	$Z1_{\min}$	$Z1_{\max}$	5
CAC	$Z2_{\min}$	$Z2_{\max}$	5





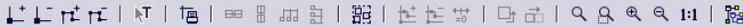
modeFRONTIER Work Flow

modeFRONTIER 3.1.0 (build 2005.01.14 HJS) - Project :TRUCK_NSGA.prj

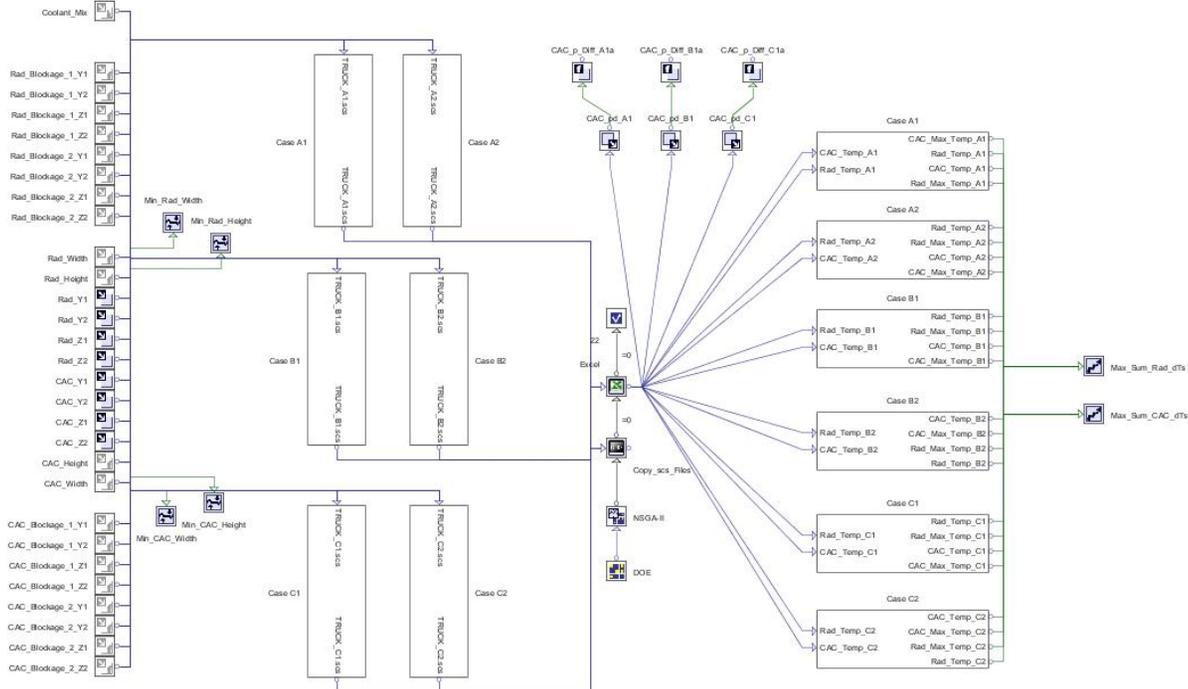
File Edit Project Assessment Window



Work Flow Run Logs Designs Space



Main



Logic Log Input Variables Output Variables Transfer Variables Objectives Constraints

Enabled	Name	Type	User Expression	Format
0	Max_Sum_CAC_dTs	Maximize	(CAC_Max_Temp_A1+CAC_Max_Temp_A2+CAC_Max_Temp_B1+...	0.0000E0
1	Max_Sum_Rad_dTs	Maximize	(Rad_Max_Temp_A1+Rad_Max_Temp_A2+Rad_Max_Temp_B1+R...	0.0000E0



modeFRONTIER - Input Subsystem

Input Variable Properties

Input Variable Properties	
Name	RPM_A1
Description	
Format	0.0000E0
Variable Type	Constant
Value	0.0
MORDO Properties	
Distribution	None
Data Output Connector	
TRUCK_A1.scs	<input checked="" type="checkbox"/>

Constants

Enabled	Name	Type	User Expression	Format
0	Max_Sum_CAC_dTs	Maximize	(CAC_Max_Temp_A1+CAC_Max_Temp_A2+CAC_Max_Temp_B1+...	0.0000E0
1	Max_Sum_Rad_dTs	Maximize	(Rad_Max_Temp_A1+Rad_Max_Temp_A2+Rad_Max_Temp_B1+R...	0.0000E0

Connection to .scs File

Connection to Rest of System

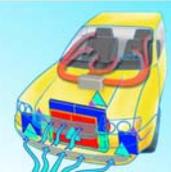


Integration: modeFRONTIER modifies the .scs file

The screenshot shows the 'Template Input Editor' window with a code editor and a variable selection list. The code editor contains several blocks of code with variables defined in red. A red circle highlights the line `KOMP_POS_X = <VAR name="CAC_Y1" format="0.0000E0"/>`. A callout box points to this line with the text: "... and marks the position in the .scs file where it is to be inserted". Below the code editor is a table with columns 'Name' and 'References'. A red circle highlights the first five rows of the table, and a callout box points to it with the text: "User selects variable from list ...".

```
661 BEMERKUNG = 'Radiator Tank Blockage'  
662 KOMP_POS_X = 150  
663 KOMP_POS_Y = <VAR name="Rad_Blockage_1_Y1" format="0.0000E0"/>  
664 KOMP_POS_Z = <VAR name="Rad_Blockage_1_Z1" format="0.0000E0"/>  
665 $ -----  
666 (SYS_KOMP_FW)  
667 AKT_BREITE = 50  
668 AKT_HOEHE = <VAR name="CAC_Height" format="0.0000E0"/>  
669 AKT_TIEFE = 10  
670 PARAMETER_1 = 1  
671 PARAMETER_2 = 1  
672 PARAMETER_3 = 1  
673 PARAMETER_4 = 1  
674 PARAMETER_5 = 1  
675 OPTIMIERUNG_BREITE = '=====  
676 OPTIMIERUNG_HOEHE = '=====  
677 KOMP_KENNUNG = 'FW9'  
678 BEMERKUNG = 'CAC Tank Blockage'  
679 KOMP_POS_X = 75  
680 KOMP_POS_Y = <VAR name="CAC_Blockage_1_Y1" format="0.0000E0"/>  
681 KOMP_POS_Z = <VAR name="CAC_Blockage_1_Z1" format="0.0000E0"/>  
682 $ -----  
683 (SYS_KOMP_LLK)  
684 AKT_BREITE = <VAR name="CAC_Width" format="0.0000E0"/>  
685 AKT_HOEHE = <VAR name="CAC_Height" format="0.0000E0"/>  
686 AKT_TIEFE = 64  
687 DURCHSTROEMUNG = 'GEG_Y_RICHTG'  
688 EINTRITT_POS = 'RECHTS_OBEN'  
689 VERSCHMUTZUNGSGRAD = 0  
690 OPTIMIERUNG_BREITE = '+Y'  
691 OPTIMIERUNG_HOEHE = '=Z'  
692 KOMP_KENNUNG = 'LLK1'  
693 BEMERKUNG = ''  
694 KOMP_POS_X = 75  
695 KOMP_POS_Y = <VAR name="CAC_Y1" format="0.0000E0"/>  
696 KOMP_POS_Z = <VAR name="CAC_Z1" format="0.0000E0"/>  
697 $ -----
```

	Name	References
11	<input checked="" type="checkbox"/> CAC_Width	1
12	<input checked="" type="checkbox"/> CAC_Y1	2
13	<input checked="" type="checkbox"/> CAC_Y2	1
14	<input checked="" type="checkbox"/> CAC_Z1	2
15	<input checked="" type="checkbox"/> CAC_Z2	1
16	<input checked="" type="checkbox"/> CAC_mf_A1	1
17	<input checked="" type="checkbox"/> CAC_p_A1	1
18	<input checked="" type="checkbox"/> Control_Temp_A1	1
19	<input checked="" type="checkbox"/> Coolant_Mix	1
20	<input checked="" type="checkbox"/> RAM_Air_A1	1
21	<input checked="" type="checkbox"/> RPM_A1	1
22	<input checked="" type="checkbox"/> Rad_Blockage_1_Y1	2
23	<input checked="" type="checkbox"/> Rad_Blockage_1_Z1	1





Integration Excel File Interface

Microsoft Excel - PACCAR_R_6.xls

Type a question for help

	A	B	C	D	E	F	G	H
1	Excel Sheet for TRUCK							
2								
3		Radiator Entry	CAC Exit Temperature	CAC dP	Directory	File		
4	Case A1:	0	0	0	C:\Work\Frontier\KULI\TRUCK	TRUCK_A1.scs		
5	Case A2:	0	0	0	C:\Work\Frontier\KULI\TRUCK	TRUCK_A2.scs		
6	Case B1:	0	0	0	C:\Work\Frontier\KULI\TRUCK	TRUCK_B1.scs		
7	Case B2:	0	0	0	C:\Work\Frontier\KULI\TRUCK	TRUCK_B2.scs		
8	Case C1:	0	0	0	C:\Work\Frontier\KULI\TRUCK	TRUCK_C1.scs		
9	Case C2:	0	0	0	C:\Work\Frontier\KULI\TRUCK	TRUCK_C2.scs		
10								
11								
12								
13								
14								
15								
16								
17								
18								
19								
20								
21								

↑

For each case the Excel file passes the location of the file, and the file name to the VB macro.

Excel is also used to extract the 2 temperatures and the dp across the CAC

KULI / Sheet2 / Sheet3 /

Ready

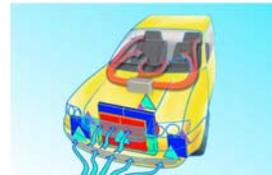


Integration

Running KULI in Batch Mode

```
Sub Auto_Open()  
Application.DisplayAlerts = False  
KULIA1  
KULIA2  
KULIB1  
KULIB2  
KULIC1  
KULIC2  
End Sub  
Sub KULIA1()  
Dim calcOK As Boolean  
Dim folder As String  
Dim fileKULI As String  
Dim Temp  
  
'Getrennte Eingabe von Ordner und filename  
  
folder = Cells(4, 5)  
If Right(folder, 1) = "\" Or Right(folder, 1) = "/" Then folder = Left$(folder, Len(folder) - 1)  
fileKULI = folder & "\" & Cells(4, 6)  
  
If Dir(fileKULI, vbNormal) = "" Then ' File exists ?  
  
    MsgBox "File not found", , fileKULI ' no - Error  
  
    Exit Sub  
  
End If  
  
'set a new KULI-controller  
Set KULI = New KuliAnalysisCtr2  
'change directory name to your settings  
KULI.KuliFileName = fileKULI  
'initialize the cooling system  
calcOK = KULI.Initialize()  
  
'KULI calculates the values  
KULI.SimulateOperatingPoint (1)  
  
Cells(4, 2) = KULI.GetCOMValueByID("EntryTempIM")  
Cells(4, 3) = KULI.GetCOMValueByID("ExitTempIM")  
Cells(4, 4) = KULI.GetCOMValueByID("PressureDifferenceIM")  
  
'End KULI-analysis  
KULI.CleanUp  
Set KULI = Nothing
```

KULI runs 6 times every time
the Excel file is opened





modeFRONTIER - Output Subsystem

modeFRONTIER 3.1.0 (build 2005.01.14 HJS) - Project :TRUCK_NSGA.prj

File Edit Project Assessment Window Help

Work Flow Run Logs Designs Space

Case A1

Values Calculated by KULI

Connection to Rest of System

Maximum Allowable Temperatures (Constants)

Enabled	Name	Type	User Expression	Format
0	Max_Sum_CAC_dTs	Maximize	(CAC_Max_Temp_A1+CAC_Max_Temp_A2+CAC_Max_Temp_B1+...	0.0000E0
1	Max_Sum_Rad_dTs	Maximize	(Rad_Max_Temp_A1+Rad_Max_Temp_A2+Rad_Max_Temp_B1+R...	0.0000E0

modeFRONTIER 3.1.0 (build 2005.01.14 HJS) - Project:TRUCK_NSGA.prj

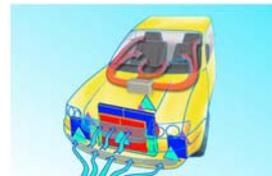
MODE: EDIT

ESTECO



Run Statistics

- Population Size: 32
- Number of Generations: 200
- Total Number of Simulations: 6400
(many repeated designs)
- Algorithm: NSGA-II
(Genetic Algorithm)
- Time: Approx 15 hours on
DELL Inspiron 8500, 2.4 GHZ

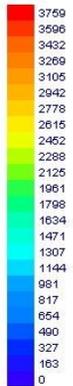
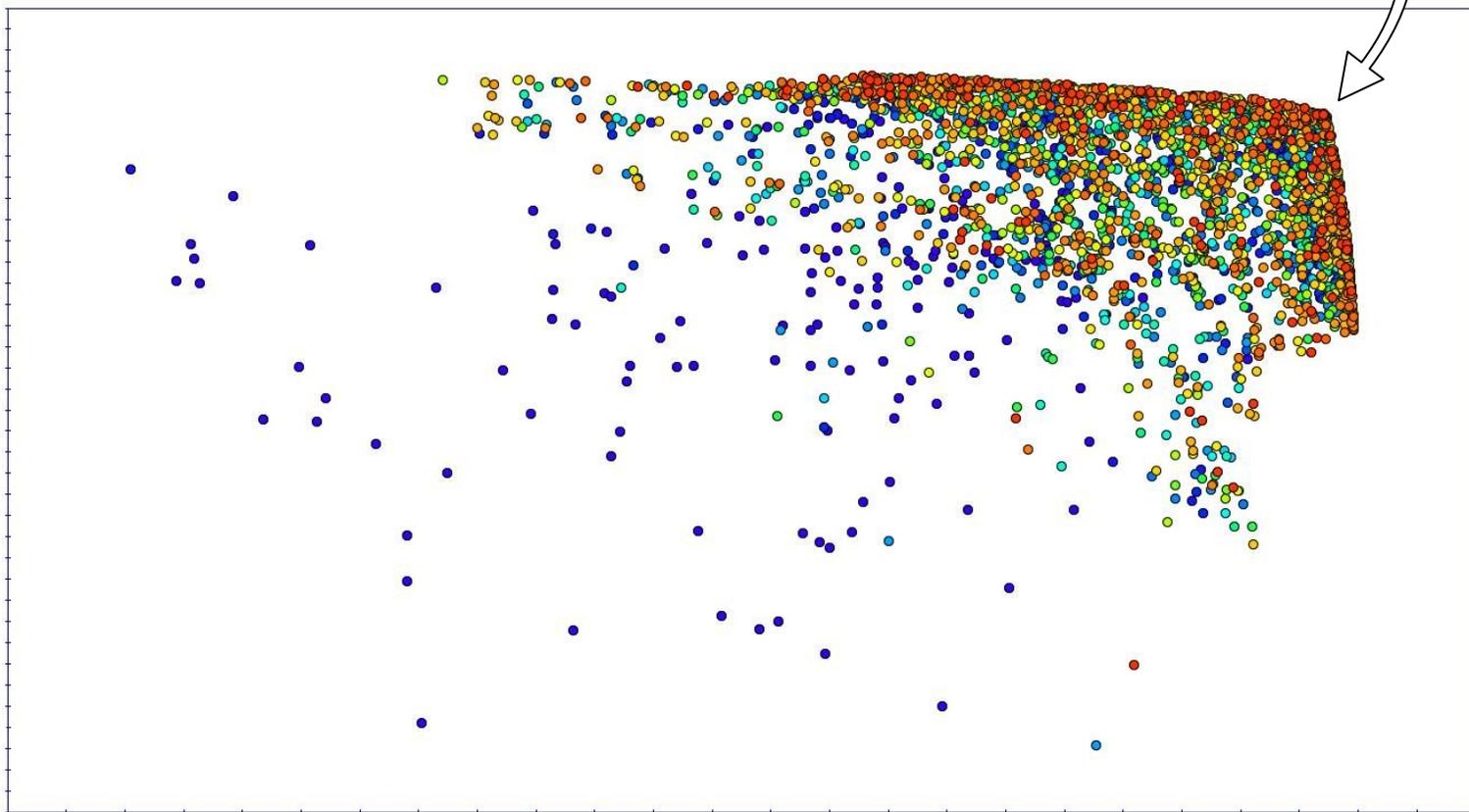




Results – Scatter Chart

Optimum Point

TRtot



TCACtot

modeFRONTIER 3.1.0 (build 2005.01.14 HJS) - Project :TRUCK_NSGA.prj

File Edit Project Assessment Window

Work Flow Run Logs Designs Space

Navigation icons for the software interface.

Bubble Chart - Max_Sum_CAC_dTs vs. Max_Sum_Rad_dTs vs. ID on Designs Table

5 sec

Help

Navigation icons for the software interface.

Navigation icons for the software interface.

Doe Table Designs Table Work Table_0 Correlation Matrix - [CAC_ Multi-History Chart - [Max_ Scatter Chart - Max_Sum_ Parallel Coordinates - [R_ Bubble Chart - Max_Sum_ Significance - Output Vari_

Bubble Chart - Max_Sum_CAC_dTs vs. Max_Sum_Rad_dTs vs. ID on Designs Table

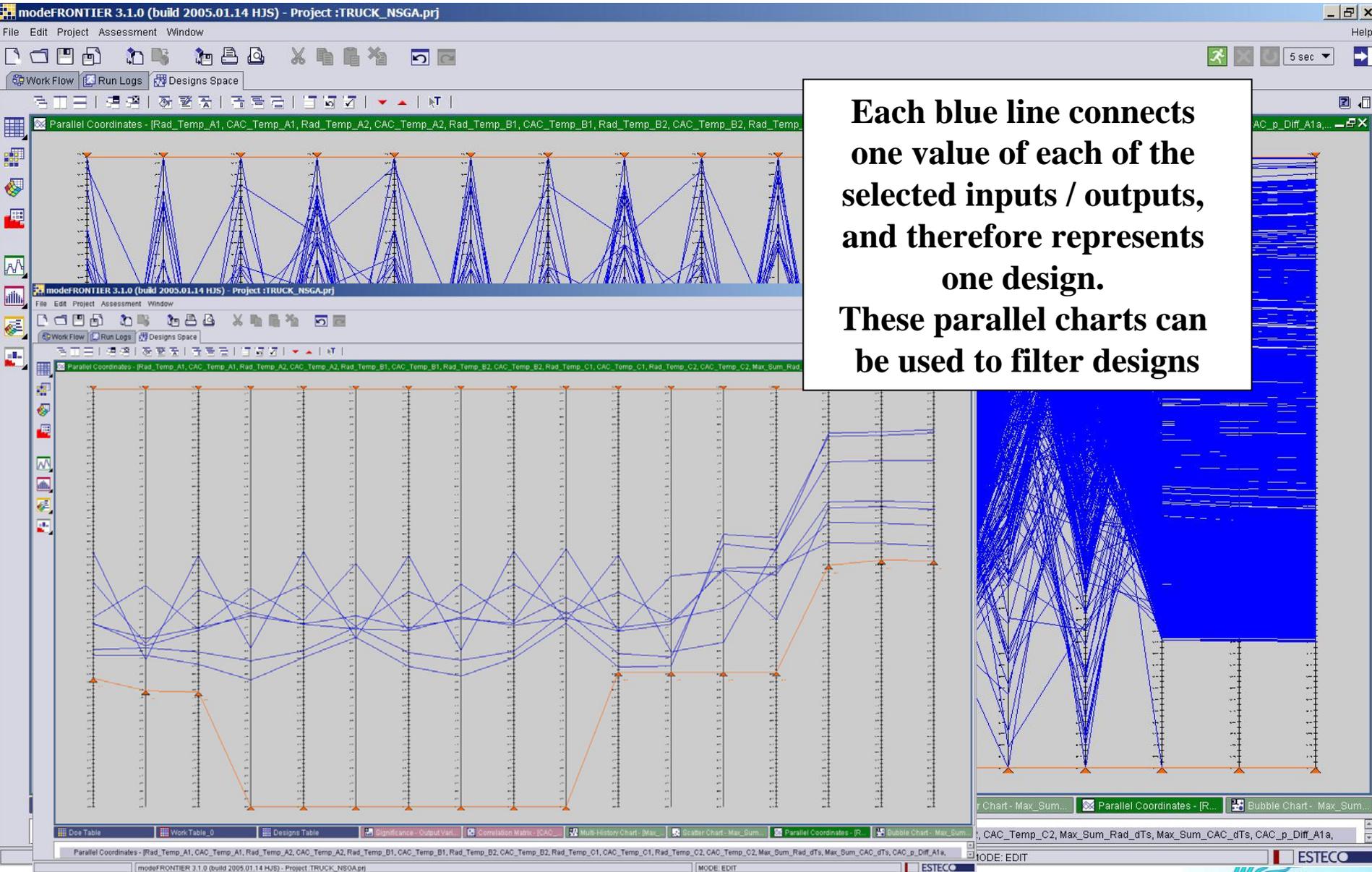
modeFRONTIER 3.1.0 (build 2005.01.14 HJS) - Project:TRUCK_NSGA.prj

MODE: EDIT

ESTECO



Postprocessing - Parallel Charts

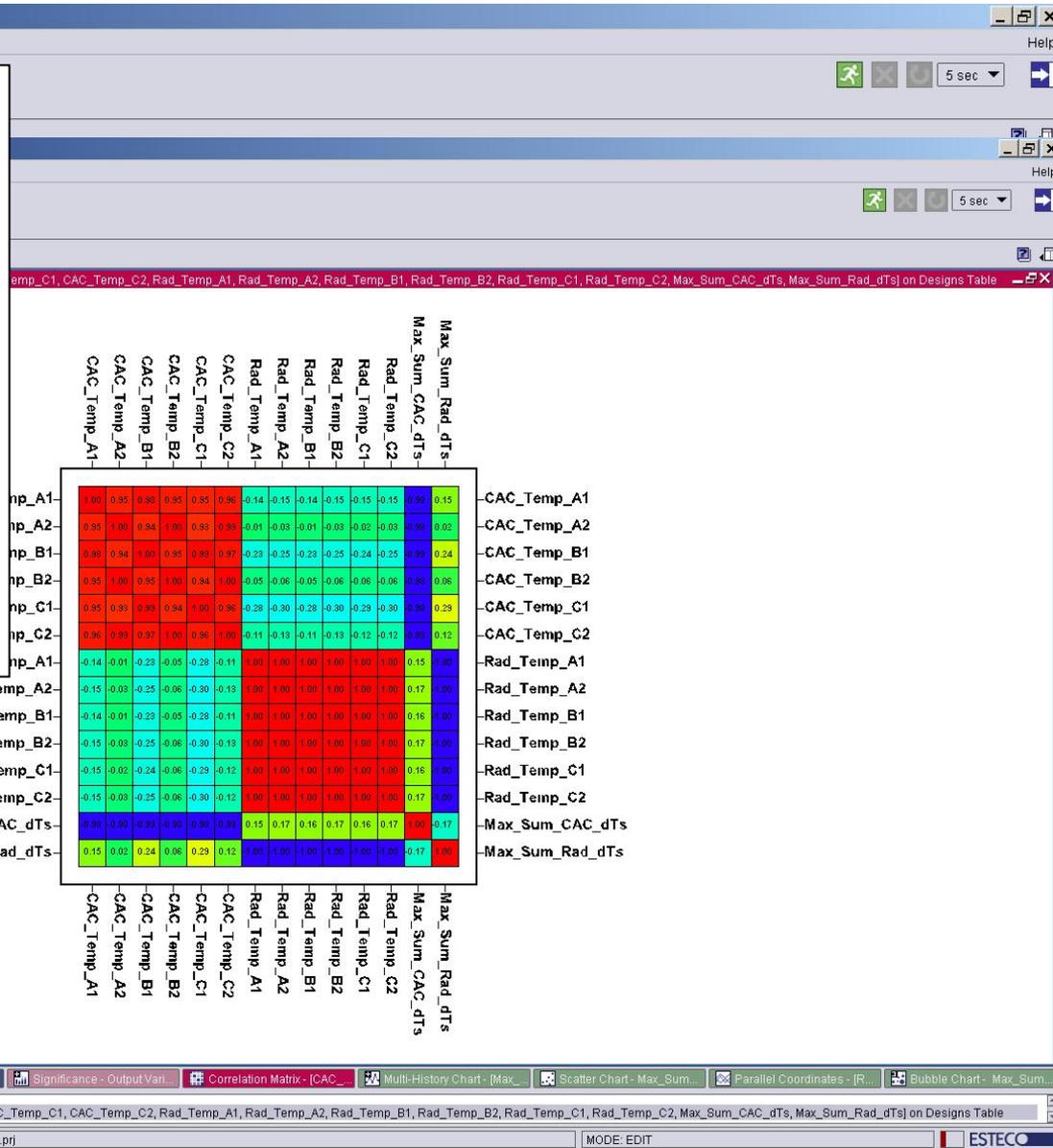




Postprocessing – Correlation Matrix

The Correlation Matrix is extremely useful for determining the extent to which inputs or outputs are correlated. If, for example, we have 8 objectives, and we see that 2 of them are strongly correlated to each other, we can get rid of one, reducing the problem to one of 7 objectives. Similarly, strong correlation between any pair of inputs would allow the elimination of some inputs.

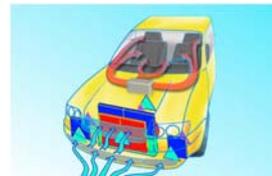
Obviously, the fewer Objectives and inputs we have, the more efficient will be the optimization





General Remarks

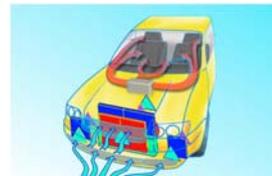
- The engine studied biased heat rejection to the radiator. modeFrontier recognized this and developed a stacked system that balanced the cores to the engine.
- Generally, at the completion of the optimization process, the engineer / designer is presented with several Pareto Frontiers (Trade-Off Curves) – one for every set of 2 objectives.
- In this case there was only a single Pareto Frontier (as we only had 2 objectives), and the optimal point was easy to select





General Remarks (contd)

- The choice of one design over another is usually associated with an improvement in at least one of the goals at the expense of at least one of the others. This is the trade-off.
- Once a design has been chosen, a robust design analysis can be performed (using the MORDO module in modeFrontier) to ensure that the performance does not deteriorate rapidly in the case where there are small changes in input parameters, operating conditions, etc.





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