Multi-Objective Optimization of Fuel Consumption and NOx Emissions for a Heavy-Duty Direct Injection Diesel Engine

23rd May 2018

Tim Franken[1,4], Alexander Duggan[2], Feng Tao[3] and Fabian Mauß[1,4]

[1]Brandenburg University of Technology, [2]ESTECO North America, [3]Cummins Inc., [4]LOGE GmbH

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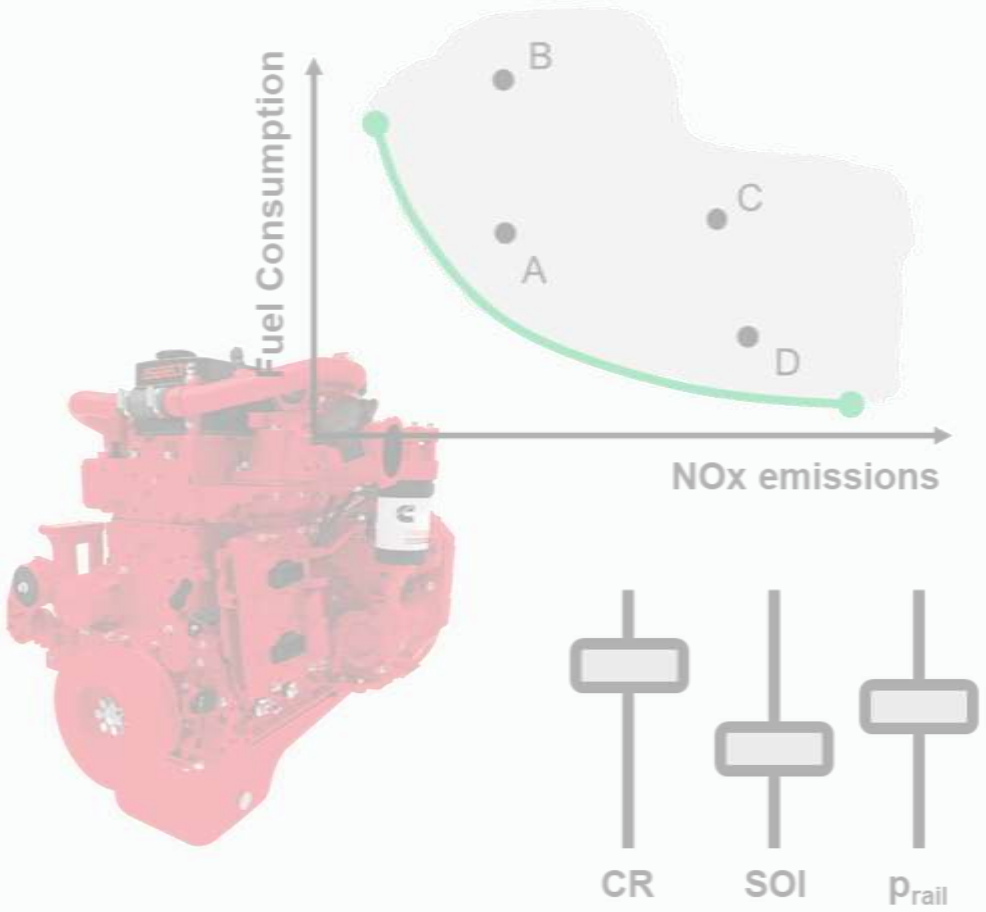
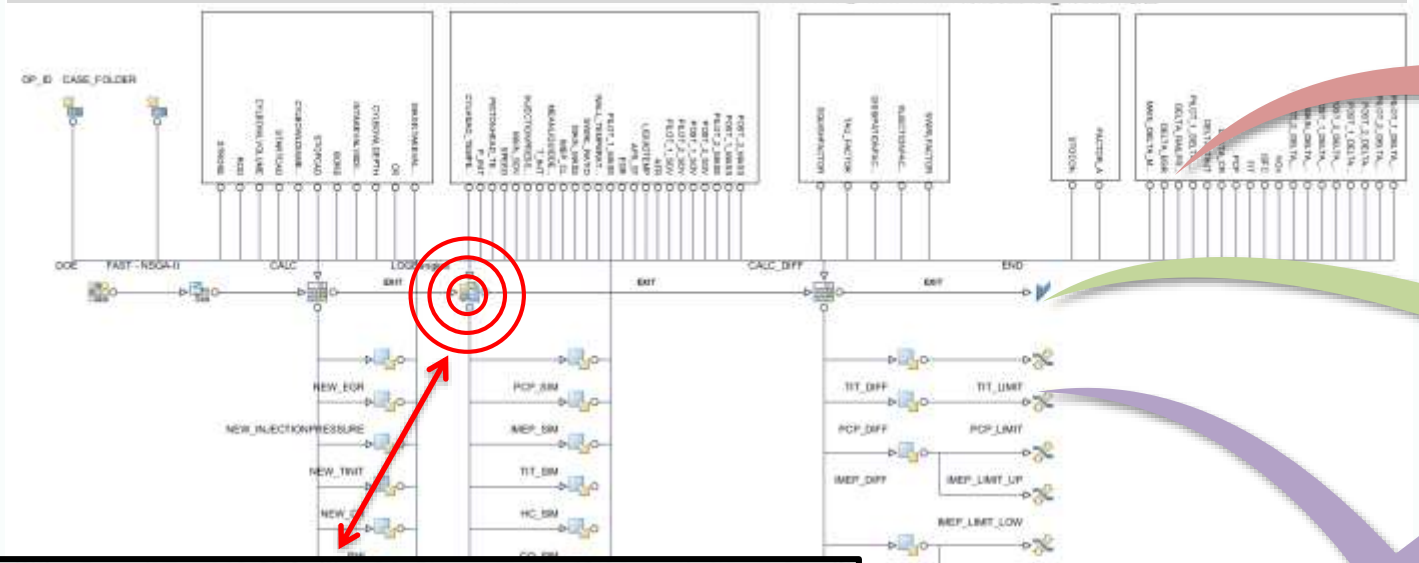
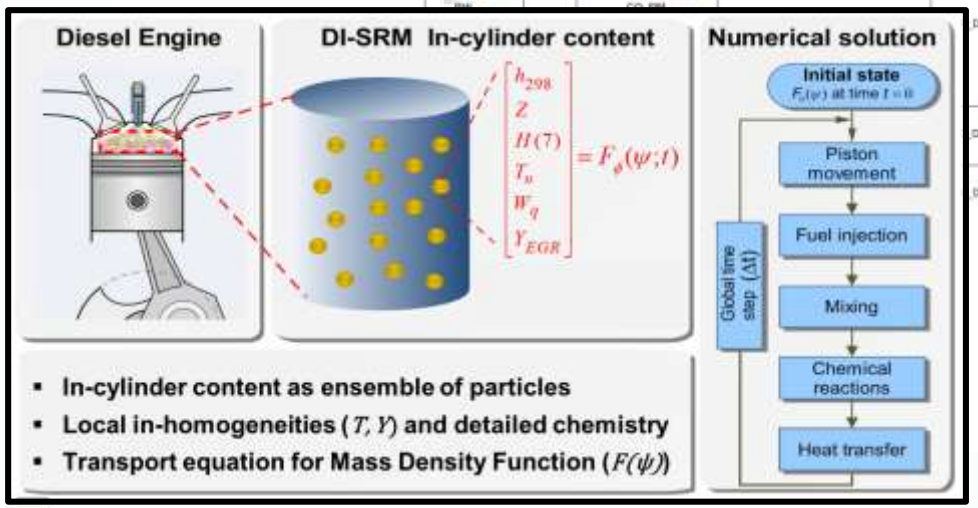


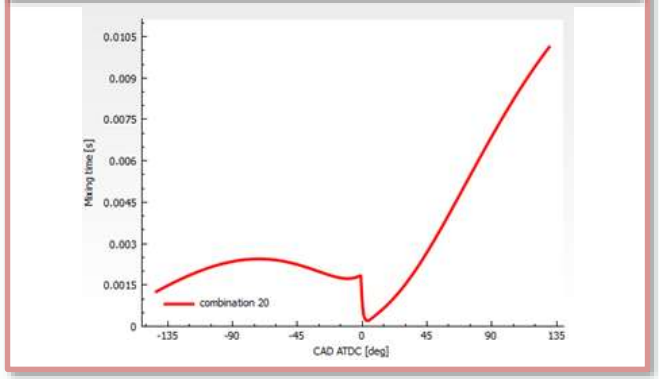
Simulation Supported Engineering Process

modeFRONTIER and SRM coupling

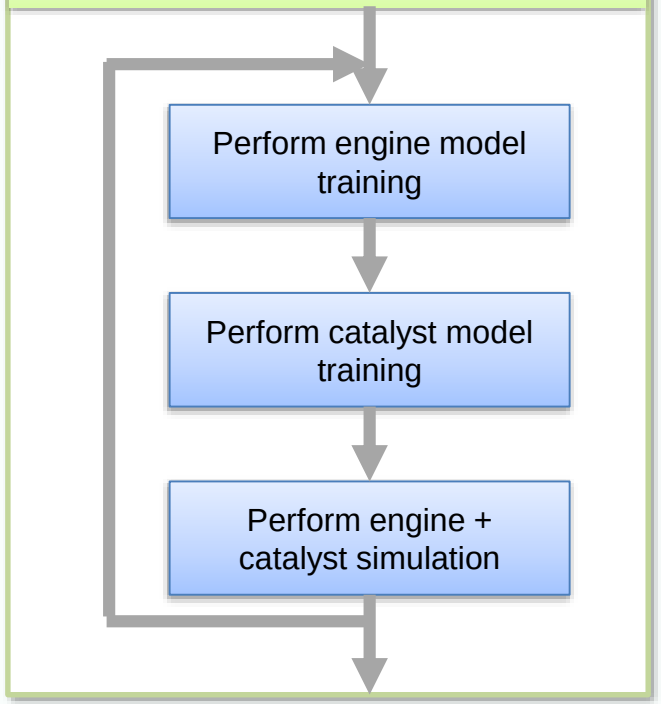




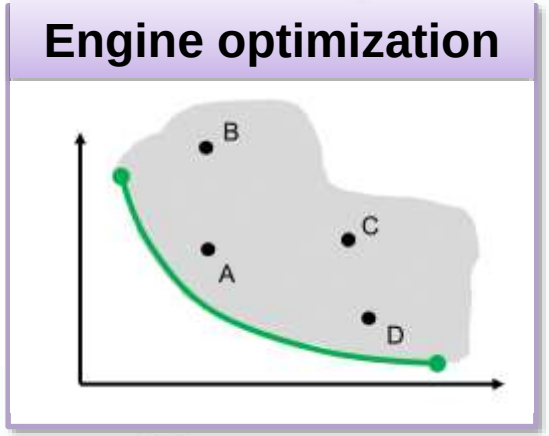
Mixing time calibration



Process automation



Engine optimization



Phenomenological Turbulence Modeling

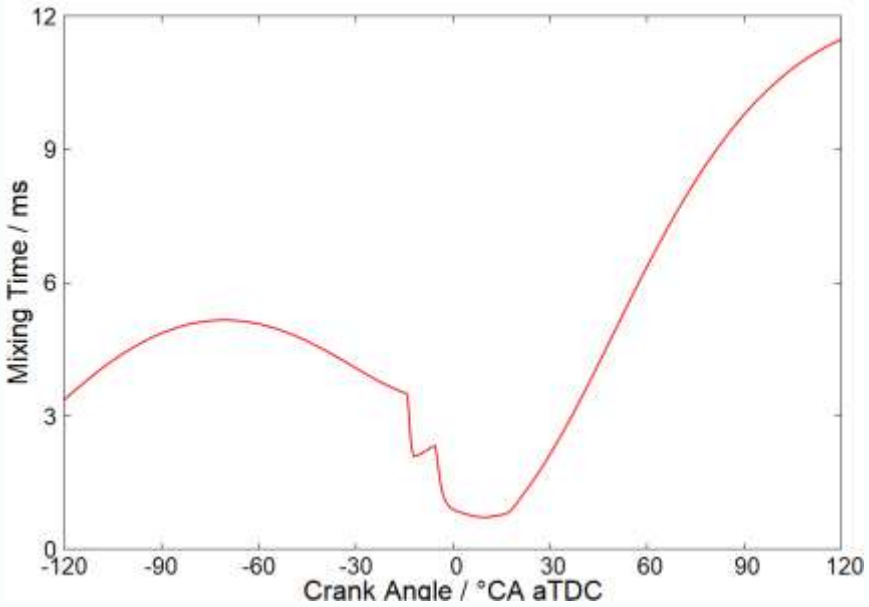
DENSITY SQUISH INJECTION SWIRL

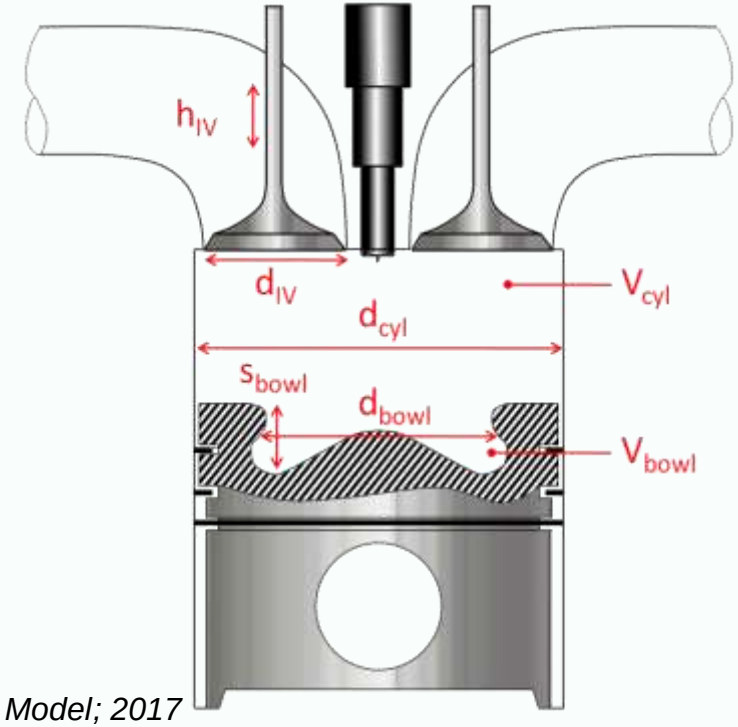
$$\frac{dk}{d\varphi} = \left(-\frac{2}{3} \cdot \frac{k}{V_{cyl}} \cdot \frac{dV_{cyl}}{dt} - \varepsilon + \left[C_{sq} \cdot \frac{k_{sq}^{\frac{3}{2}}}{dt} \right]_{TDC < \varphi < EVO} + C_{inj} \cdot \frac{dk_{inj}}{dt} + C_{sw} \cdot \frac{c_m^{\,3}}{l} \right) \cdot \frac{1}{6 \cdot n} \qquad \text{(Eq. 1)}$$

Source: P. Kozuch; Phenomenological model for a combined nitric oxide and soot emission calculation in DI diesel engines; 2004

$$\varepsilon = C_{diss} \frac{k^{\frac{3}{2}}}{l} \qquad \text{(Eq. 2)}$$

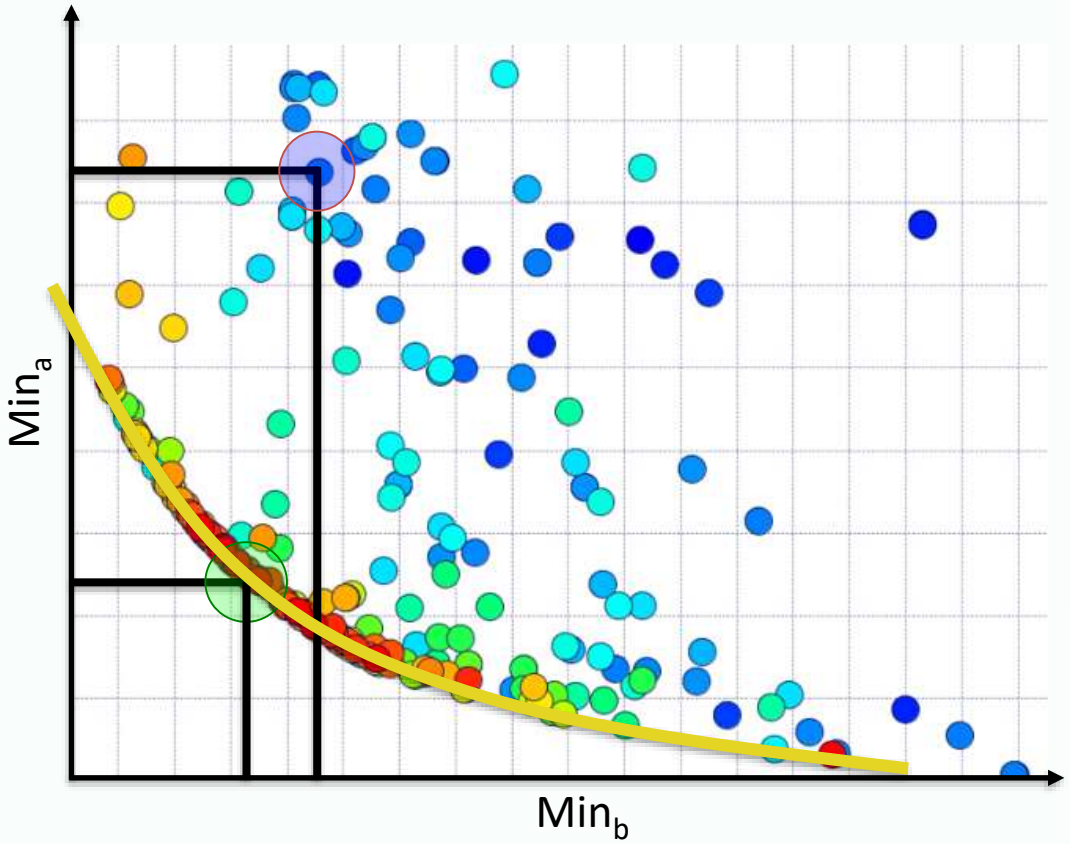
$$\tau_{\phi} = C_{\tau} \frac{k}{\varepsilon} \qquad \text{(Eq. 3)}$$





Source: Franken et al.; Advanced Preditctive Diesel Combustion Simulation using Turbulence Model and Stochastic Reactor Model; 2017

Multi-Objective Optimization



Dominated design: exist solutions with better (lower) values of both objectives

Pareto front: there doesn't exist solutions with better values for both objectives

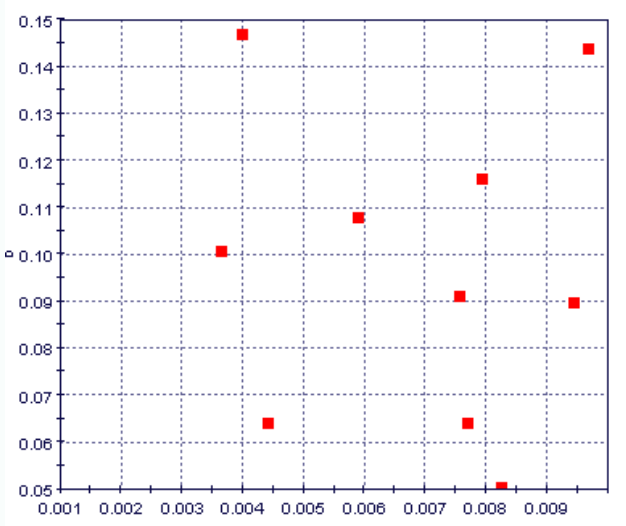
(X, Y) belongs to Pareto front if: $\forall i \nexists (x^*, y^*): f_i(x^*, y^*) \leq f_i(X, Y)$

Incremental Space Filler

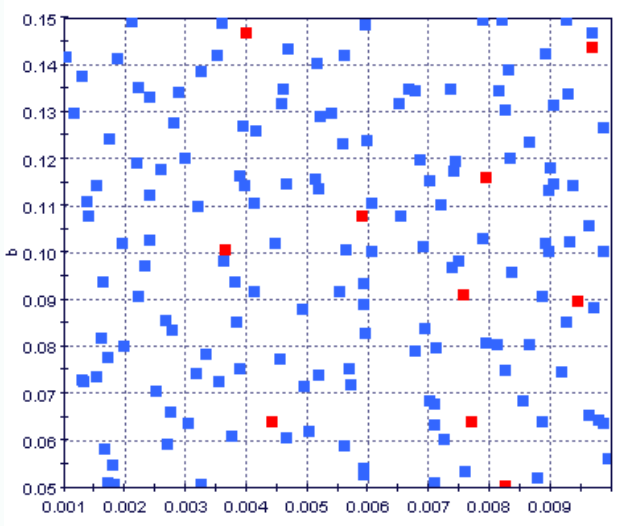
Incremental Space Filler

Augmenting algorithm considering the existing points and adding new points sequentially by maximizing the minimum distance from the existing points

- ✓ Suitable for RSM training and GA optimization
- ✓ Uniform space filling
- ✓ Rejects unfeasible designs



Initial DOE

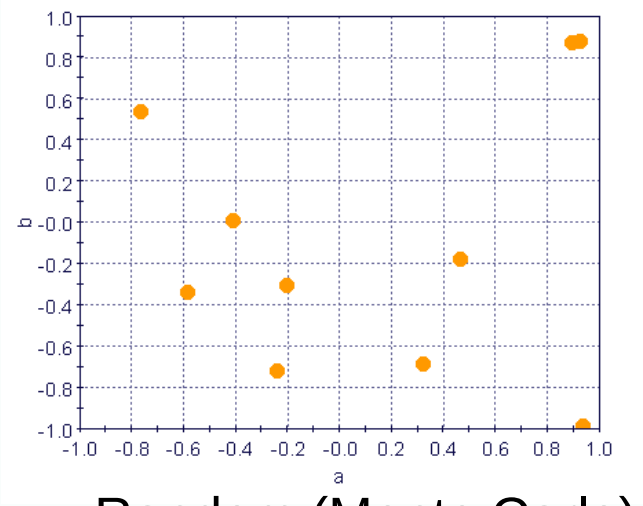


Points added using ISF

Uniform Latin Hypercube

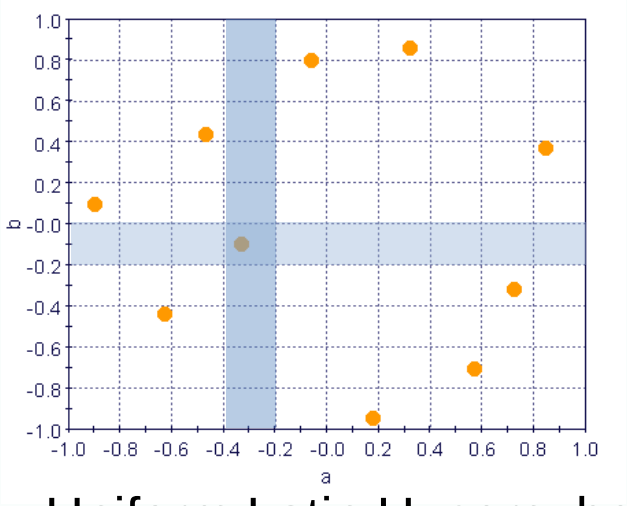
Uniform Latin Hypercube

- ✓ **Stochastic space-filler** DOE algorithm (advanced Monte Carlo sampling)
- ✓ Generates random numbers conforming to the uniform distribution
- ✓ Achieves high **uniformity** levels for each variable
- ✓ Tries to **minimize correlations** between input variables and **maximize the distance** between generated designs
- ✓ Suitable for RSM training and GA optimization



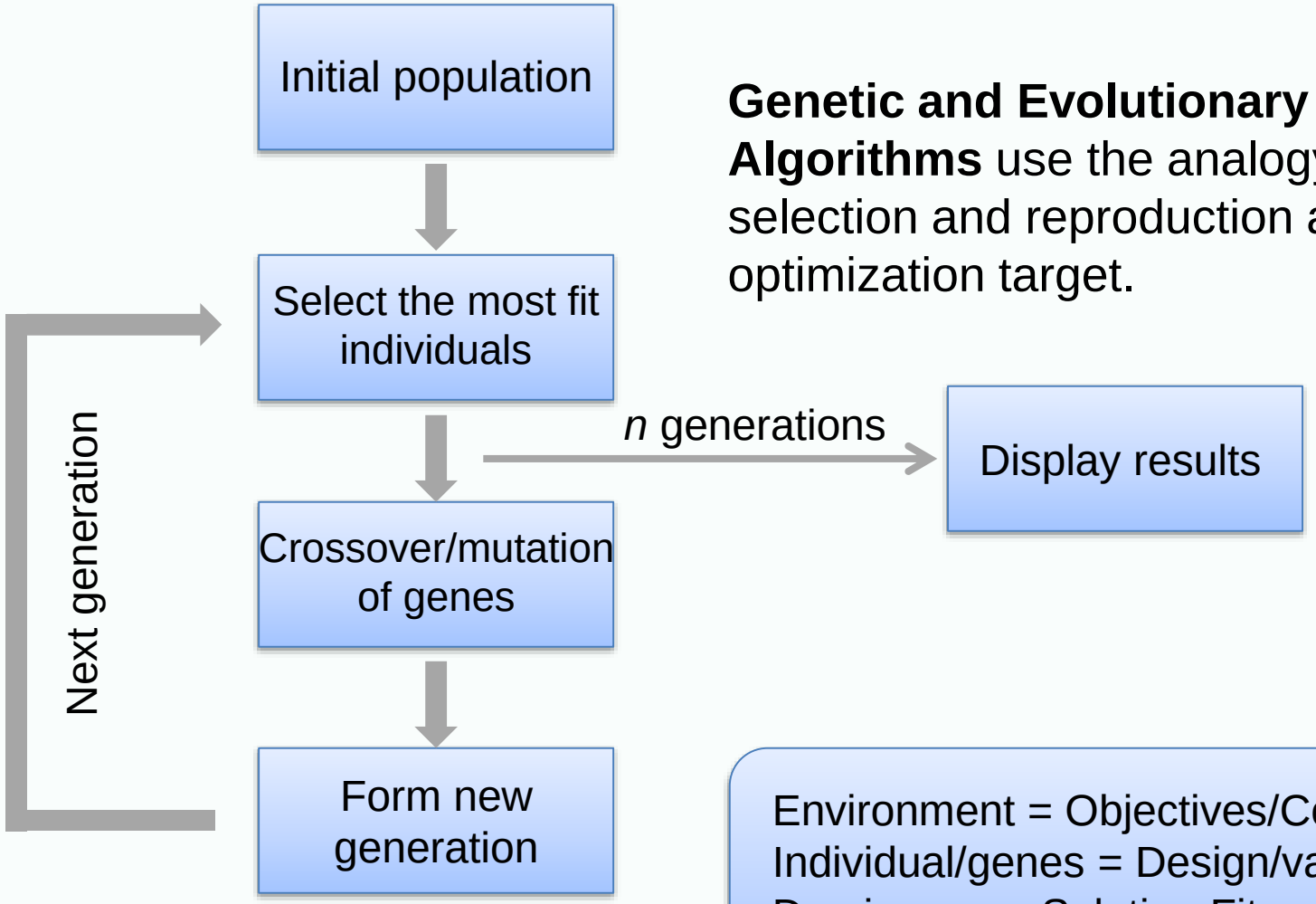
Random (Monte Carlo)

$n = 10$



Uniform Latin Hypercube

Genetic Algorithms

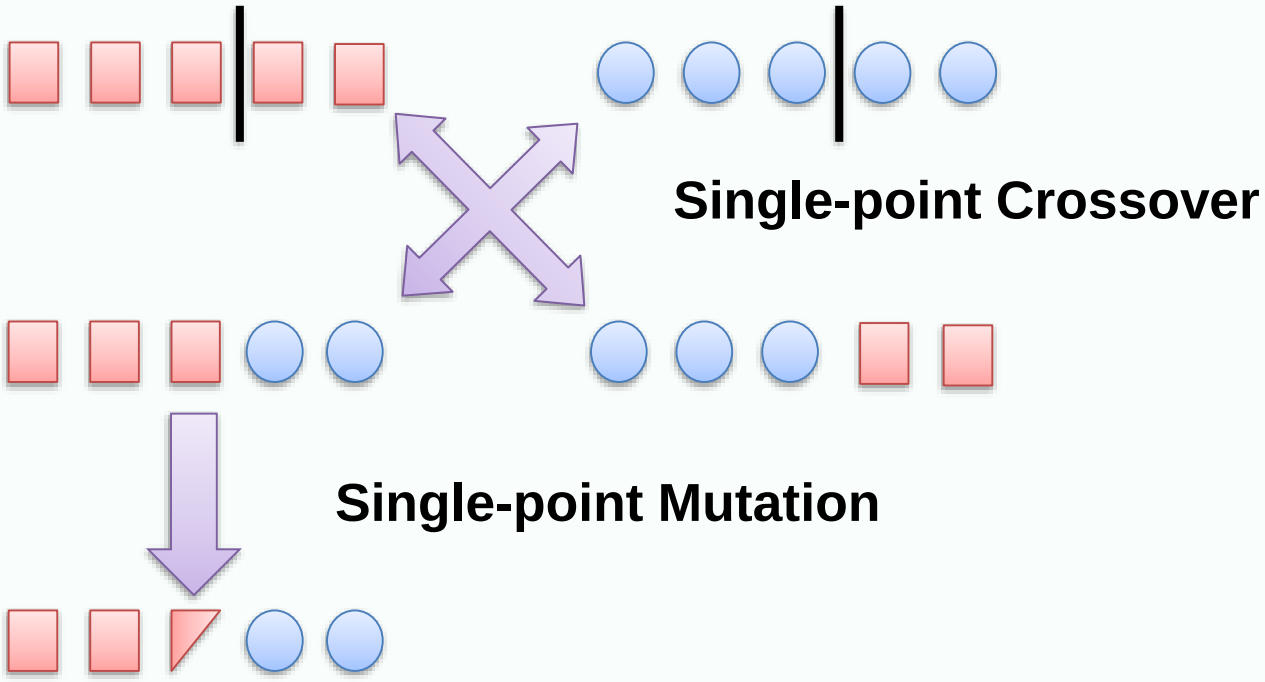


Genetic and Evolutionary Algorithms use the analogy of natural selection and reproduction as optimization target.

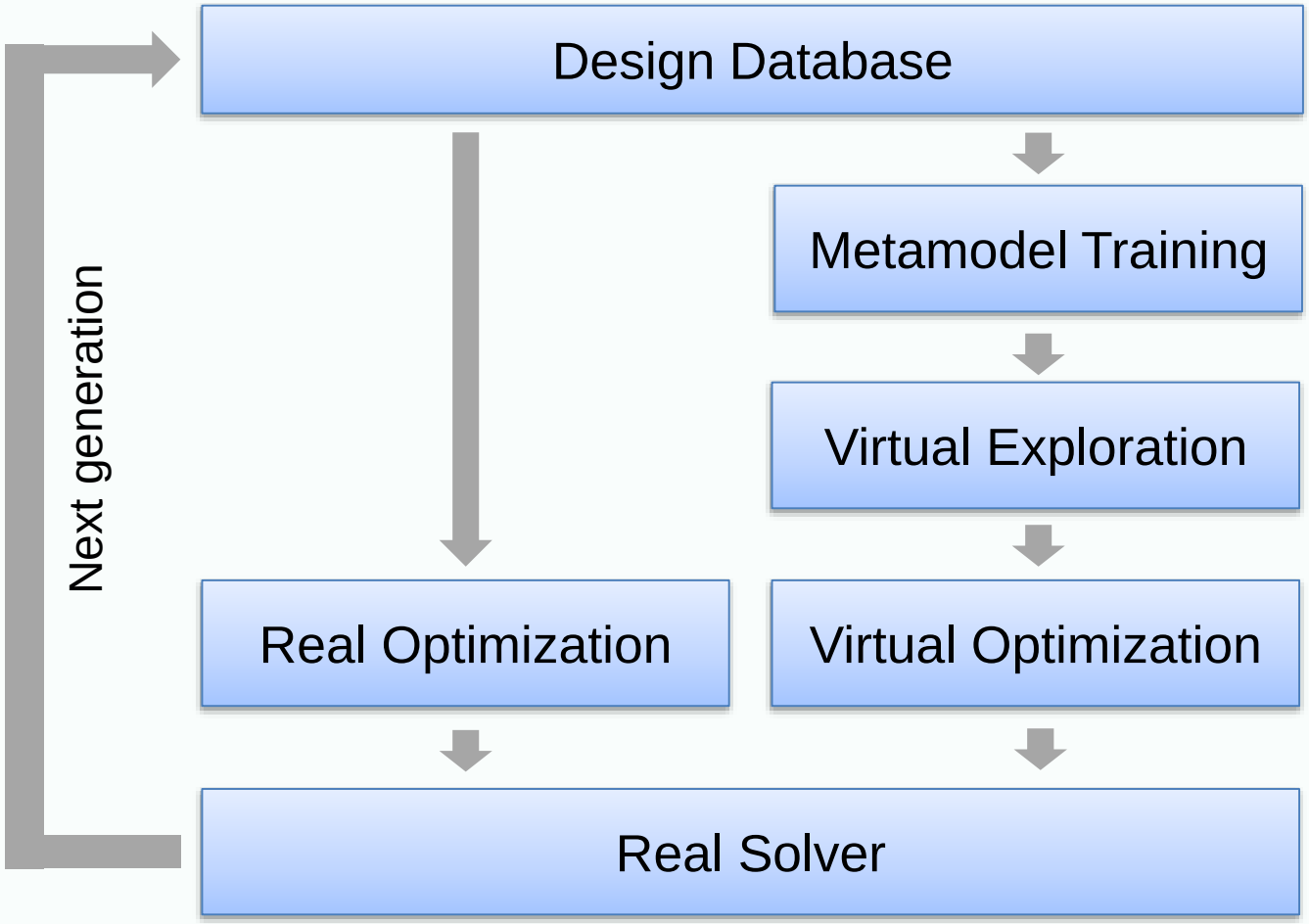
Environment = Objectives/Constraints
Individual/genes = Design/values
Dominance = Solution Fitness

Genetic Algorithms

- ✓ Each individual (design) is coded by a binary string
- ✓ Best individuals are selected (by fitness or dominance criteria), and operators are applied to generate a new population



FAST Optimization Algorithm



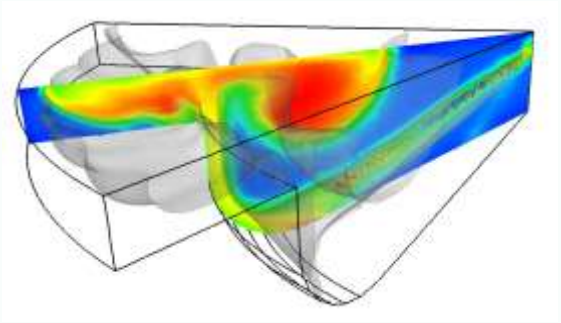
Metamodels are Polynomials, Radial-Basis-Functions, Kriging and Neural Networks.

Evaluation of the real and virtual optimization results running them in SRM.

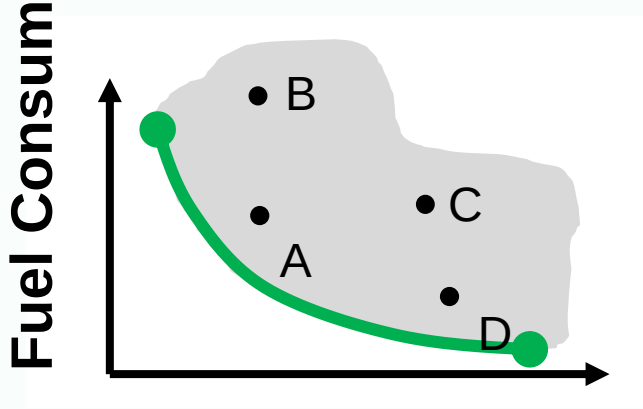
What is the objective of this work?

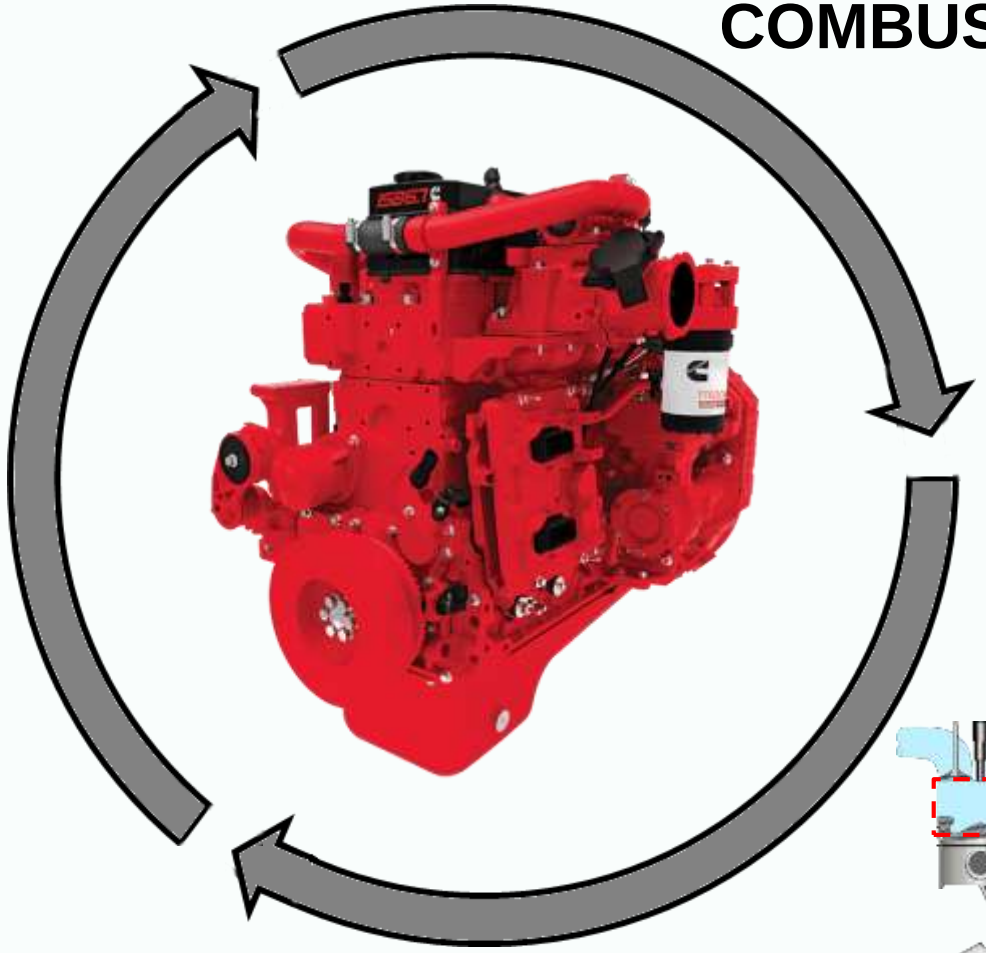
ESTECO um 2018 EFFECTIVE EFFICIENCY

COMBUSTION CONCEPT

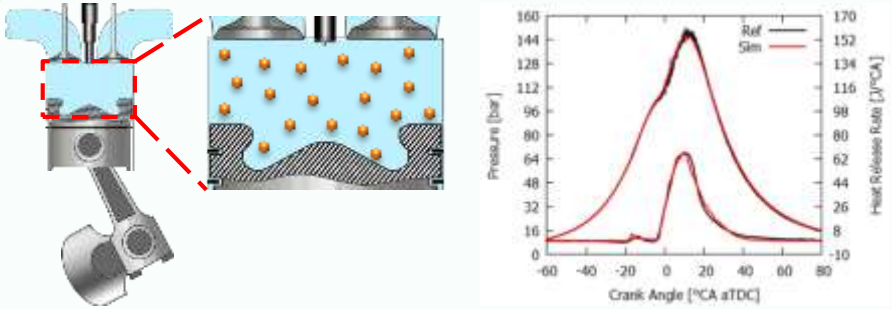


MULTI-OBJECTIVE OPTIMIZATION





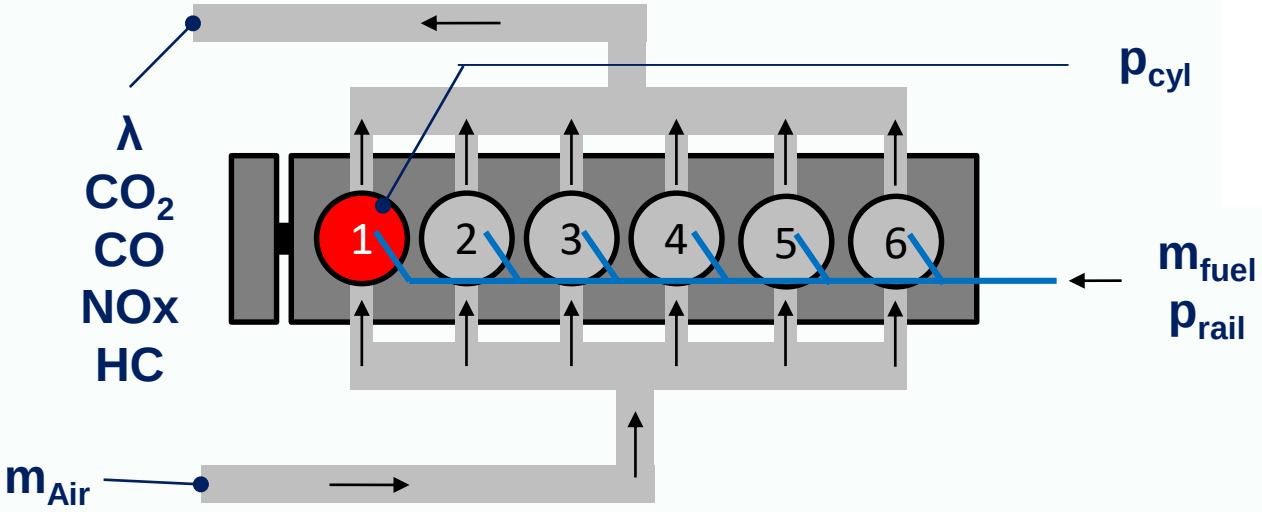
0D SRM TRAINING



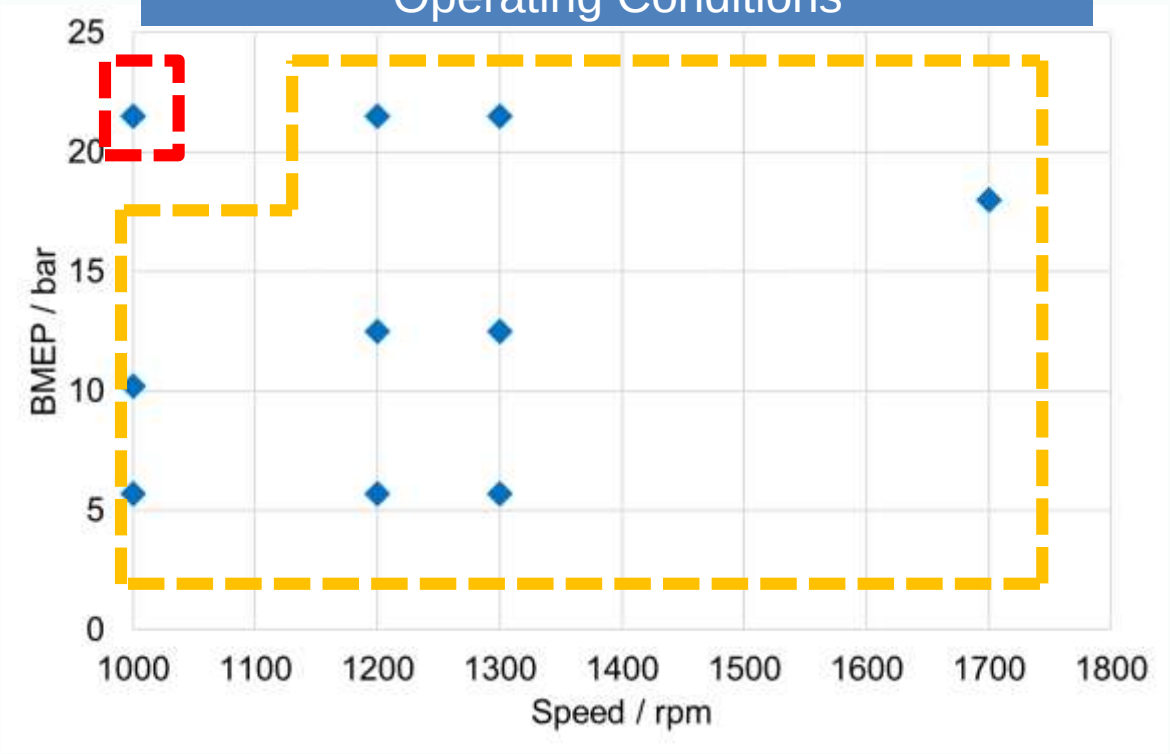
Engine Map Measurements

Engine Specifications

Parameter	Value
Type	Heavy-Duty Diesel
Displacement	6.7l
EGR	No external EGR
Injector	Direct Injection
Cylinders	6



Operating Conditions



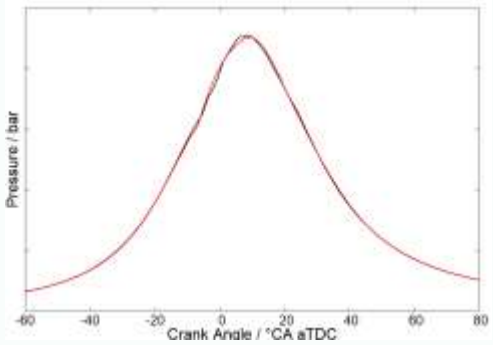
Single Main Injection

Pilot+Main Injection

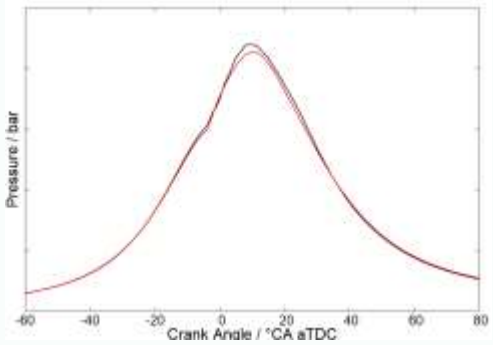
0D SRM Training

Experiment — Simulation

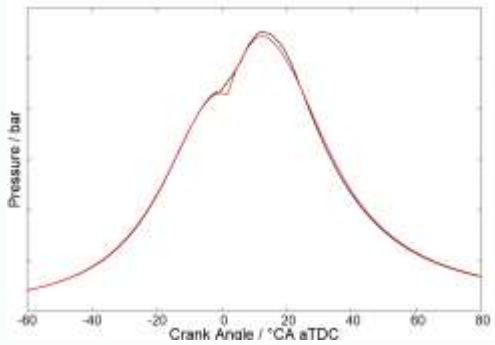
1700rpm, 18bar



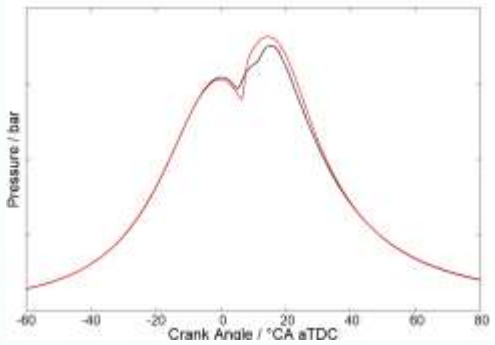
1300rpm, 21.5bar



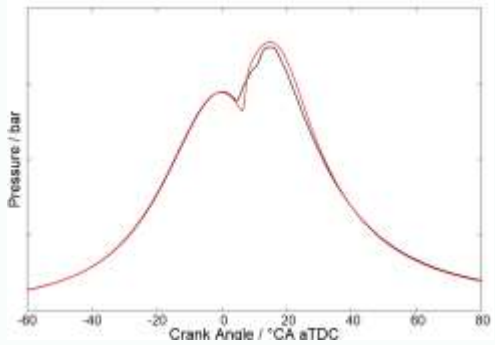
1300rpm, 12.5bar



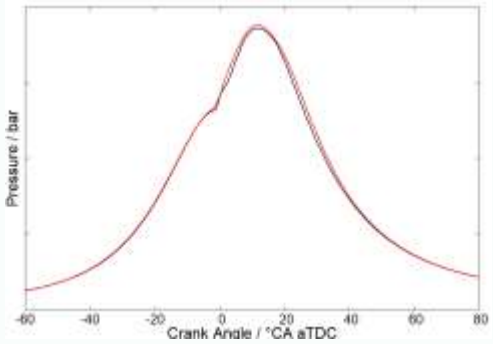
1300rpm, 5.7bar



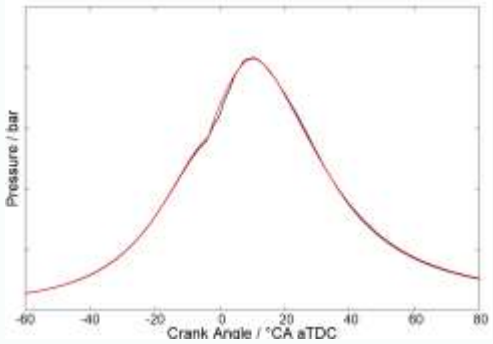
1200rpm, 5.7bar



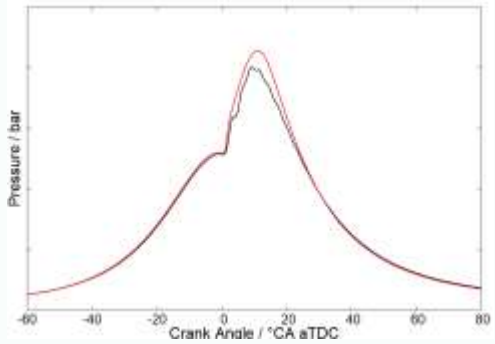
1200rpm, 12.5bar



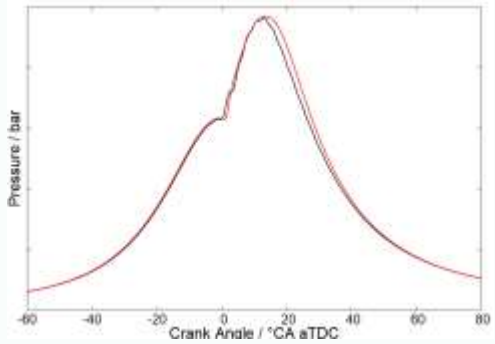
1200rpm, 21.5bar



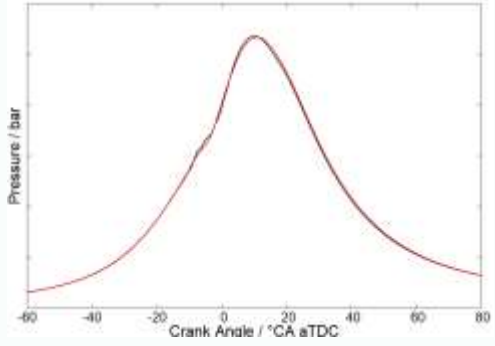
1000rpm, 5.7bar



1000rpm, 10.2bar



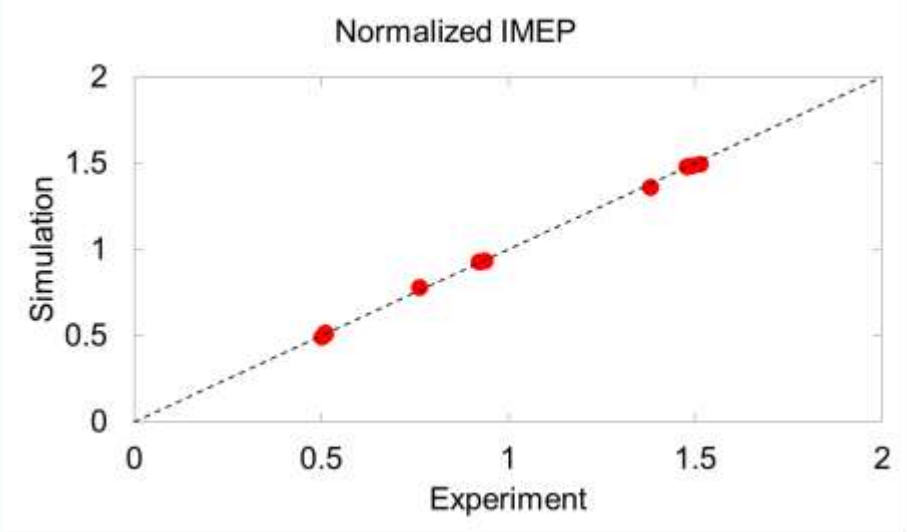
1000rpm, 21.5bar

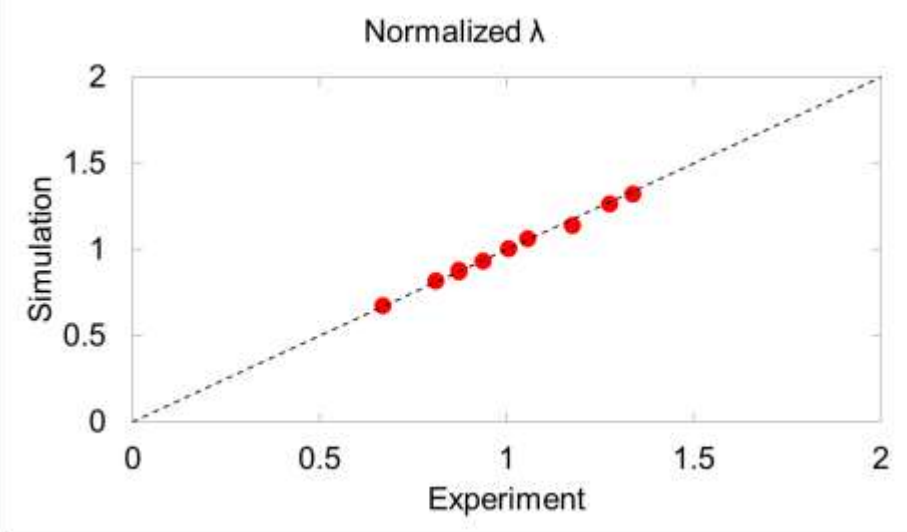


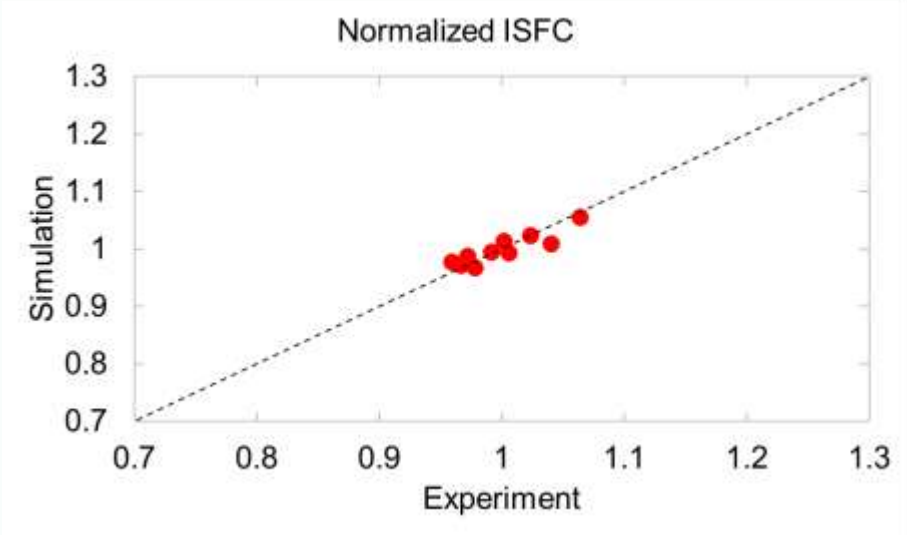
C_{sq}	C_{inj}	C_{sw}	C_{diss}	C_{τ}	C_h
1.0	1.7	7.4	1.6	0.5	15

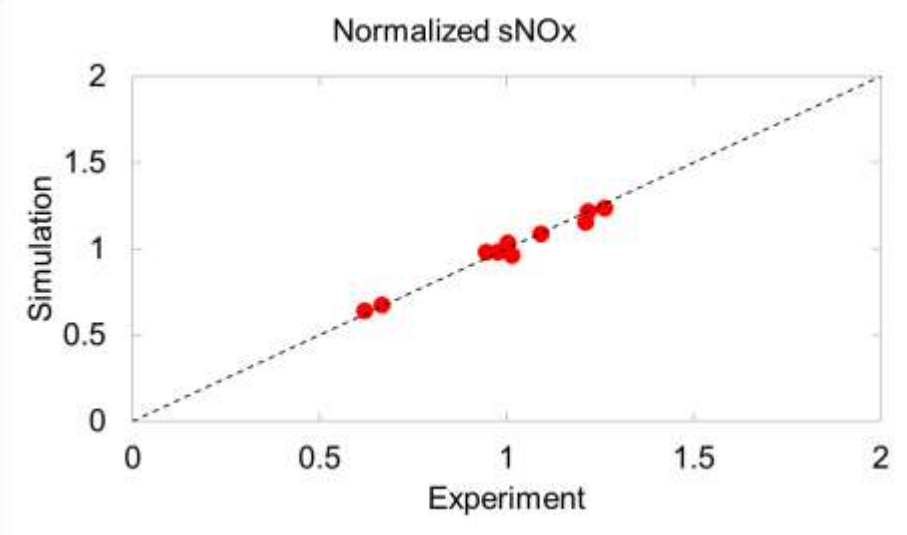
0D SRM Training

$$Normalized\ x = \frac{x_i}{\bar{x}}$$



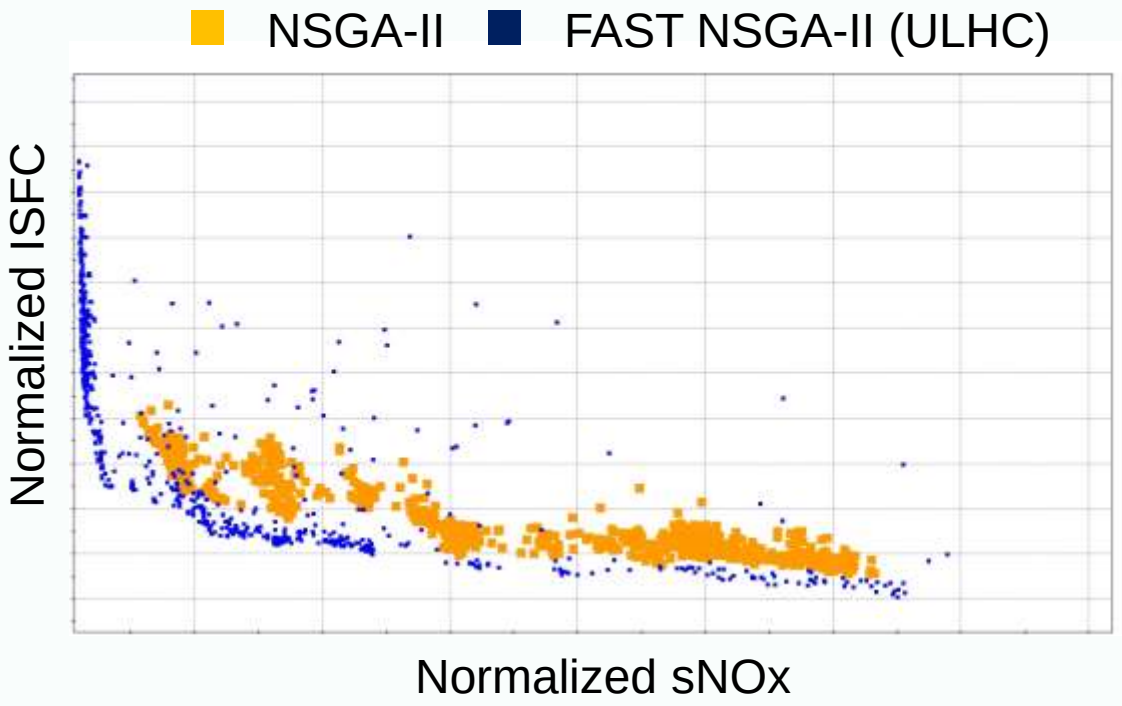






Algorithm Selection

- ✓ The FAST NSGA-II predicts a **well defined Pareto Front** compared to NSGA-II, and needs **less designs** to do so.
- ✓ The Uniform Latin Hypercube (ULHC) is **faster than the Incremental Space Filler algorithm.**
- ✓ The **Radial Basis Function** is not used for the virtual optimization because it is **computational too expensive**.



- ✓ The **FAST NSGA-II** algorithm together with the **Uniform Latin Hypercube** space filler algorithm is selected for optimization.

Optimization Task

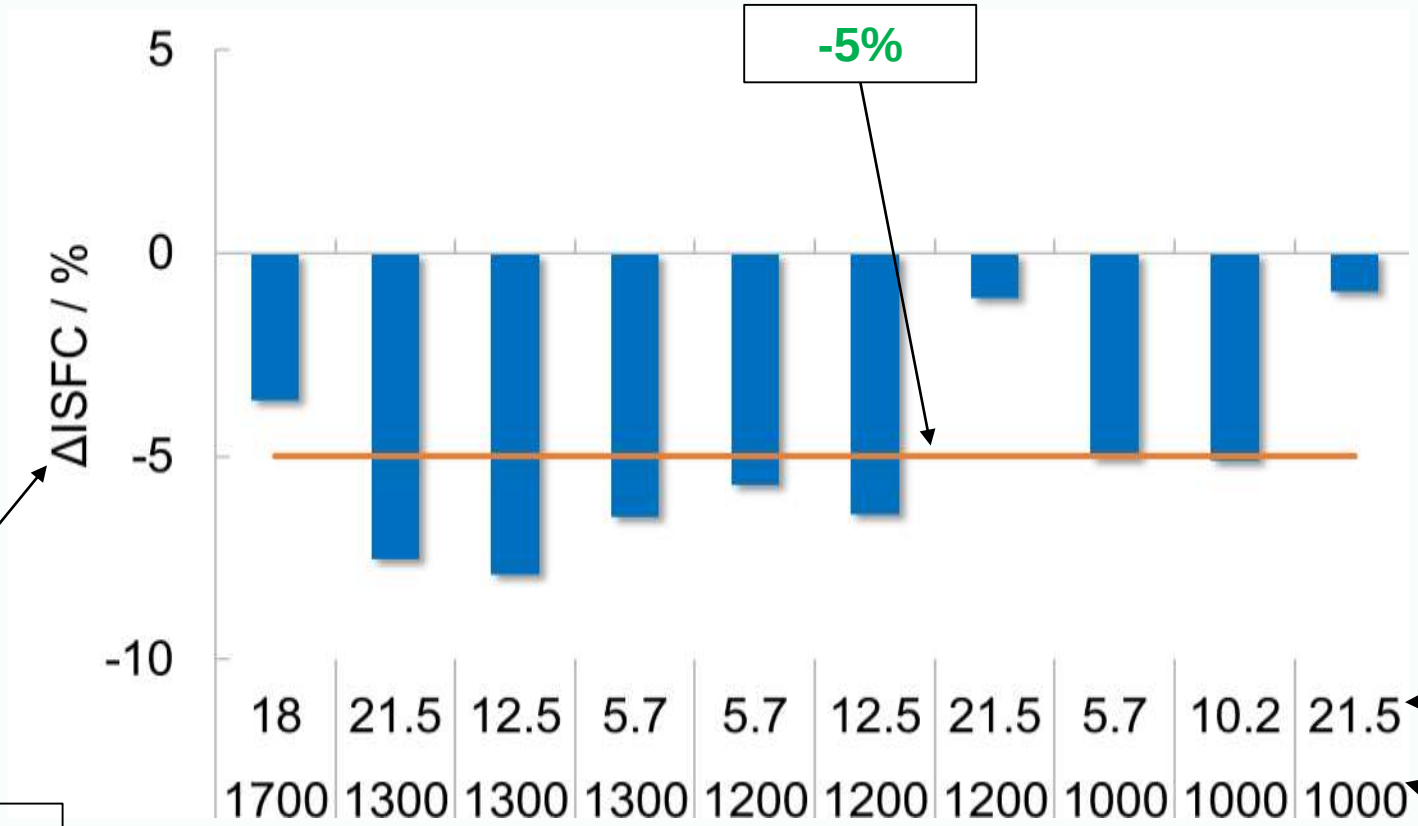
1. Minimize **ISFC and sNOx emissions** for each operating point.

2. Do not exceed **200bar peak cylinder pressure** (PCP) and **1000K turbine inlet temperature** (TIT). The **air-fuel-ratio** (AFR) is allowed to change between **-3.0 and +3.0**.

3. Optimize the operating parameters of each operating point individually:
   A. Start of Injection: **-16°CA aTDC to +6°CA aTDC**,
   B. Injection Pressure: **800bar to 2000bar**,
   C. Compression Ratio: **15 to 21**,
   D. Initial Temperature: **340K to 390K**,
   E. External EGR: **0% to 20%** (mass-based).

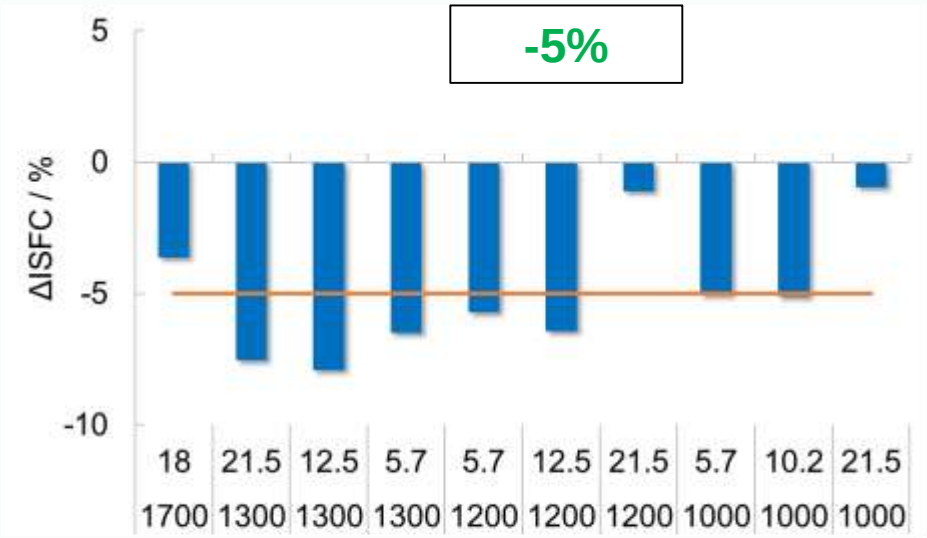
How the results are presented

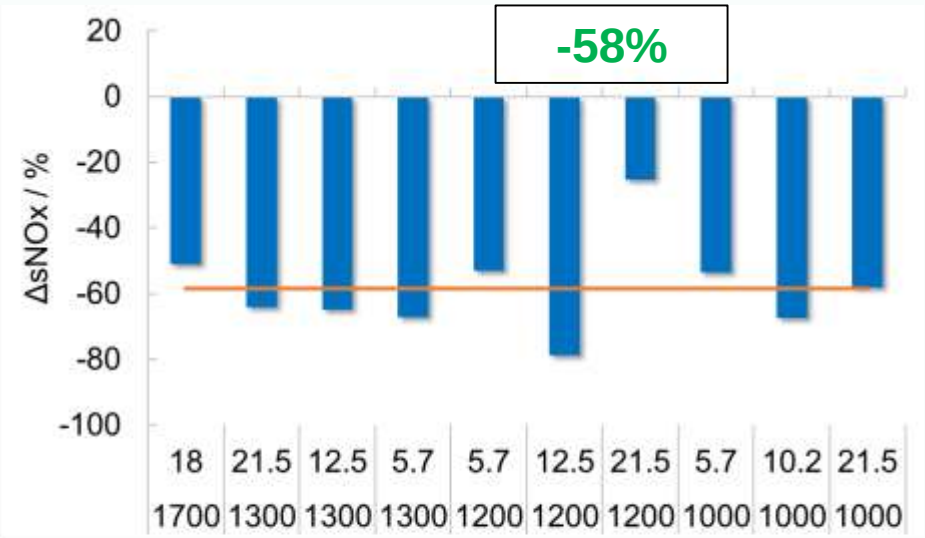
Average of all operating points:



$$\Delta x = \left(\frac{x_{exp} - x_{sim}}{x_{exp}}\right) \cdot 100\%$$

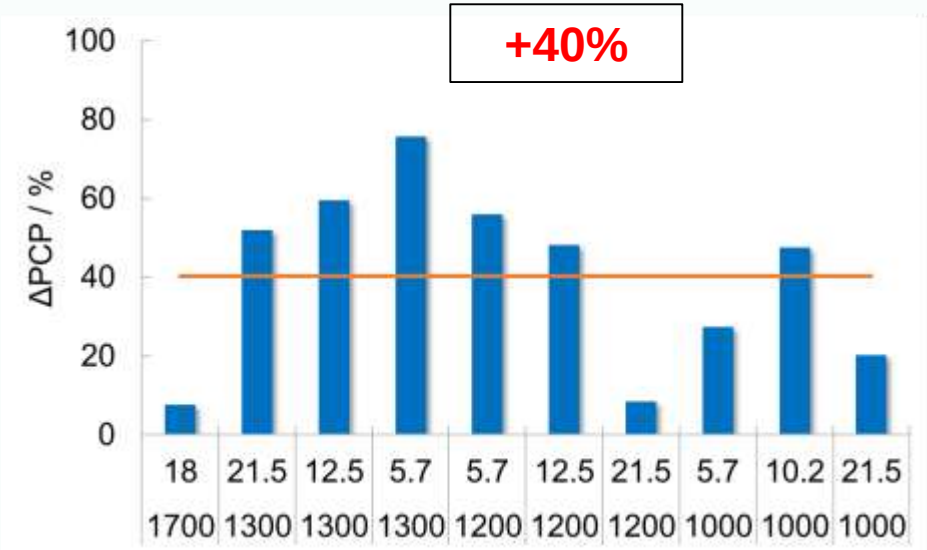
Optimization Results

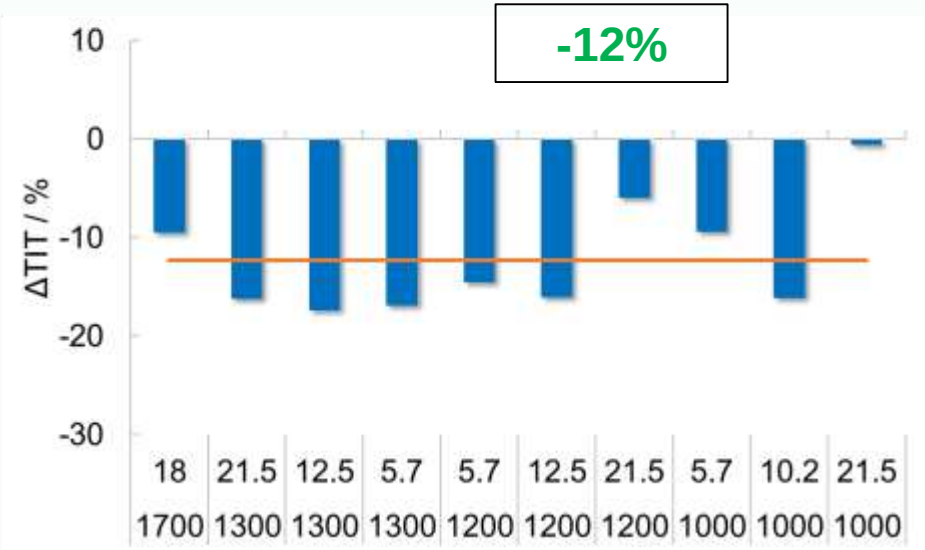




BMEP /bar

Speed / rpm

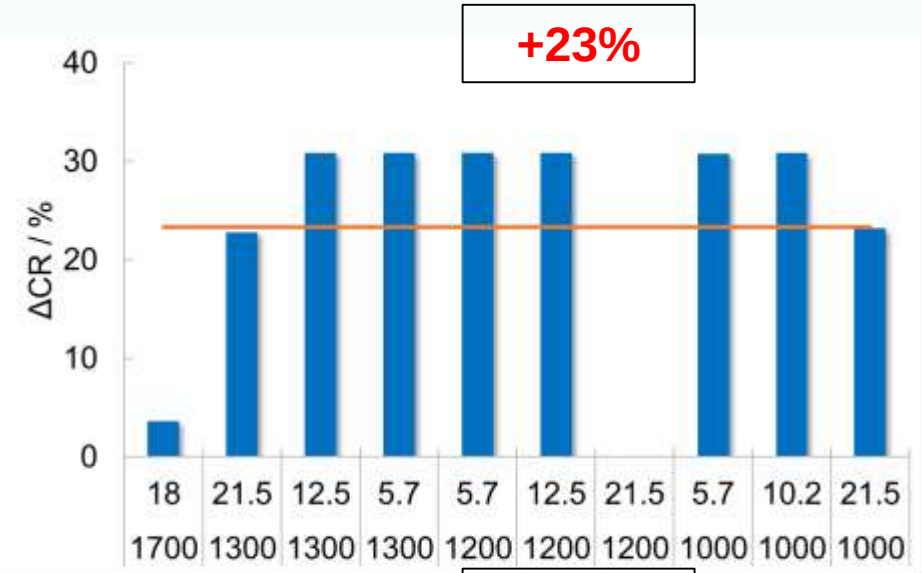


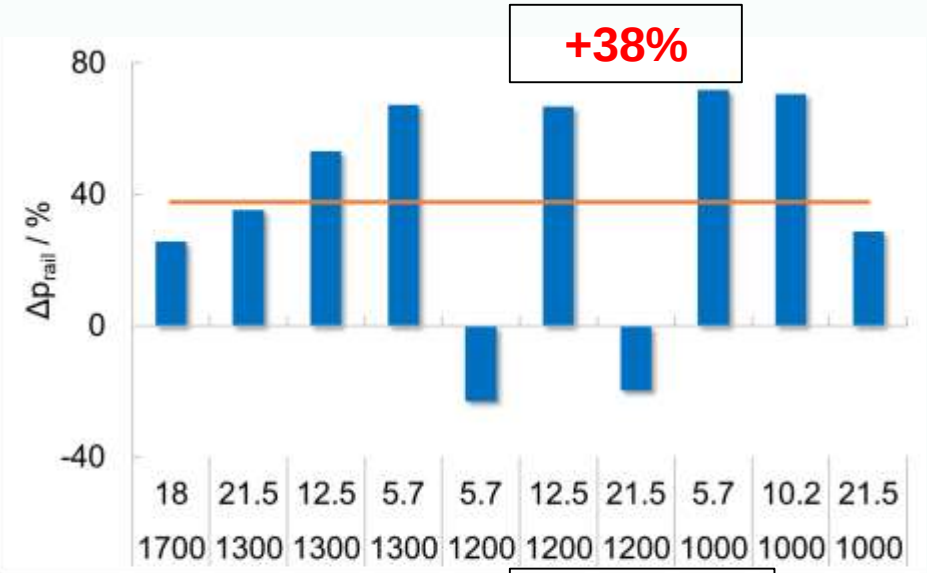


BMEP /bar

Speed / rpm

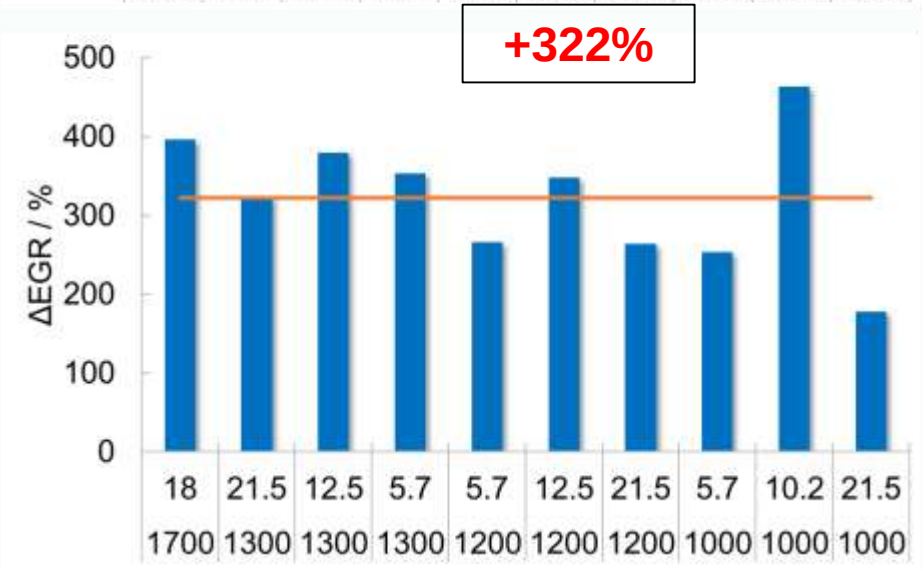
Optimization Results

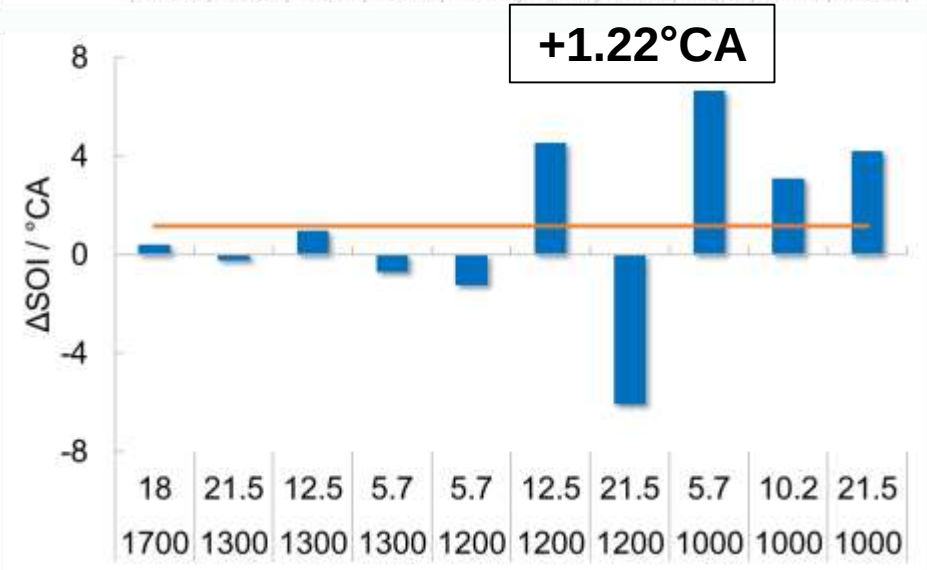




BMEP /bar

Speed / rpm





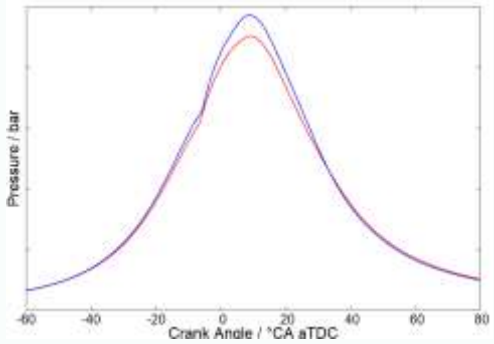
BMEP /bar

Speed / rpm

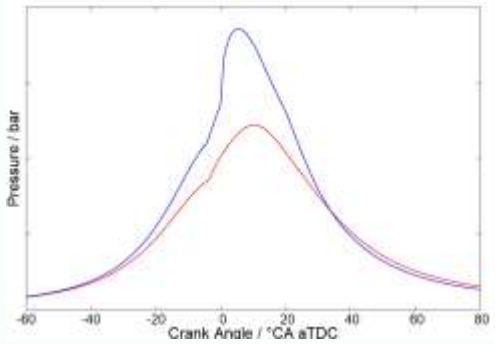
Optimization Results

Base Simulation — Optimization

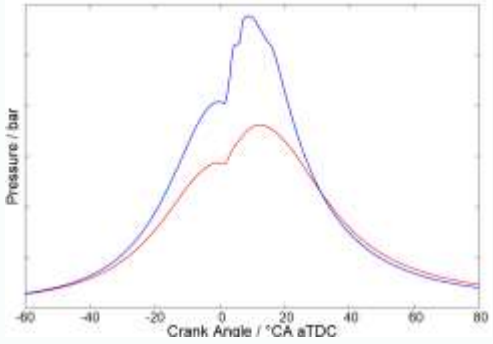
1700rpm, 18bar



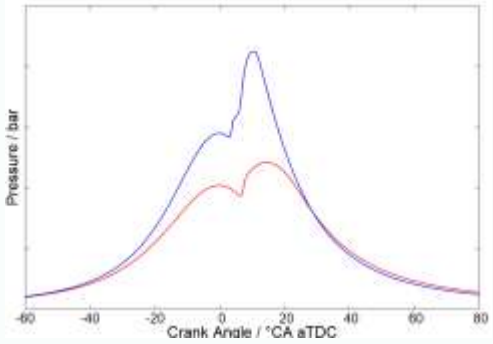
1300rpm, 21.5bar



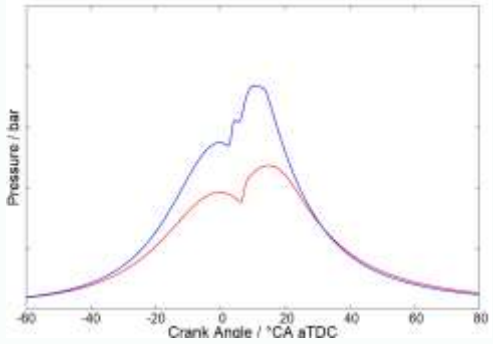
1300rpm, 12.5bar



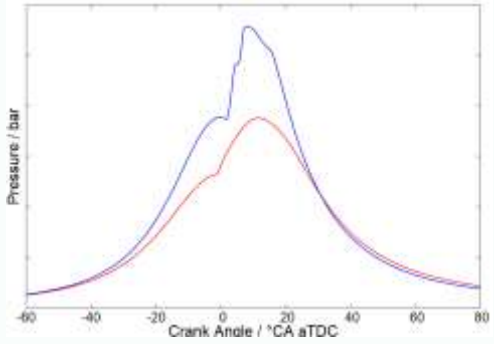
1300rpm, 5.7bar



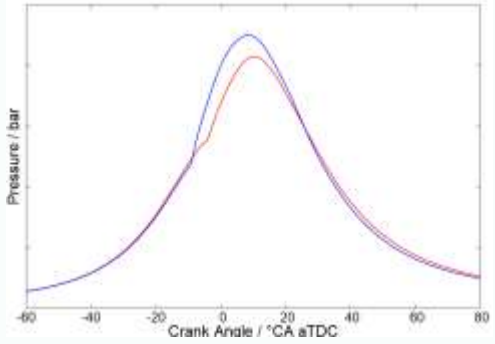
1200rpm, 5.7bar



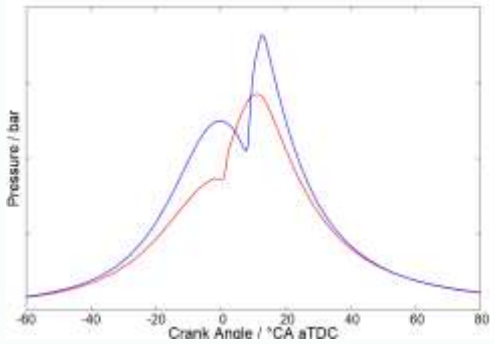
1200rpm, 12.5bar



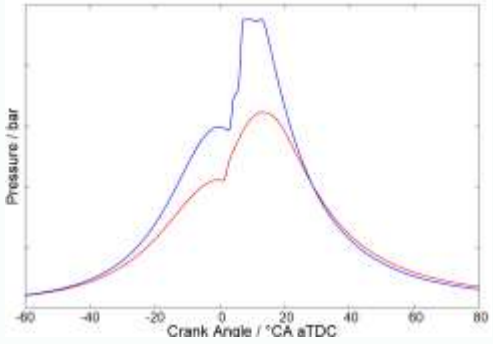
1200rpm, 21.5bar



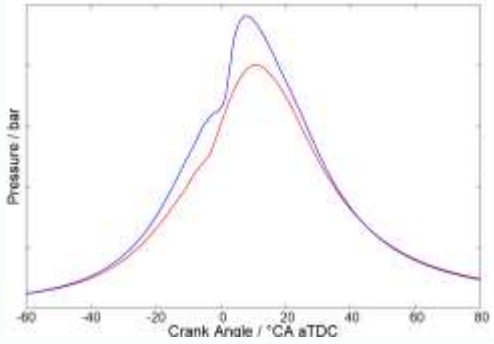
1000rpm, 5.7bar



1000rpm, 10.2bar



1000rpm, 21.5bar



- The **compression ratio** is most effective for **part load** operating point efficiency.
- **Full load** operating points are highly limited by **PCP and TIT**.

Conclusions

- ✓ **Simulation Supported Engineering Process** based on modeFRONTIER and SRM is successfully established.
- ✓ Global SRM mixing time training is 60% faster due to **process automation**.
- ✓ **Tabulated chemistry** accelerates the SRM simulation by factor 1000 compared to online chemistry.
- ✓ The **modeFRONTIER and SRM** based optimization process takes **1.8min/design** and is faster compared to a CFD based optimization approach (up to 16h/design).
- ✓ The **FAST NSGA-II algorithm** with the **ULHC space filler** performed the best for the Heavy-Duty Diesel engine optimization.
- ✓ The **ISFC** could be reduced by 5% in average and the **sNOx emissions** are reduced by 58% in average.

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THANK YOU FOR YOUR ATTENTION

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