Optimization of a Main Engine Driven Roof Top Bus Air-Conditioning System

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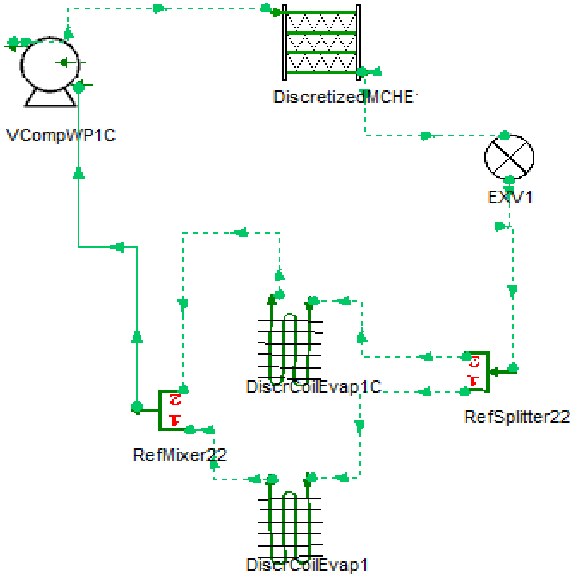
Introduction

- The use of Bus air-conditioning (AC) system has been steadily growing in the emerging markets.
    - The Indian bus market is around 40,000 units a year. (expected to double in a decade), making it the second largest behind China.
    - Only 2% of these are Air conditioned.
- AC system is the second biggest energy consumer in a bus.
- In the Emerging markets, In addition to fuel efficiency, there is even more emphasis on the <u>product cost.</u>
- Thus, there is a need to develop an affordable and efficient bus AC system featured by low product cost, economical operation and stable passenger thermal comfort.
- This leads to a thermoeconomic optimization exercise, taking into account the compromise between an economical system size and efficient refrigeration.

System Components & Variables



Compressor :

- A variable speed open type reciprocating compressor
- RPM to represent volumetric displacements.

HX Coils :

most of the parameters (except size) are imposed on the design engineer by established manufacturing practices, e.g., heat transfer surfaces or tube definition.

- Condenser : A microchannel Brazed Al Coil
- Evaporator : copper tube and aluminum fin coil

Other system component :

TXV, liquid receiver, filter-dryer and piping network, which are not significantly affected by the variation of the design parameters and hence not considered in the optimization.

An in-house refrigeration system balancing tool is used to simulate the steady state performance of the AC system.

- Each component model is represented using a set of nonlinear equations
- The set of nonlinear multi-equations are solved simultaneously for output variables

Design Variables

Variable			
Compressor RPM	2000	2250	2500
Condenser Face length(m)	1.2	1.4	1.6
Condenser tube width (mm)	25.4	18	
Evaporator Face length(m)	1.2	1.5	1.8
Evaporator Tube OD (mm)	7	8	
Evaporator Fin pitch (FPI)	12.7	14	
Refrigerants	R134a	R407C	

Approximations for Optimization

Detailed simulation models are typically complex and computationally demanding. Response surface based metamodels for objective functions were used to save computational effort.

Response Surface Methodology provides a formalized approach to global space approximations

The response surface is an approximate relationship between the response (objective and constraint functions) and the design variables.

$$f(\mathbf{x}) = \hat{f}(\mathbf{x}) + \varepsilon$$

RSM

Experiment Design (DOE)

- Experimental Design tell which alternatives to simulate so that the desired information is obtained with the least amount of simulation
- Conduct Experiments using the Simulation Tool for the variables “off-line” from the optimization.
- Several “experimental designs” available using different orthogonal array properties
- Full Factorial Design is used here (216 runs for each refrigerant)

Quadratic Response Surface

$$\hat{f}(\mathbf{x}) = a_0 + \sum_{i=1}^{n} a_i x_i + \sum_{i=1}^{n}\sum_{j=i}^{n} a_{ij} x_i x_j$$

- Quadratic fit includes intercept (zero-order), first-order, and second-order terms
- There are $(n+1)(n+2)/2$ coefficients (a_0, a_i, a_{ij}) that must be computed

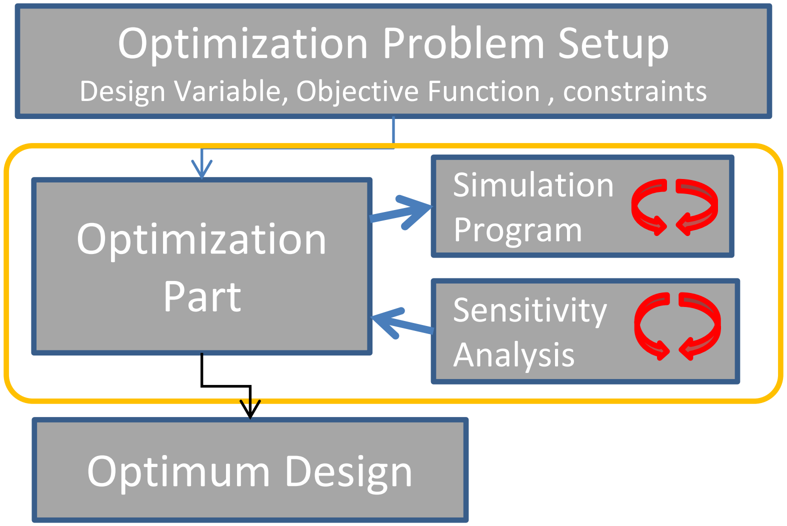
Response Surface Coefficients

- Once a response surface model (here, a quadratic equation) is chosen, coefficients must be determined (a_0, a_i, a_{ij} are unknown)

Use regression to find coefficients (Least squares solution)

Optimization Method

Conventional Optimization



Optimization Problem Setup
Design Variable, Objective Function , constraints

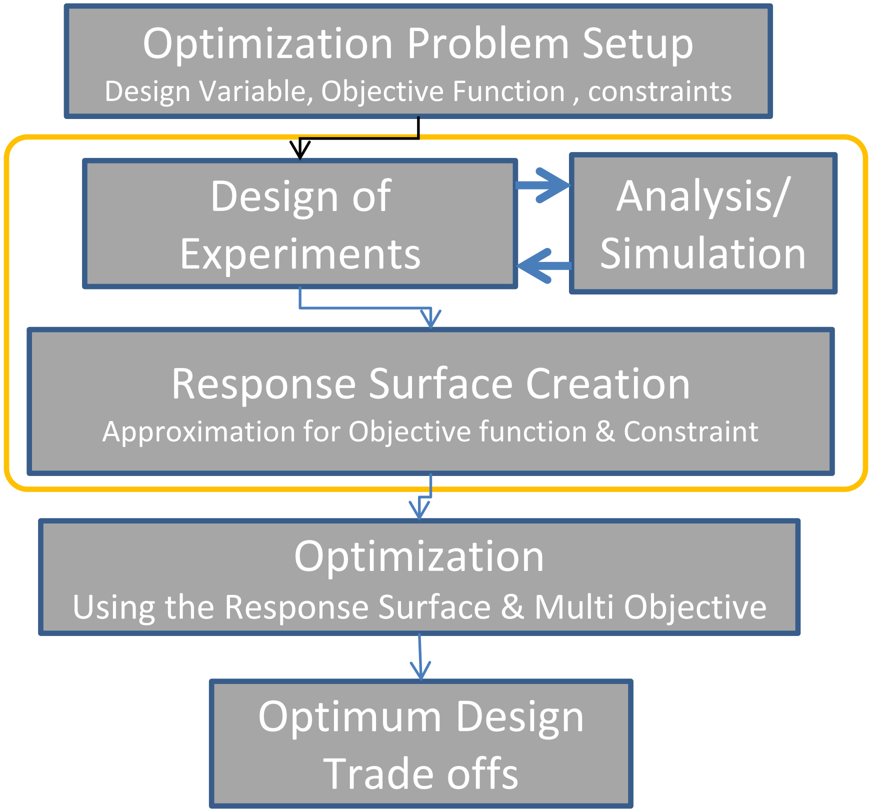
Optimization Part

Simulation Program

Sensitivity Analysis

Optimum Design

Response Surface based Optimization



Optimization Problem Setup
Design Variable, Objective Function , constraints

Design of Experiments

Analysis/ Simulation

Response Surface Creation
Approximation for Objective function & Constraint

Optimization
Using the Response Surface & Multi Objective

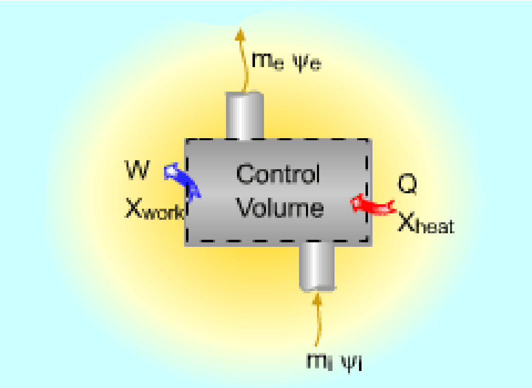
Optimum Design
Trade offs

Multi Objective Criterion

- In Real Life optimization, We may consider one or more of criteria as the objective function.
- Example :
  - By Considering thermodynamic criterion, the system will be an ideal system from thermodynamic point of view, but it might not be able to pass the economic criterion.
  - By considering only the economic criterion, the system will be the cheapest one, but this system might not be a well designed system from thermodynamic points of view .
  - Both of these systems are not acceptable
- The goal. Is to have a system that satisfies all of the optimization criteria as much as possible simultaneously. This can be obtained by multi-objective optimization techniques

- In this paper thermoeconomic criteria for multi-objective optimization is considered
  - the second law criterion (the total exergy destruction of the system) is considered as the thermodynamic objective function.
  - The economic objective function is the total product cost of the system.

Exergy loss as Thermodynamic Criteria



$$Ex_{\,in} - Ex_{\,Out} + Ex_{\,Q} + Ex_{\,w} = Ex_{\,des}$$

Where,

$Ex_{\,des}$: total Exergy destruction

$Ex_{\,Q}$: Exergy flow due to heat transfer.

Ex_w :Exergy associated with the work interaction.

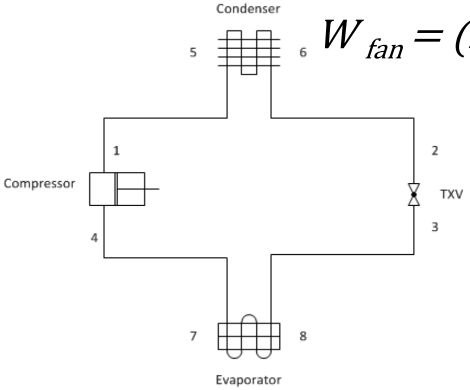
$Ex_{\,in}$ and $Ex_{\,Out}$ are the exergies of the inlet and outlet streams

$$Ex_{\,des\ Cond} = m_{\,r}\,(ex_2 - ex_3) + m_{\,air\ Cond}\,(ex_{\,air\ in} - ex_{\,air\ out}) + W_{\,fan}$$

$$W_{\,fan} = (\Delta P\ \ m_{\,air\ Cond}) / (\rho_{\,air}\,\eta_{\,stat})$$

$$W_{\,Comp} = m_{\,r}\,(\,h_{2\_isen} - h_1)/\eta_{\,isen}$$

$$Ex_{\,des\ Comp} = m_{\,r}\,(ex_1 - ex_2) + W_{\,Comp}$$



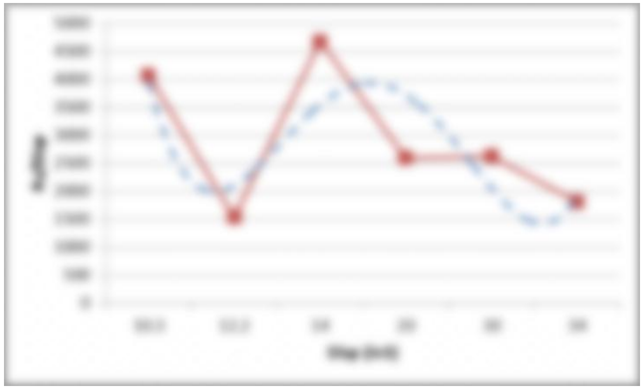
$$Ex_{\,des\ TXV} = m_r\,(ex_3 - ex_4)$$

$$Ex_{\,des\ evap} = m_{\,r}\,(ex_4 - ex_1) + m_{\,air\ evap}\,(ex_{\,air\ in} - ex_{\,air\ out}) + W_{\,fan}$$

$$W_{\,fan} = (\Delta P\ \ m_{\,air\ evap}) / \rho_{\,air}$$

Exergy relations are developed based on the book by Ibrahim Dincer and Marc A Rosen (2009)

Component Cost Functions



Evaporator Cost:

- Cu Tube & Al Fin coil
- Function of Cu & Al LME

Condenser Cost:

- Microchannel Brazed Aluminum Coil
- Function of Al LME

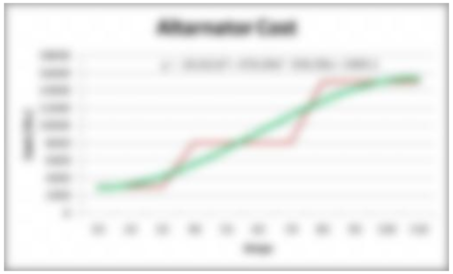
Compressor cost:

- determined according to the equation suggested by Wall (1991)
- $C_1 = a_1 k_1 \frac{V_2}{0.9 - \eta_1} \frac{p_3}{p_2} \ln \frac{p_3}{p_2}$

a_1 , the annuity factor

k_1 , Compressor cost per volumetric rate (based on internal cost information)

η_1 , isentropic efficiency (obtained from the experimental data)



Fans and blowers cost :

- based on a cost factor as a function of airflow

Alternator Cost:

- Based on a cost factor based on power

Objective Functions & Constraints

Objective Functions

$$J_{Thermodynamic} = Ex_{\,des\ Total}$$

$$J_{Product\ cost} = C_{Comp} + C_{Cond} + C_{Evap} + C_{evap\ Blower} + C_{cond\ Fan} + C_{alternator}$$

Constraints

g_1 : Discharge pressure < Max discharge pressure

g_2 : COP $_{Min}$, (based on internal product development standard)

g_3 : Condensing temp > Ambient temp + ΔT

g_4 : Evaporating Temp < Inlet Air Temp – ΔT

g_5 : COP > COP $_{Carnot}$

g_6 : Evaporator PD$_{ref}$ < Evaporator PD$_{Allowable}$

g_7 : Condenser PD$_{ref}$ < Condenser PD$_{Allowable}$

g_8 : Evaporating temp < inlet air dew point temp

Addl Constraints :

All costs are non-negative

All exergy terms are non-negative.

The target cooling capacity (defined as a nonlinear equality constraint) .

Goal Programing

Weighted Sum Approach

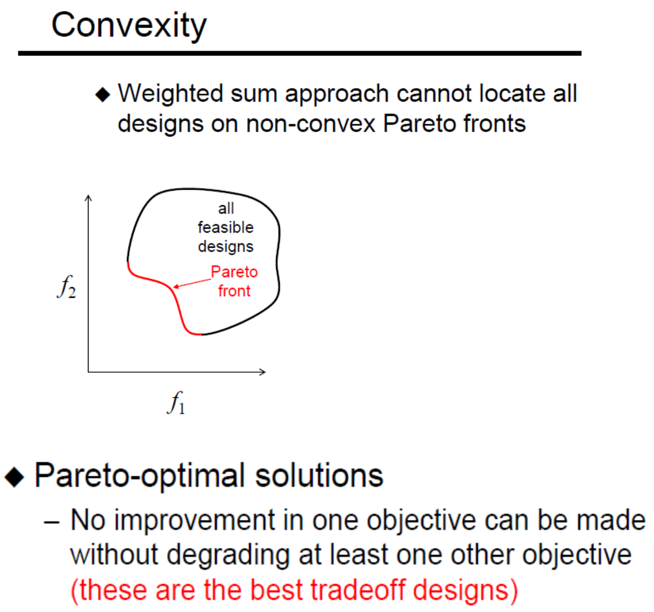
$$\text{minimize} \quad \Phi(\mathbf{x}) = a_1\phi_1(\mathbf{x}) + a_2\phi_2(\mathbf{x}) + \cdots + a_{n_{obj}}\phi_{n_{obj}}(\mathbf{x})$$

$$\text{subject to} \quad g_j(\mathbf{x}) \le 0 \quad j = 1, m$$

$$h_k(\mathbf{x}) = 0 \quad k = 1, l$$

$$x_i^L \le x_i \le x_i^U \quad i = 1, n$$

- Weights are not known apriori
- Issue with Convexity



Convexity

◆ Weighted sum approach cannot locate all designs on non-convex Pareto fronts

◆ Pareto-optimal solutions

– No improvement in one objective can be made without degrading at least one other objective (these are the best tradeoff designs)

Goal Programming

Basic Idea:

Instead of optimizing a single valued objective function, try to meet a number of pre–specified goals

How do you handle the goals?

- Determine a set of “ideal” goals.
- Determine a metric in the goal space to measure the distance to the ideal goal.
- Minimize the distance to the “ideal” goal.

$$\begin{array}{ll} \text{minimize} & \gamma \\ \text{subject to} & f_l(\mathbf{x}) - w_l\,\gamma \le f_l^G \qquad l = 1, n_{obj} \\ & g_j(\mathbf{x}) \le 0 \\ & h_k(\mathbf{x}) = 0 \\ & x_i^L \le x_i \le x_i^U \end{array} \qquad \mathbf{x} = \left\{ \begin{array}{c} x_1 \\ x_2 \\ \vdots \\ x_n \\ \gamma \end{array} \right\}$$

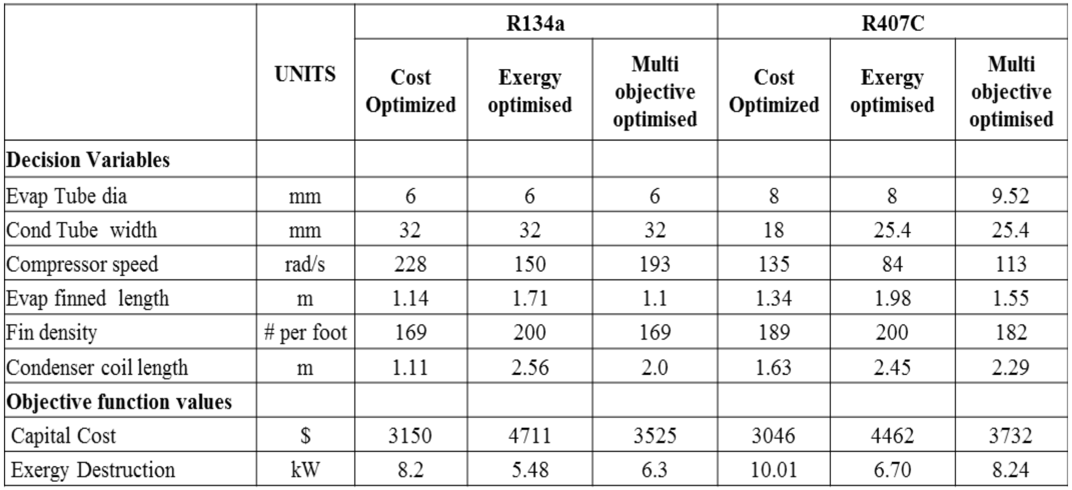
Tool

- Used in-house System simulation tool to develop the meta data
- Developed Optimization program in Matlab (Decoupled to the System simulation tool)
  - » Can be used to get the (Lite) performance characteristics of the system
  - » Can do “What – if” for Application (Specialty orders)
  - » Can give a single objective & Multi objective optimizes designs for a wide Capacity Ranges.
  - » Can generate Trade offs (through Pareto frontier)
  - » Reduce the Product development cycle

Results & Discussion

Three optimization scenarios are considered

- single-objective thermodynamic optimized,
- single-objective economic optimized, and
- multi-objective optimized.



	UNITS	R134a			R407C		
		Cost Optimized	**Exergy optimised**	**Multi objective optimised**	**Cost Optimized**	**Exergy optimised**	**Multi objective optimised**
Decision Variables							
Evap Tube dia	mm	6	6	6	8	8	9.52
Cond Tube width	mm	32	32	32	18	25.4	25.4
Compressor speed	rad/s	228	150	193	135	84	113
Evap finned length	m	1.14	1.71	1.1	1.34	1.98	1.55
Fin density	# per foot	169	200	169	189	200	182
Condenser coil length	m	1.11	2.56	2.0	1.63	2.45	2.29
Objective function values							
Capital Cost	$	3150	4711	3525	3046	4462	3732
Exergy Destruction	kW	8.2	5.48	6.3	10.01	6.70	8.24

Single Vs Multi objective

	Capital Cost	**Running Cost**
economic optimization	↓33%	↑35%
thermodynamic optimization	↑ 50%	↓35%
Multi Objective Optimization	↓25%	↓23%

Comparison with base line

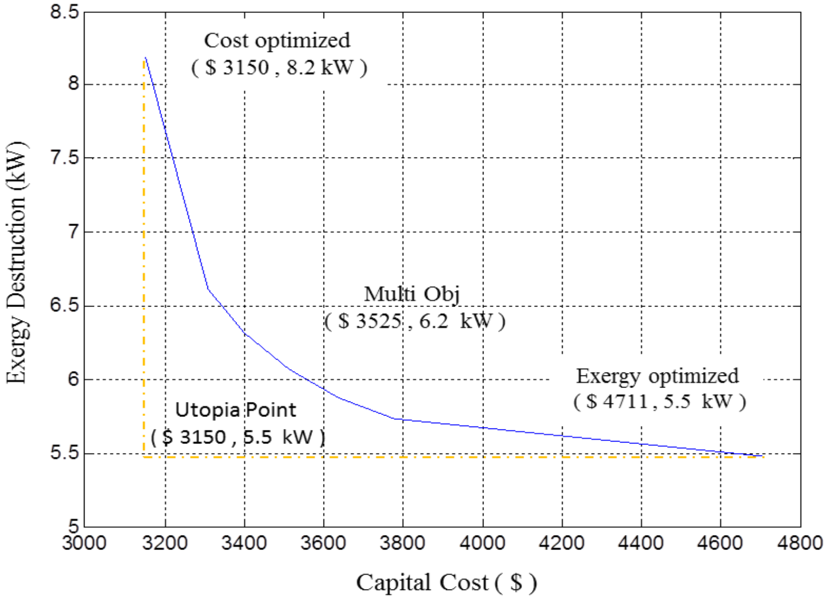
	Capital Cost	**Running Cost**
economic optimization	↓15%	↓2%
thermodynamic optimization	↑ 25%	↓34%
Multi Objective Optimization	↓4%	↓21%

The results shows that the multi-objective design more acceptably satisfies all criteria than other two single-objective optimized designs.

Results & Discussion

Pareto frontier

- Utopia Point ($ 3150, 5.5 kW)
- The multi objective optimization yields the best solution in terms of cost and efficiency ($ 3525, 6.2 kW), which is represented by the minimum distance point from the utopia point on the Pareto optimal curve.
- This Pareto frontier can be used to aid the process of decision-making by considering the tradeoffs.



Pareto frontier for R134a, 25kW case

Future Work

- Code optimization (for fast execution)
- Optimization using Genetic Algorithm
  - » Capability to deal with Discrete Variables
- Improved (and Automatic) Cost Models
- Web based

Thank You