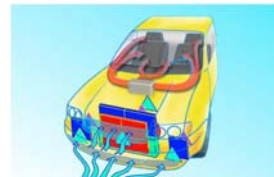




MultiObjective Optimization in Commercial Vehicle Cooling Layout

Using Genetic Algorithms to Improve
Engine Cooling Performance

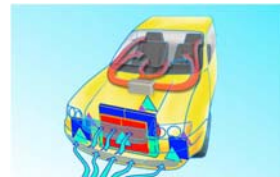
Nader Fateh
Esteco North America





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)

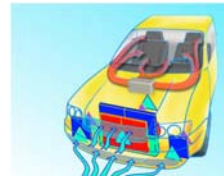




Optimization

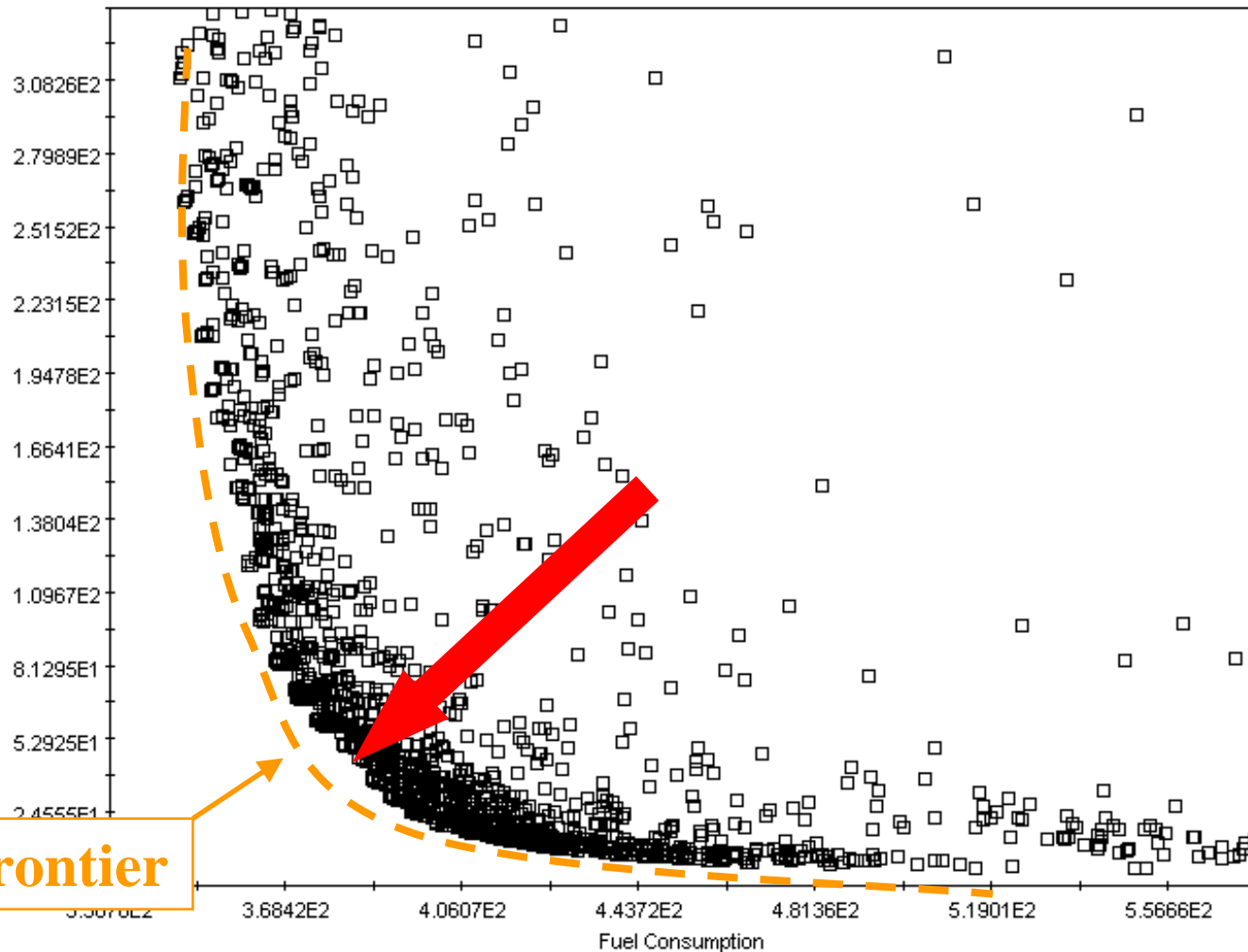
Single-objective vs Multi-objective

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



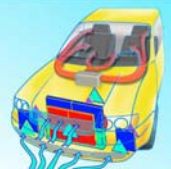
Pareto Frontier (Trade-Off Curve)

NOX



Pareto Frontier

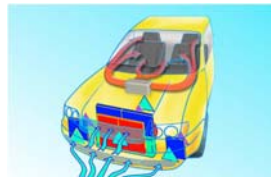
Fuel Consumption





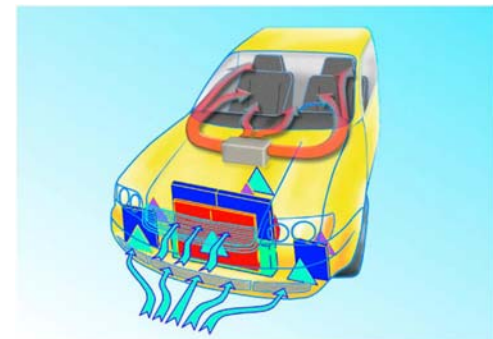
Genetic Algorithms

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

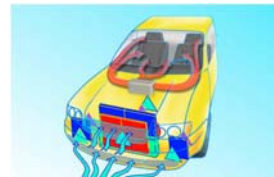


KULI 5.2



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

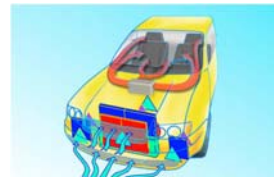
- **KULI** can be run through Excel, using VB macros and COM objects
- **modeFRONTIER** has a direct interface to Excel, so that it can directly enter the input parameters into the Excel file, run macros, and extract the output data
- Not all variables can be modified through the COM objects - **modeFRONTIER**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





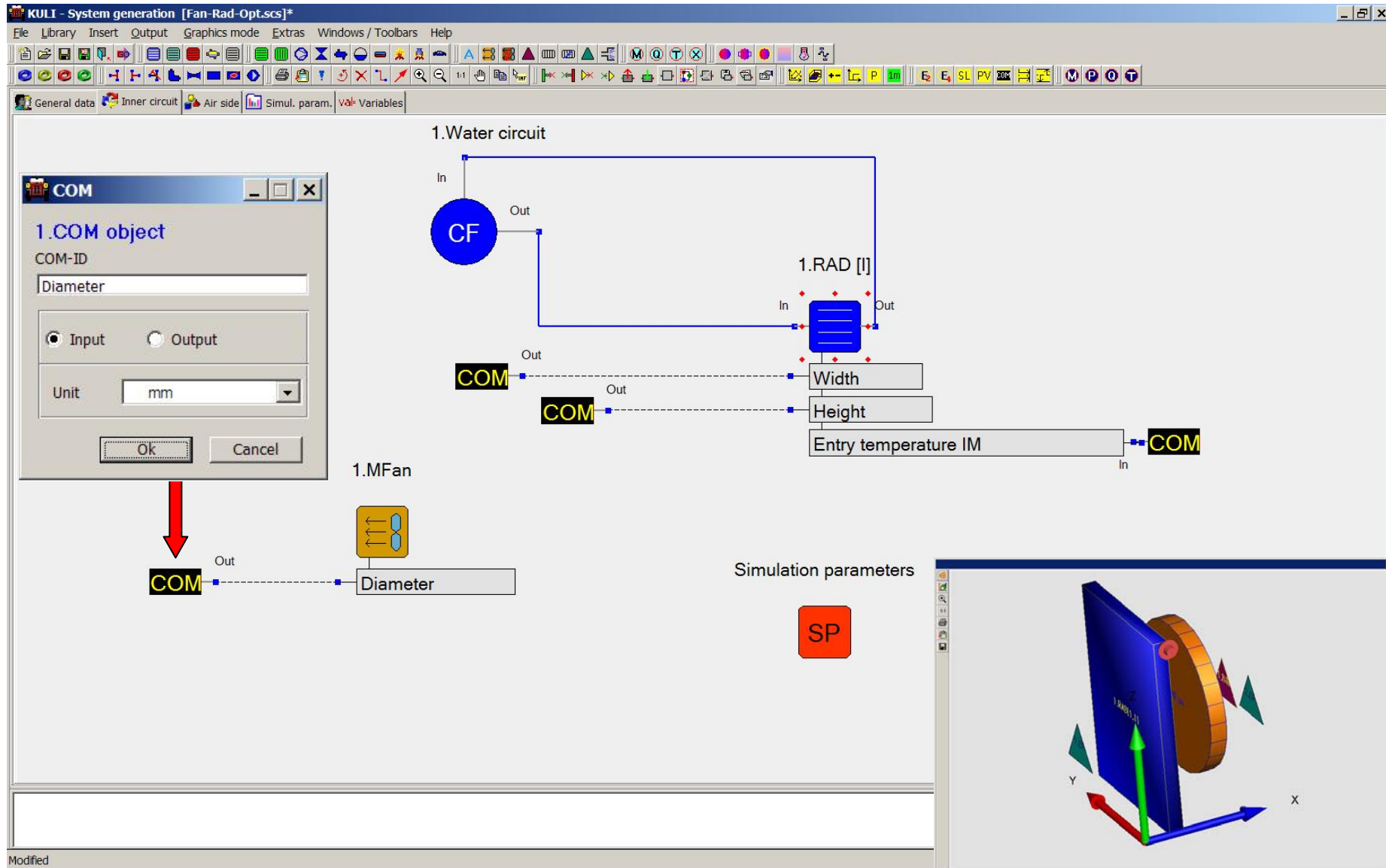
Coupling **modeFRONTIER** and **KULI** through Excel

- 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 - Excel File

Microsoft Excel - Fan-Rad-Opt.xls

File Edit View Insert Format Tools Data Window Help Adobe PDF

Type a question for help

F40

	A	B	C	D	E	F	G	H	I	J	K	L
1	Example Fan Radiator Optimization											
2	Location of KULI File:											
3	Ambient Temperature °C	20				Path:	C:\Work\Kuli\NF-Fan-Rad-Opt					
4	Relative Humidity %	50				File:	Fan-Rad-Opt.scs					
5												
6	Fan Diameter	Radiator Width	Radiator Height	Radiator Entry Temp IM °C								
7												
8	600	600	800									
9												
10												
11												
12												
13												
14												
15												
16												
17												
18												
19												
20												
21												
22												
23												
24												
25												
26												
27												
28												
29												
30												

Location of **KULI** File to be run

Name of **KULI** File to be run

Output Value: This will be calculated by **KULI** and fed to **modeFRONTIER**

Input Values: These will be set by **modeFRONTIER**

KULI / Sheet2 / Sheet3

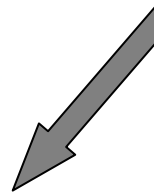
Ready



KULI - Excel VB Macro

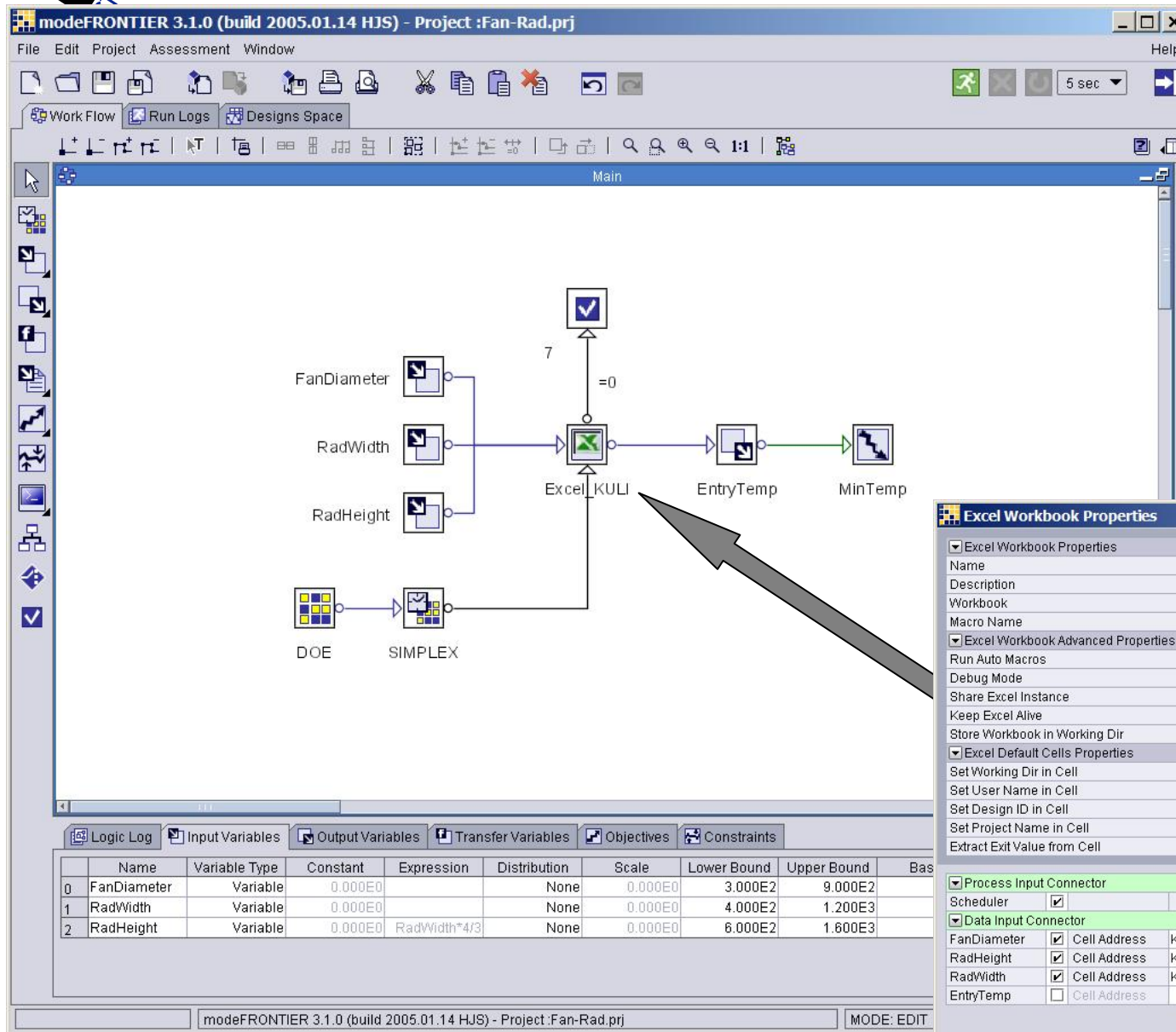
```
Sub KULIIF()  
    Dim calcOK As Boolean  
    Dim folder As String  
    Dim fileKULI As String  
    Dim Temp  
  
    'Getrennte Eingabe von Ordner und filename  
  
    folder = Cells(3, 8)  
    If Right(folder, 1) = "\" Or Right(folder, 1) = "/" Then folder = Left$(folder, Len(folder) - 1)  
    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

Edit Workbook

Interactive Selection

Excel Workbook Properties

Name Excel_KULI

Description

Workbook C:\Work\KULI\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 dialog box is titled "Excel Workbook Properties". It contains two main sections: "Excel Workbook Properties" and "Excel Workbook Advanced 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: ☒ Cell Address: KULI!A8
- RadHeight: ☒ Cell Address: KULI!B8
- RadWidth: ☒ Cell Address: KULI!C8
- EntryTemp: ☐ Cell Address:

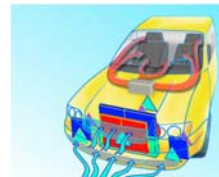
Process Output Connector:

- EndOK7: ☒ Condition: =0
- Data Output Connector:
- EntryTemp: ☒ Cell Address: KULI!D8

Buttons: OK, Preview, Cancel, Help

Annotations:

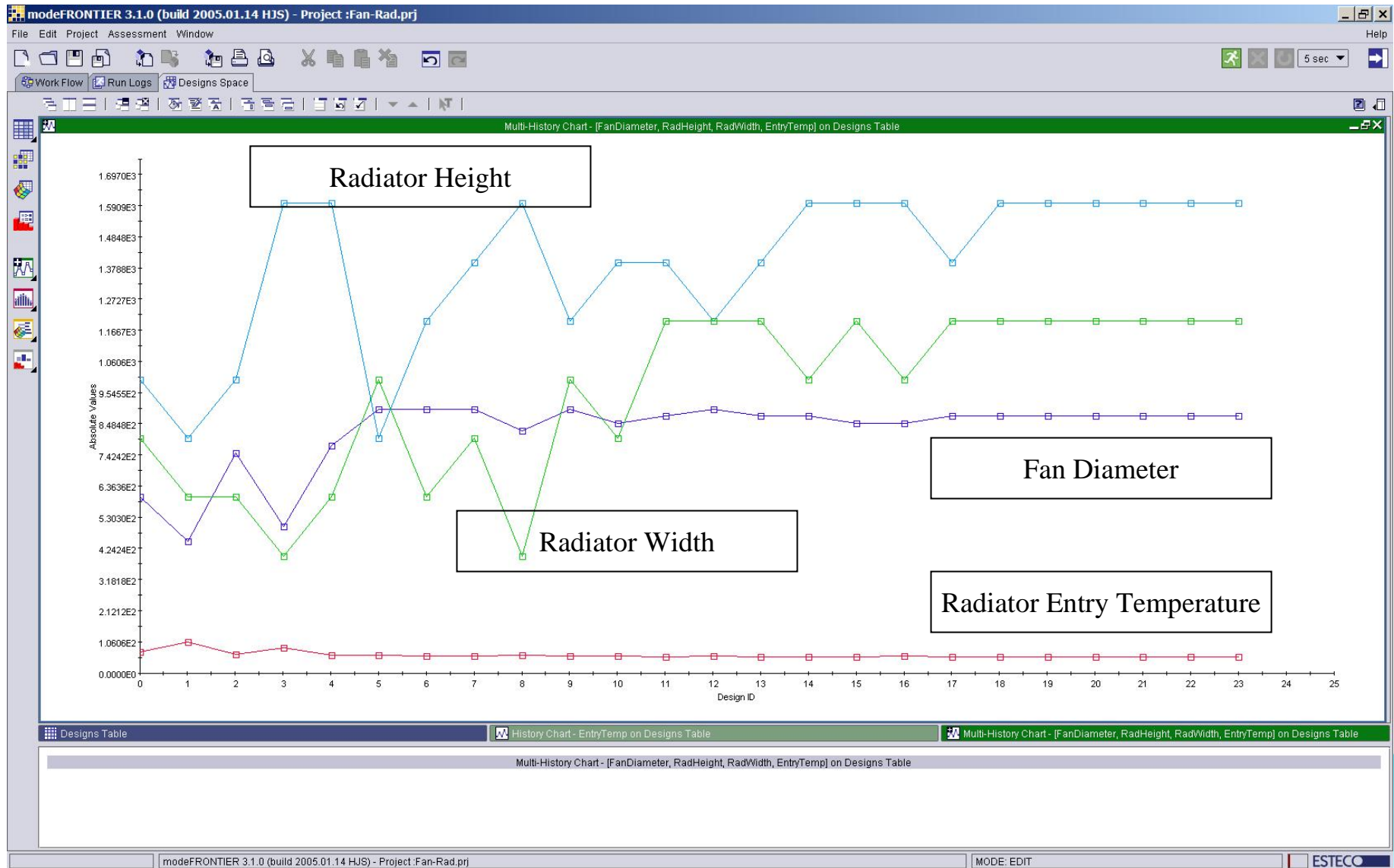
- A red circle highlights the Name, Description, Workbook, and Macro Name fields. An arrow points to a text box: "Name of Excel file".
- A red circle highlights the Data Input Connector section. An arrow points to a text box: "modeFRONTIER sets the values for the variables in the Excel worksheet".
- A red circle highlights the Data Output Connector section. An arrow points to a text box: "modeFRONTIER extracts the value of the output parameter".





modeFRONTIER

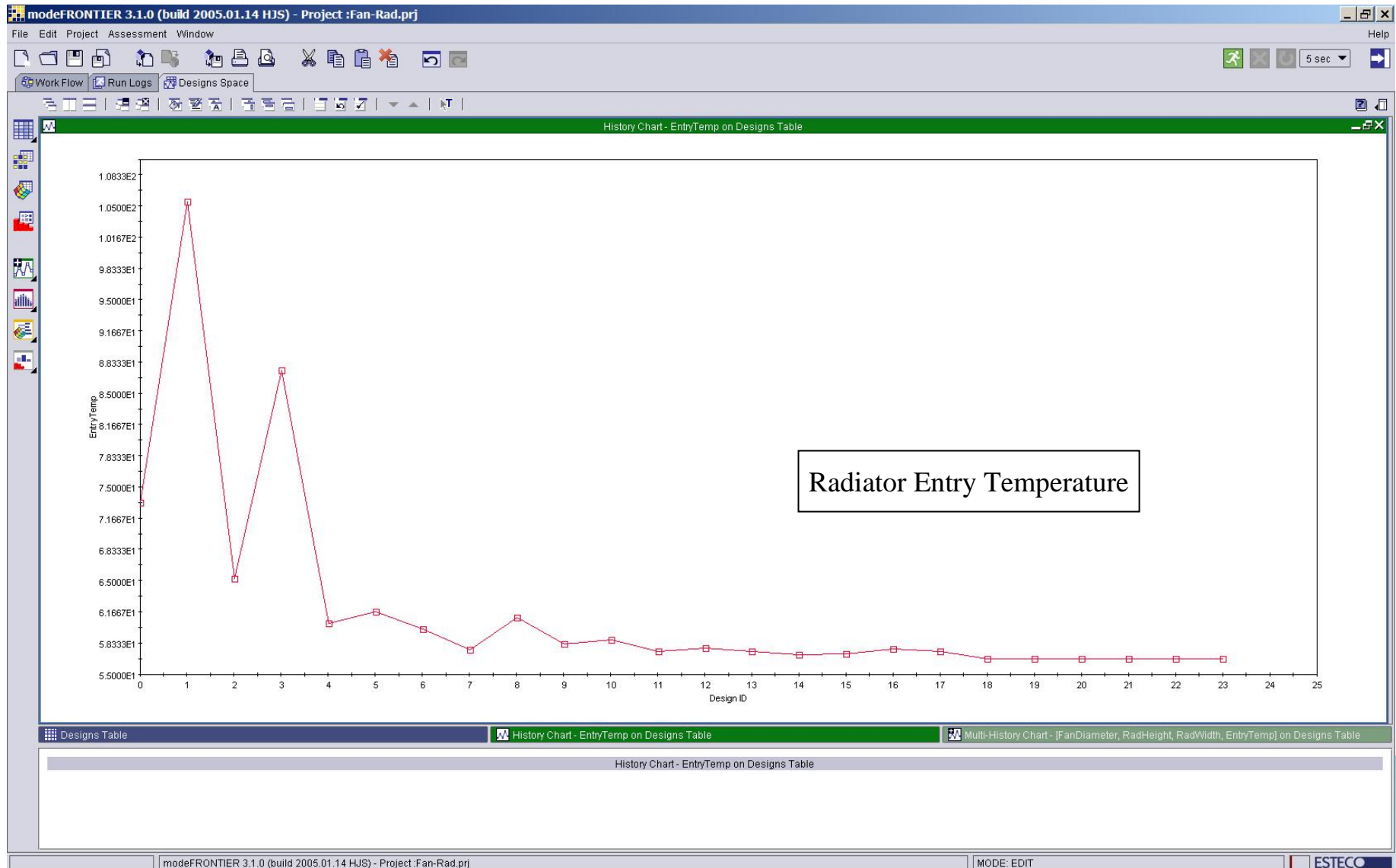
Solution Development





modeFRONTIER

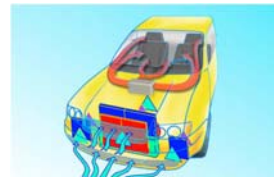
Radiator Entry Temperature





The TRUCK Model

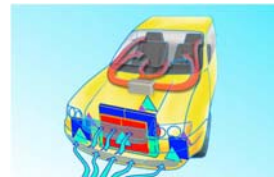
- Given three engine ratings, with 2 operating points (peak power and peak torque) each, the goal was to maximize cooling capacity of a heat exchanger package which would pass all 6 cases.
- For each case, there was a maximum allowable Radiator Exit Temperature, and CAC Entry Temperature, given by the 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**:

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

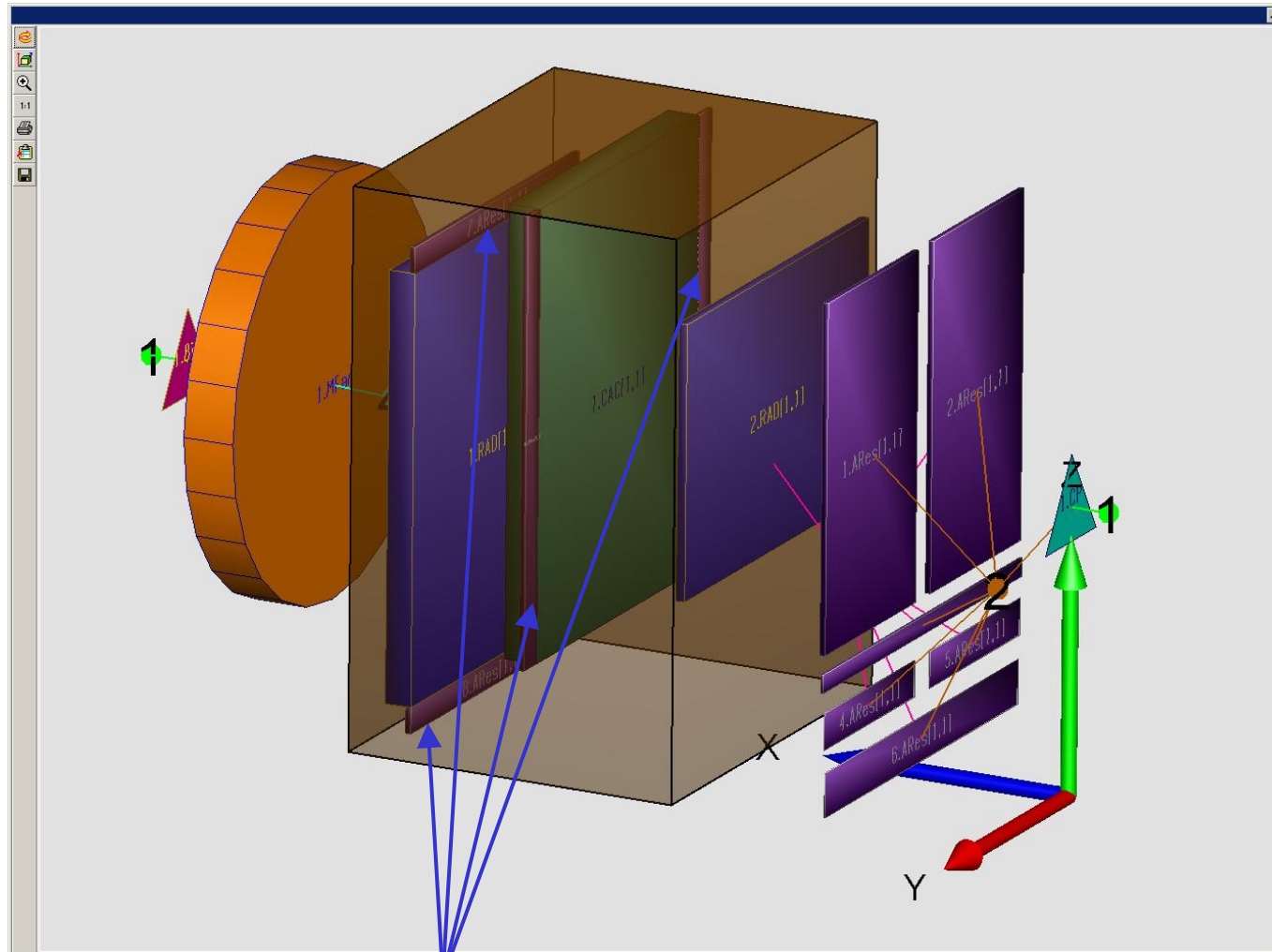
$$T_{CAC_{tot}} = \sum_{n=1}^6 (T_{CAC_{nmax}} - T_{CAC_n})$$

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

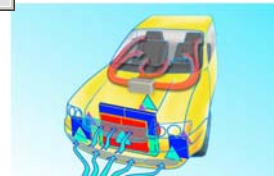
- Two objectives were defined: to maximize each of $T_{R_{tot}}$ and $T_{CAC_{tot}}$



KULI Model



Tank Blockages

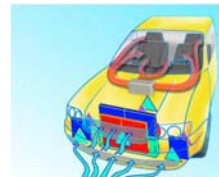




Optimization Parameters

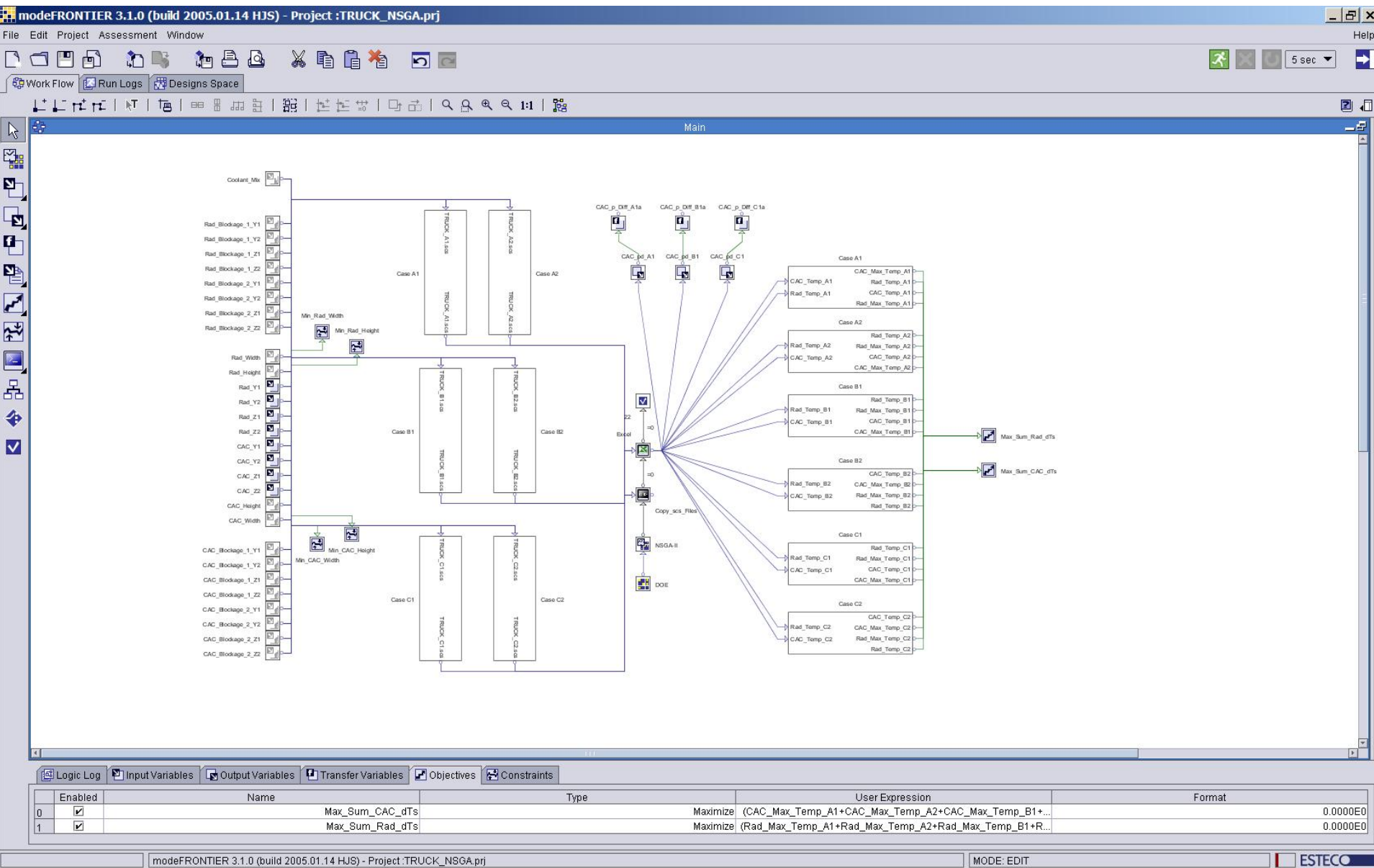
8 Independent Variables:

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 - Input Subsystem

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

File Edit Project Assessment Window

Work Flow Run Logs Designs Space

Constants

Rad_mf_A1 Rad_p_A1 Rad_Heat_A1 Control_Temp_A1

RPM_A1

Amb_Temp_A1

RAM_Air_A1

TRUCK_A1.scs

CAC_mf_A1 CAC_p_A1 CAC_T_A1

Input Variable Properties

☒ Input Variable Properties

Name	RPM_A1
Description	
Format	0.0000E0
Variable Type	Constant
Value	0.0

☒ MORDO Properties

Distribution	None	Empty	Empty
--------------	------	-------	-------

☒ Data Output Connector

TRUCK_A1.scs	<input checked="" type="checkbox"/>		
--------------	-------------------------------------	--	--

OK Preview Cancel Help

Connection to .scs File

Connection to Rest of System

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



Integration:

modeFRONTIER modifies the .scs file

Template Input Editor

File Edit

Latin OS Dependent Term.

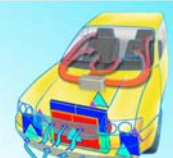
```
661 BEMERKUNG = 'Radiator Tank Blockage'
662 KOMP_POS_X = 150
663 KOMP_POS_Y = <VAR name="Rad_Blockage_1_Y1" format="0.0000E0"/>
664 KOMP_POS_Z = <VAR name="Rad_Blockage_1_Z1" format="0.0000E0"/>
665 $ -----
666 (SYS_KOMP_FW)
667 AKT_BREITE = 50
668 AKT_HOEHE = <VAR name="CAC_Height" format="0.0000E0"/>
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_LK)
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 DURCHSTROMUNG = 'GEG_Y_RICHTG'
688 EINTRITT_POS = 'RECHTS_OBEN'
689 VERSCHMUTZUNGSGRAD = 0
690 OPTIMIERUNG_BREITE = '4Y'
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 $ -----
```

... and marks the position in the .scs file where it is to be inserted

Row: 518 Col: 33 Len: 105814

	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_Y2	1

User selects variable from list ...





Integration Excel File Interface

Microsoft Excel - PACCAR_R_6.xls

Type a question for help

A3

	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\KUL\TRUCK	TRUCK_A1.scs		
5	Case A2:	0	0	0	C:\Work\Frontier\KUL\TRUCK	TRUCK_A2.scs		
6	Case B1:	0	0	0	C:\Work\Frontier\KUL\TRUCK	TRUCK_B1.scs		
7	Case B2:	0	0	0	C:\Work\Frontier\KUL\TRUCK	TRUCK_B2.scs		
8	Case C1:	0	0	0	C:\Work\Frontier\KUL\TRUCK	TRUCK_C1.scs		
9	Case C2:	0	0	0	C:\Work\Frontier\KUL\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

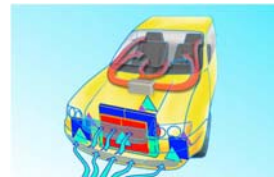


Integration

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

Work Flow Run Logs Designs Space

Case A1

Rad_Max_Temp_A1

Rad_Temp_A1

CAC_Temp_A1

CAC_Max_Temp_A1

Connection to Rest of System

Maximum Allowable Temperatures (Constants)

Values Calculated by KULI

Logic Log

Input Variables

Output Variables

Transfer Variables

Objectives

Constraints

	Enabled	Name	Type	User Expression	Format
0	<input checked="" type="checkbox"/>	Max_Sum_CAC_dTs	Maximize	(CAC_Max_Temp_A1+CAC_Max_Temp_A2+CAC_Max_Temp_B1+...	0.0000E0
1	<input checked="" type="checkbox"/>	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

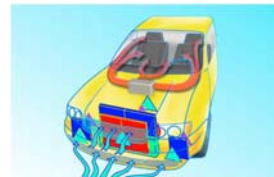
MODE: EDIT

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

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

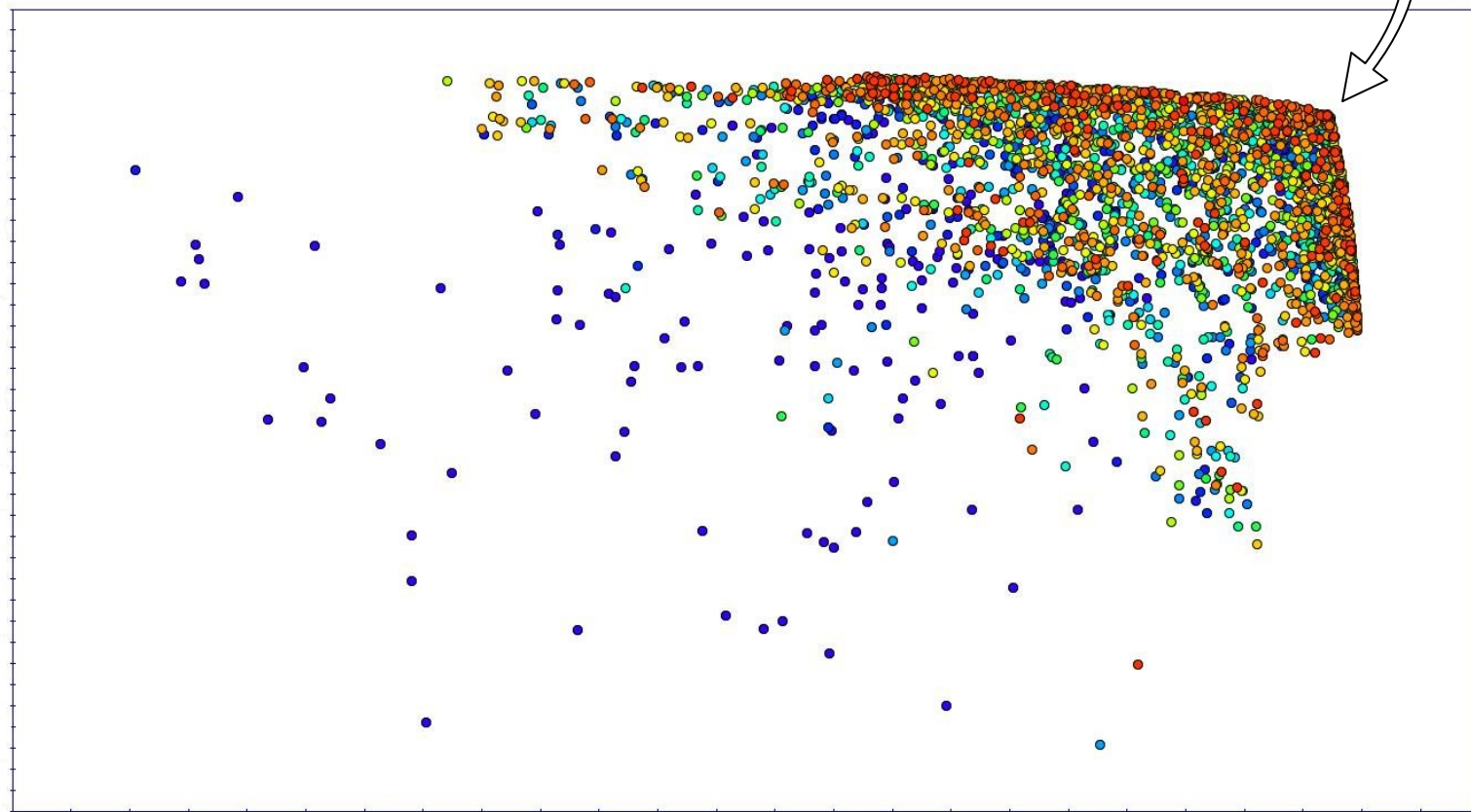
File Edit Project Assessment Window

Work Flow Run Logs Designs Space

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

Optimum Point

TRtot



TCACtot

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

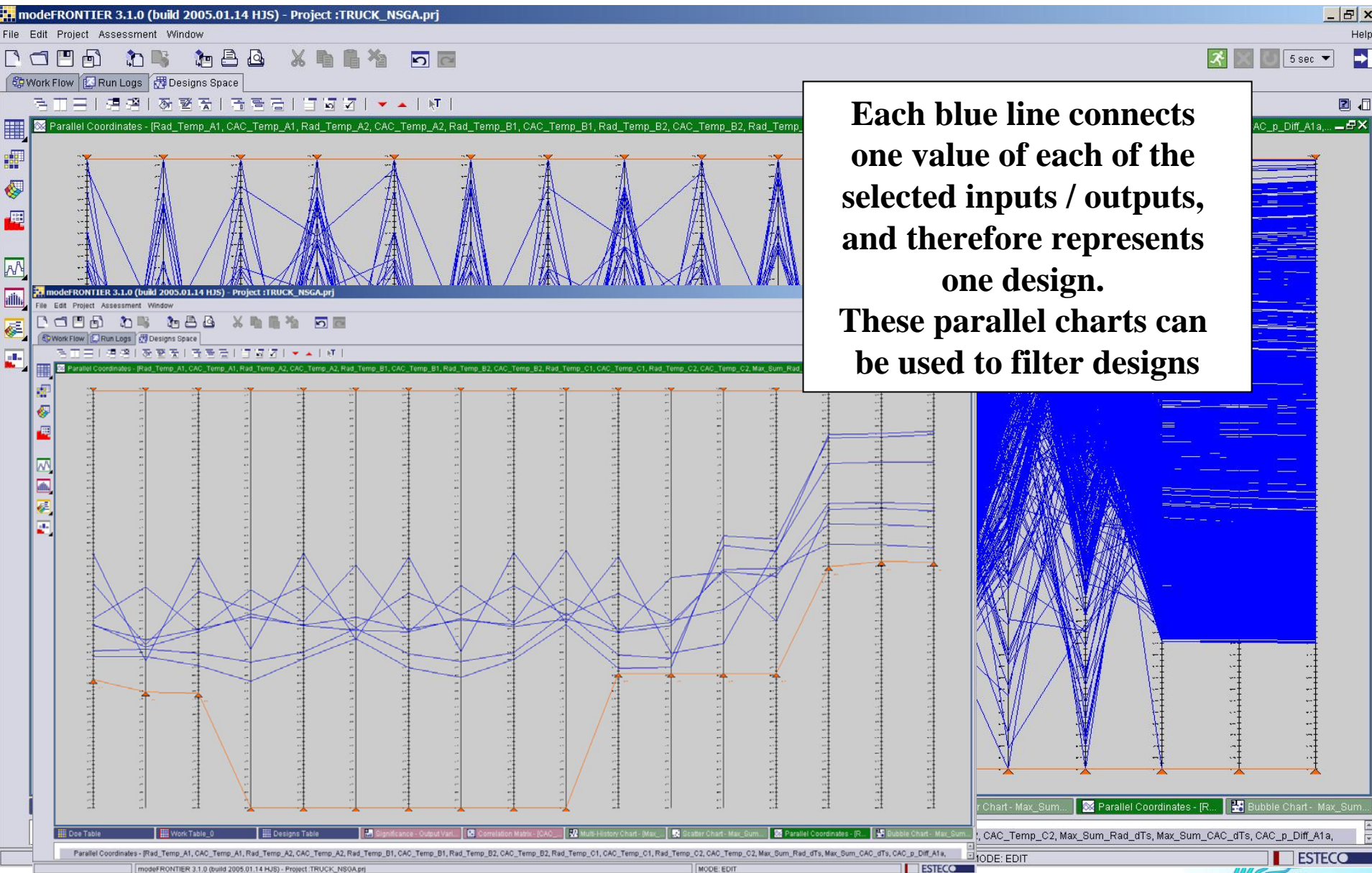
modeFRONTIER 3.1.0 (build 2005.01.14 HJS) - Project :TRUCK_NSGA.prj

MODE: EDIT

ESTECO



Postprocessing - Parallel Charts

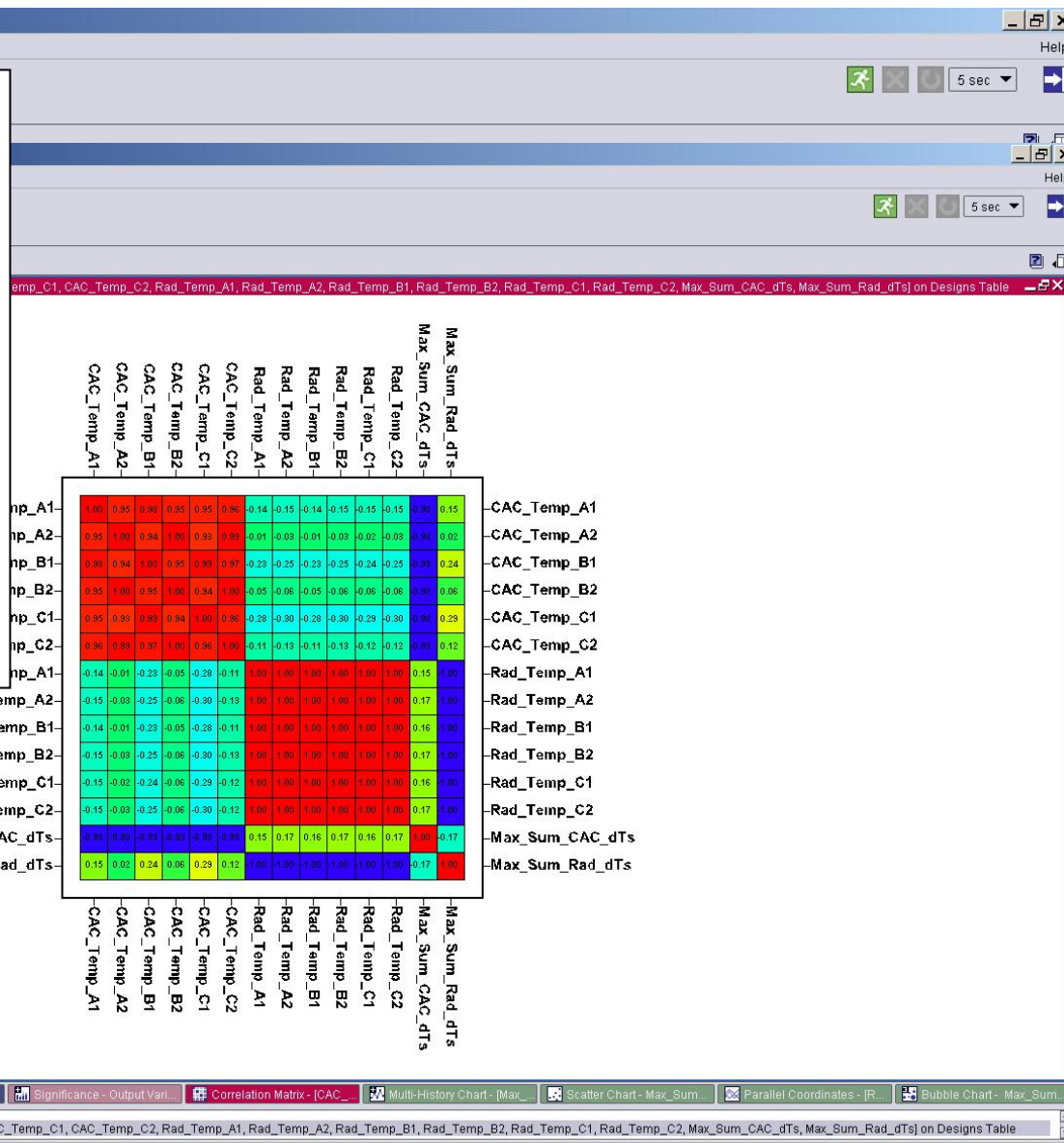
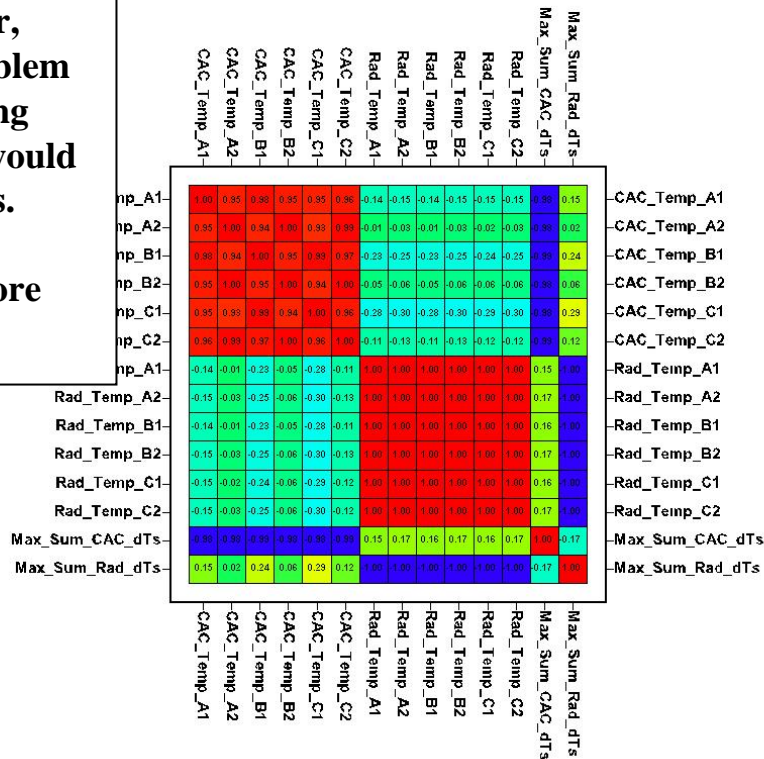




Postprocessing – Correlation Matrix

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.

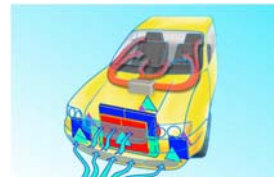
Obviously, the fewer Objectives and inputs we have, the more efficient will be the optimization





General Remarks

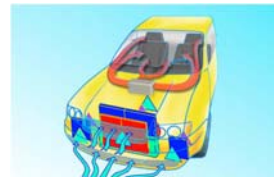
- The engine studied biased heat rejection to the radiator. modeFrontier recognized this and developed a stacked system that balanced the cores to the engine.
- Generally, at the completion of the optimization process, the engineer / designer is presented with several Pareto Frontiers (Trade-Off Curves) – 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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