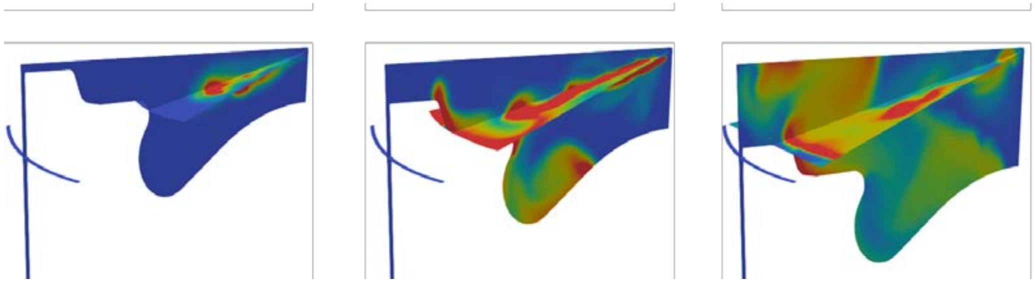
Methodology for the analysis of bowl geometry influence on combustion performance in compression-ignited engines using OpenFoam and LibICE

Fourth Two-day Meeting on
Internal Combustion Engine Simulations Using OpenFOAM® Technology

February 13-14th 2020



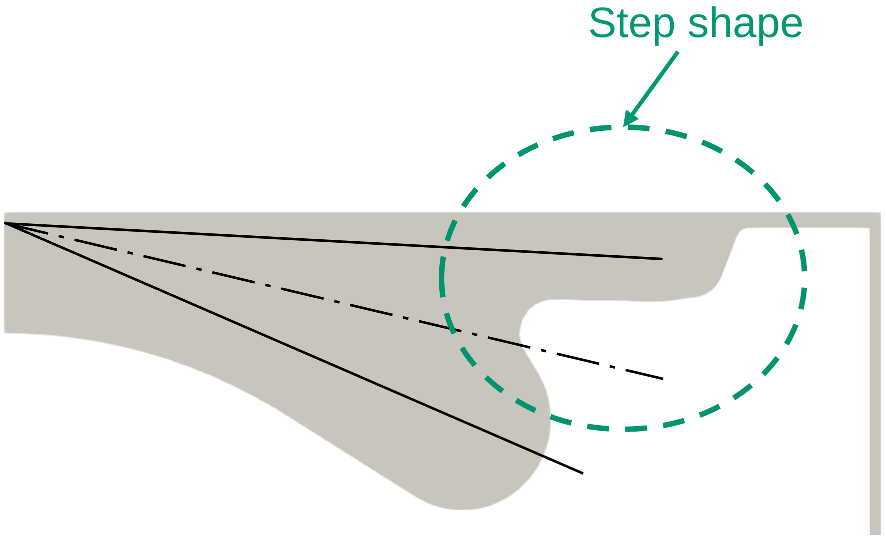
R. Novella
G. Bracho
J. Gomez-Soriano
C. Fernandes
D. Martínez-Rodríguez
T. Lucchini

Contents

- **Motivation**
- **Objectives**
- **Methodology**
  - CFD model formulation and validation
  - PSO Algorithm
  - CFD – PSO integration
- **Results**
- **Conclusions & next steps**

Motivation

- Predesign of a combustion system for EU7 specifications
- To explore the impact of design decisions with reduced experimental work
- Low levels of fuel consumption, with no penalization of NOx and soot



Displacement volume	2,2 L
Number of cylinders	4
Compression Ratio	16
Diesel Fuel System	2200 bar

Objective

- The target is to obtain a combustion system design for a compression-ignited engine, optimized with respect to the reduction of the indicated specific fuel consumption, NOx and soot emissions
- Develop a methodology for coupling CFD and Particle Swarm Optimization (PSO)

- Analyze the influence of the **combustion system** configuration on the combustion performance
    - Bowl Geometry → Automated piston bowl shape generation
    - Number of nozzle orifices
    - Swirl ratio

Combustion System Development Methodology

- The target is to conduct a 3D-CFD guided combustion system hardware development using efficient optimization tools.

CFD Model formulation and Validation
- Set up the CFD model
- Calibrate spray and emissions vs experiments

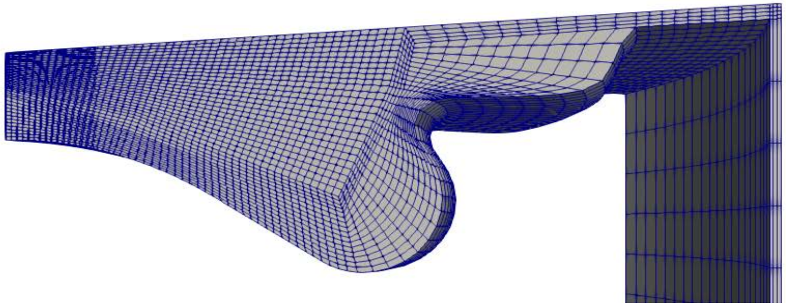
Simplified Mesh
- Build a mesh with fewer cells
- Validate the results

PSO definition
- Initial sample distribution within the design space
- Particle size determination

CFD – PSO integration
- Automated piston shape
- Automated mesh generation
- Evaluate fitness values

CFD Model formulation and Validation

- The software OpenFoam with LibICE was used to develop the model
- Fuel: NC7H16
- Sector mesh: 1/10
- Specific ROI profile from VIM

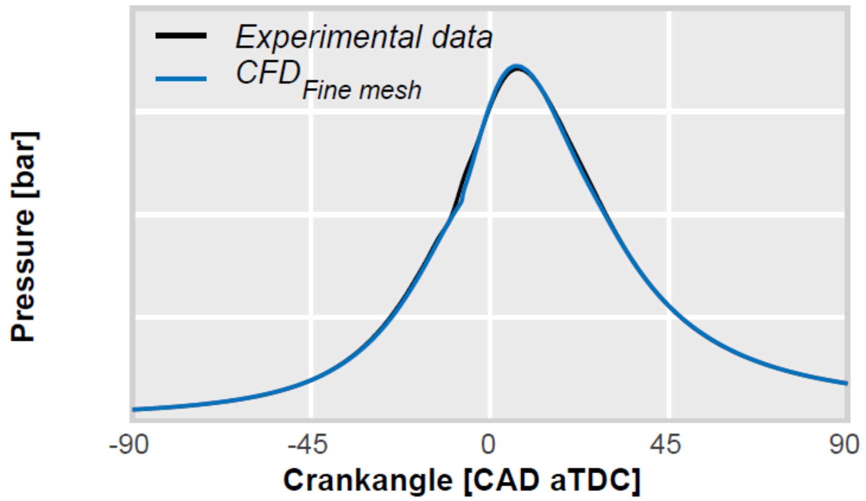


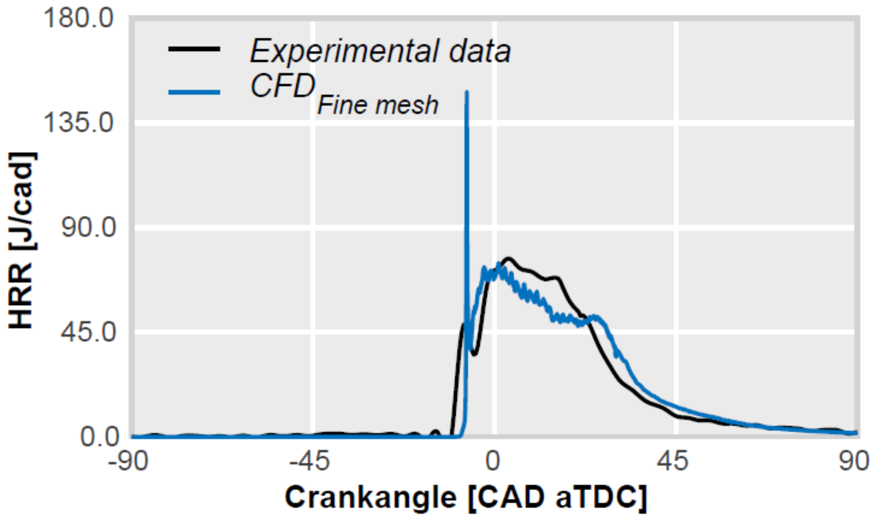
9 processors (~24h)

Dimensionality	3D
Cell count TDC	52 kCells
Cell count IVC	398 kCells
Turbulence	RNG k-ε RANS
Wall Heat Transfer	Angelberger
Spray Models	Injection: Blob Injector Break-up: KH-RT Collision: off Evaporation: standard
Combustion Model	RIF-based tabulation
Chemical Mechanism	NC7Curran
Emission Models	Soot: Leung Lindstedt Jones

CFD Model formulation and Validation

- The CFD model validation is presented in the figures
- Predictions are in good agreement with the experimental data
- Operating point: Full load

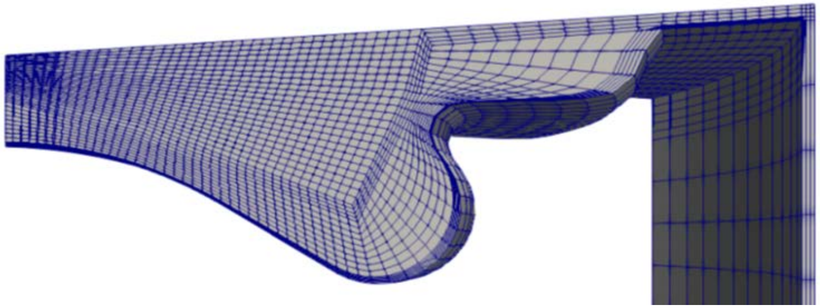




	IMEP [bar]	ISFC [g/KWh]	NOx [ppm]	YSoot [-]
Experimental	22	191	1254	4E-06
Fine mesh	22.26	192.84	1277.78	3.03E-06

Simplification of the Mesh and Validation

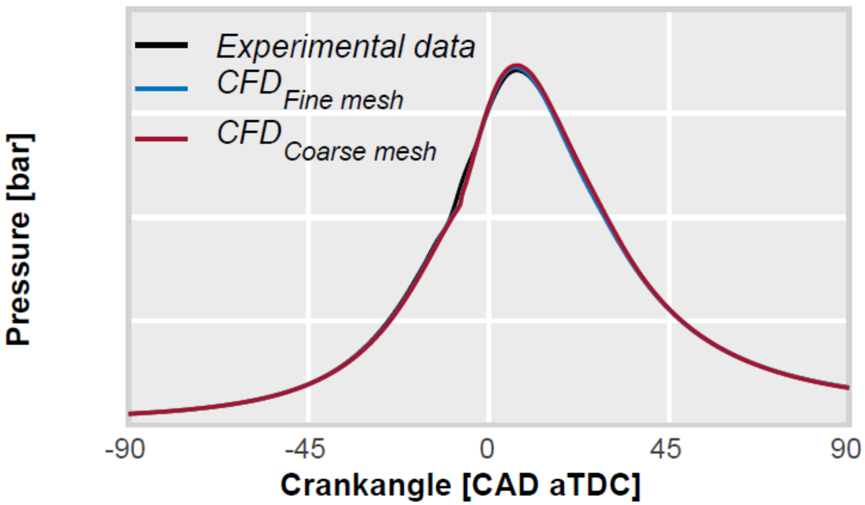
- A coarse mesh was implemented to reduce computational cost and be able to perform 1 case in less tan 17h (4 processors)

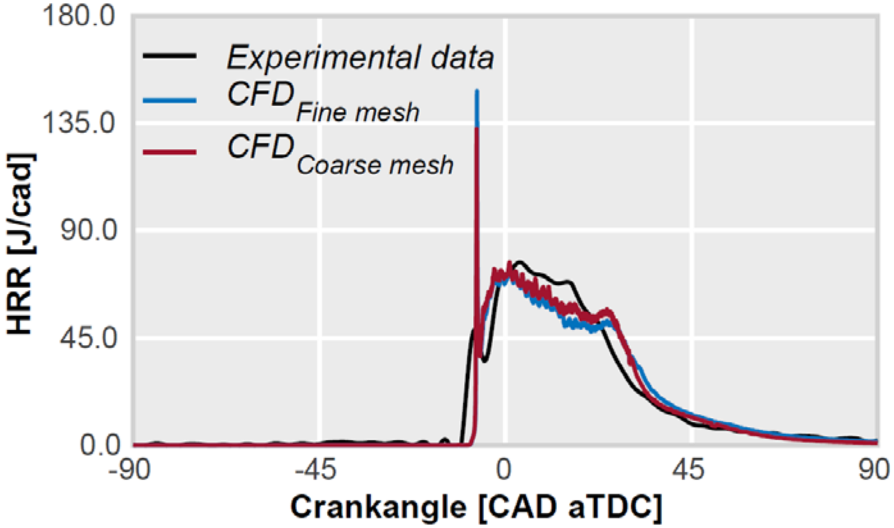


Dimensionality	3D
Cell count TDC	26.9 kCells
Cell count IVC	203.3 kCells
Turbulence	RNG k-ε RANS
Wall Heat Transfer	Angelberger
Spray Models	Injection: Blob Injector Break-up: KHRT Collision: off Evaporation: standard
Combustion Model	RIF-based tabulation
Chemical Mechanism	NC7Curran
Emission Models	Soot: Leung Lindstedt Jones

Simplification of the Mesh and Validation

- Predictions are in good agreement with the experimental data, also with the coarse mesh
- Operating point: Full load



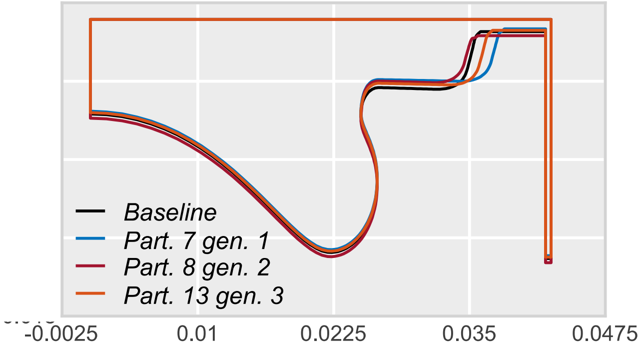


	IMEP [bar]	ISFC [g/KWh]	NOx [ppm]	YSoot [-]
Experimental	22.36	191.77	1253.72	4.18E-06
Coarse mesh	22.45	191.12	1459.97	2.10E-06

Methodology

- Coupling of the CFD with an Optimization methodology: PSO
- Moderate number of input parameters → Key inputs are included
- Objective function definition → high NOx or ISFC penalizes the objective function output

	Input parameters range			
	Geometric		Injection	Air Mgmnt.
Range	G1 [mm]	G2 [mm]	nHoles [-]	Swirl [-]
Min	-1	0	7	1.8
Max	2.5	1	10	2.2
Baseline	0	0	10	2



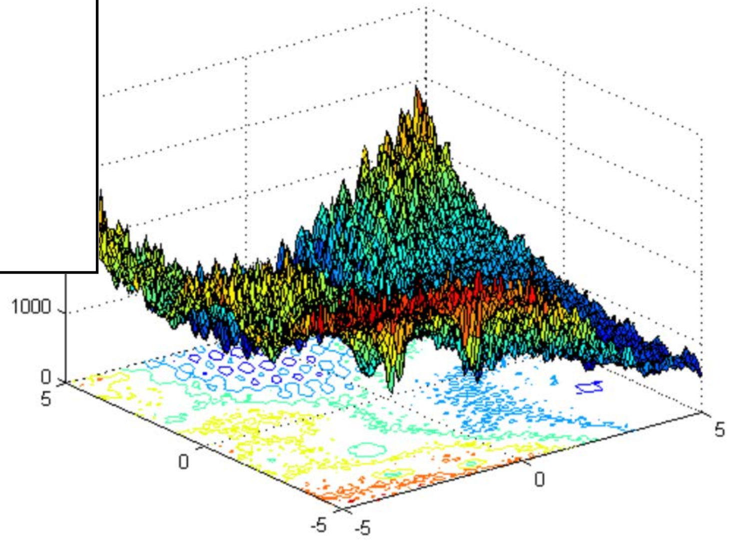
Particle Swarm Optimization - Definition

- It is inspired by social behavior of bird flocking
- Optimizes functions by iteratively trying to improve candidate solutions.
- The candidate solutions are called particles and the particles are improved moving them around the parameters search space.
- Each particle stores its best position until now (local best).
- The method stores the best position reached among all the particles during the whole process until now (global best).
- Positions and velocities of the particles are influenced by the position of its local best and the global best.

Particle Swarm Optimization - Example

- Example of particle displacement in the domain

- Function 21 of benchmark CEC2005



- Red circle: global best

Particle Swarm Optimization – Benefits / trade-offs

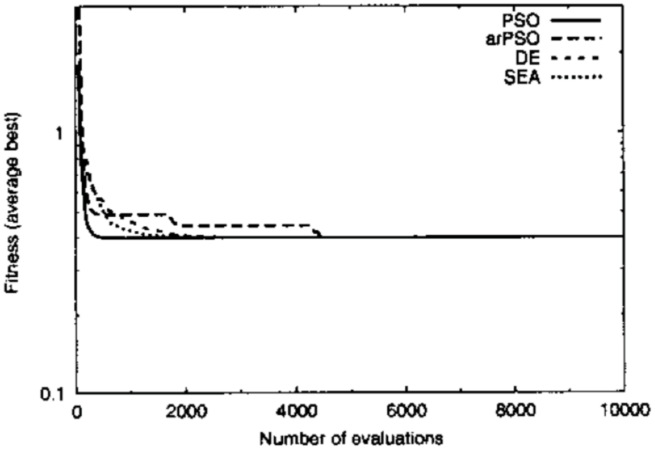
Benefits

- The cost rely on the evaluations of the function.
- PSO can search in large parameter spaces of candidate solutions.
- PSO does not require the function be differentiable.
- Easy to apply improvements.

Trade-offs

- No guarantee that an optimal solution will be found.
- Possible early stuck in local minima.

Comparison with other GAs



Formulation

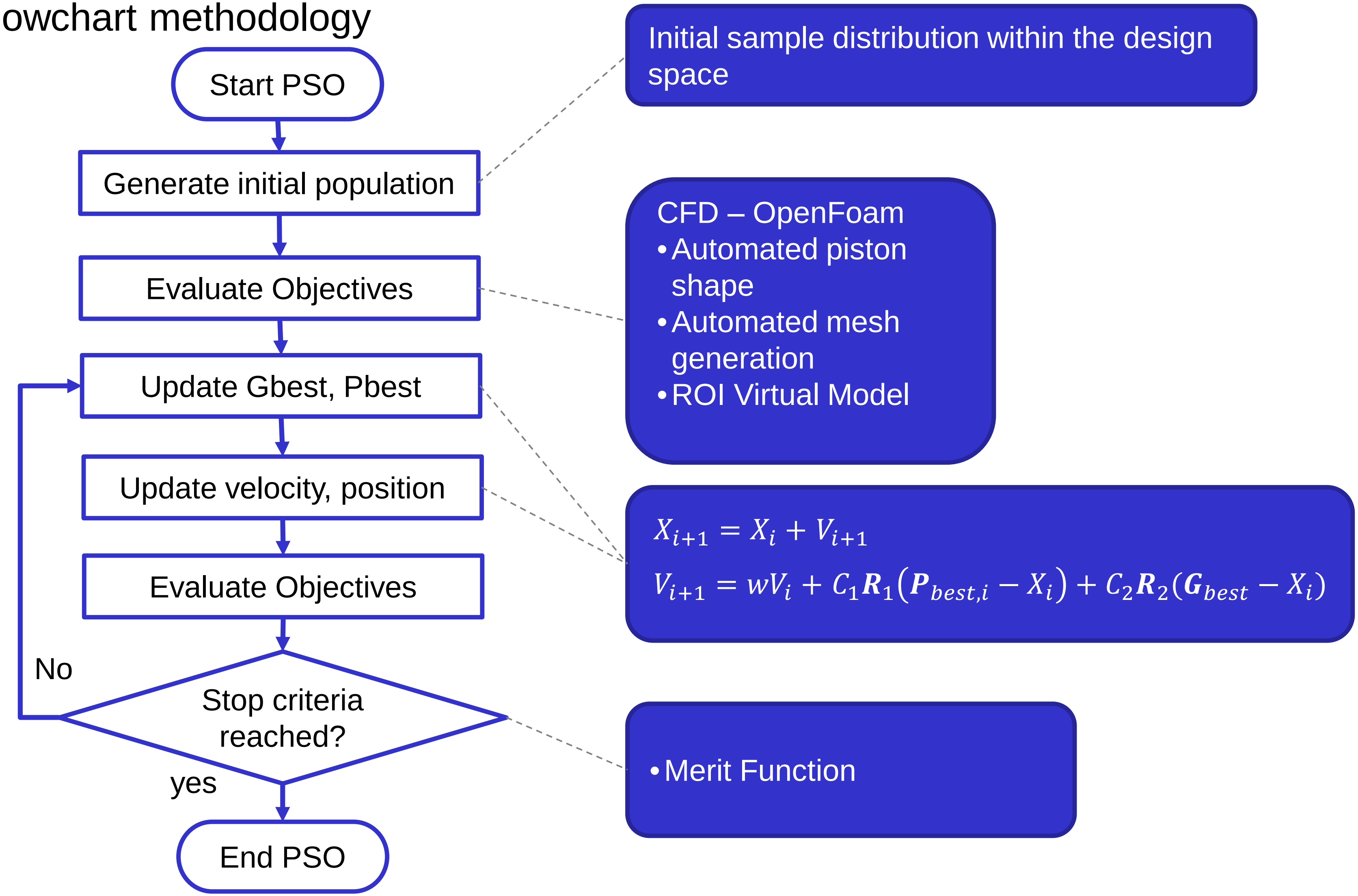
$$X_{i+1} = X_i + V_{i+1}$$

$$V_{i+1} = wV_i + C_1\boldsymbol{R}_1\left(\boldsymbol{P}_{best,i} - X_i\right) + C_2\boldsymbol{R}_2(\boldsymbol{G}_{best} - X_i)$$

J. Vesterstrom and R. Thomsen, *Proceedings of the 2004 Congress on Evolutionary Computation (IEEE Cat. No.04TH8753)*, USA, 2004

PSO – CFD Coupling:

- Flowchart methodology



Start PSO

Generate initial population

Evaluate Objectives

Update Gbest, Pbest

Update velocity, position

Evaluate Objectives

Stop criteria reached?

No

yes

End PSO

Initial sample distribution within the design space

CFD – OpenFoam
- Automated piston shape
- Automated mesh generation
- ROI Virtual Model

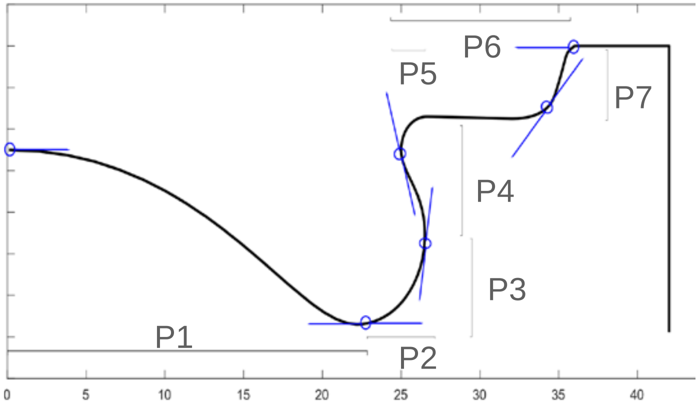
$$X_{i+1} = X_i + V_{i+1}$$

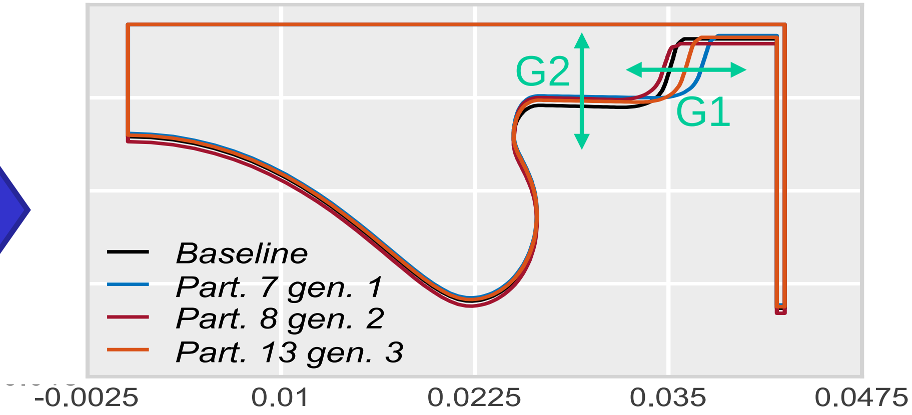
$$V_{i+1} = wV_i + C_1\boldsymbol{R}_1\left(\boldsymbol{P}_{best,i} - X_i\right) + C_2\boldsymbol{R}_2(\boldsymbol{G}_{best} - X_i)$$

- Merit Function

Methodology - Bowl geometry generator

- Geometry is generated as a surface of revolution from a parameterized profile (obtained from a Bezier curve)
- The profile can generate different types of geometries satisfying restrictions: CR
- Flexible, only bowl maximum width and depth are required
- The crevice between piston and liner was kept constant in shape
- However, for this study only the variables related to the step are modified





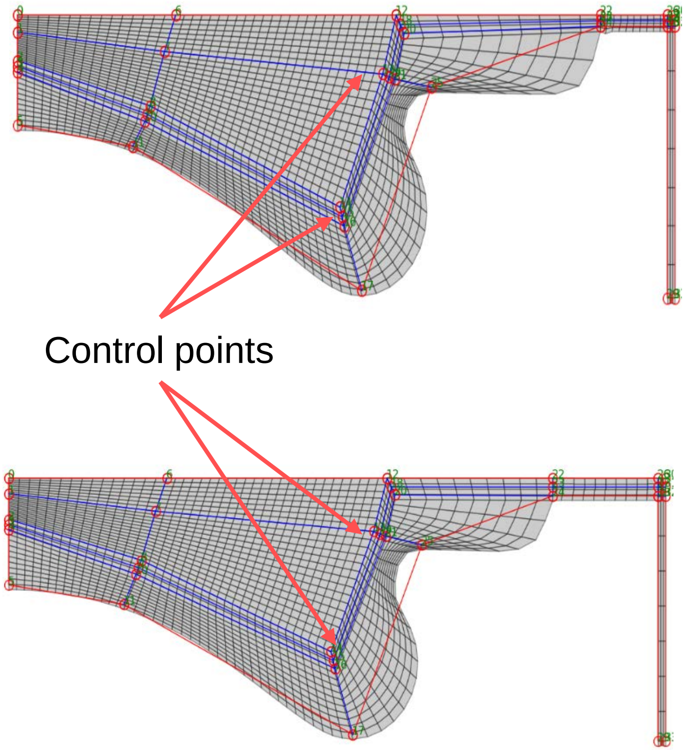
Methodology – DCC Mesh Generator

Every mesh was generated by the DCCmeshtool “automatically”.

Some considerations:

- The Bowl Bezier curve generated is an input
- The Control points for block definition were updated according the bowl step and re-entrant curvature → to avoid negative volumes and skewness issues
- The hole number was an input → to define the sector mesh
- Challenges on the angle of the spray and the orientation of the mesh

Mesh particle 7 generation 1



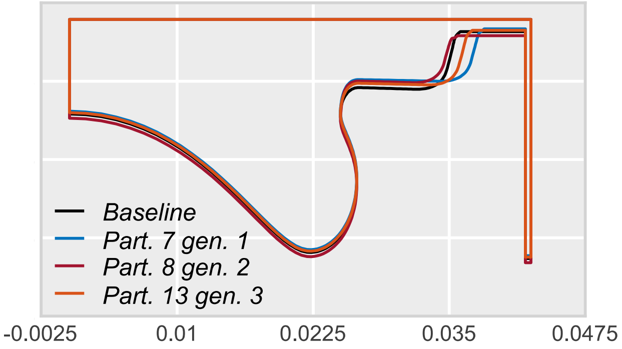
Control points

Mesh particle 8 generation 2

Methodology - Summary

- Coupling of the PSO – CFD codes
- Moderate number of input parameters → Key inputs are included
- Objective function is optimized → high NOx or ISFC penalizes the objective function output

	Input parameters range			
	Geometric		Injection	Air Mgmnt.
Range	G1 [mm]	G2 [mm]	nHoles [-]	Swirl [-]
Min	-1	0	7	1.8
Max	2.5	1	10	2.2
Baseline	0	0	10	2



Results

- The Merit function is formulated to consider the relative importance of ISFC, NOx, and soot against the baseline configuration
- A set of weighting factors were used and scaled linearly

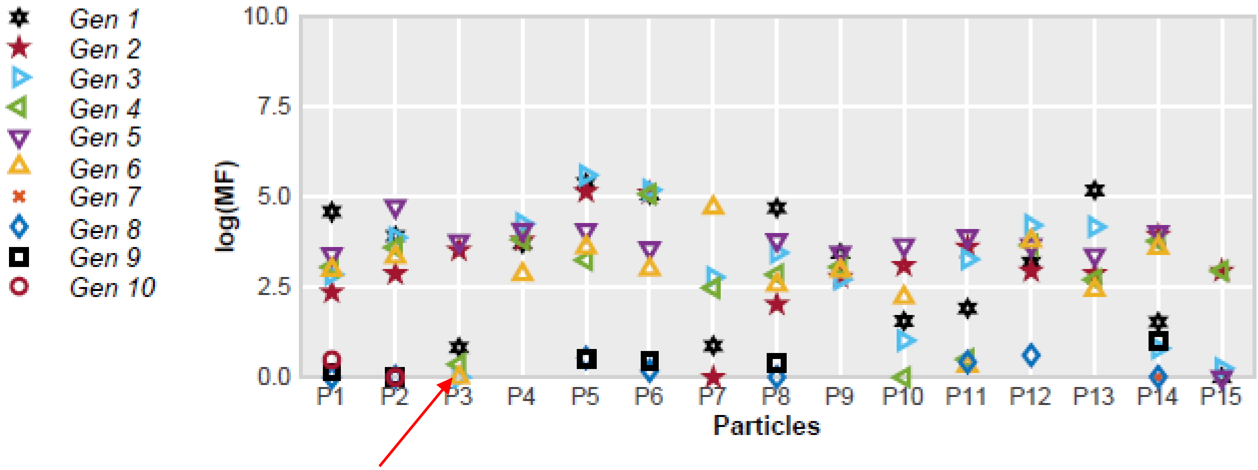
$$MF = \left(\frac{0.3481 \cdot \alpha_{x1}}{\alpha_{x1} \cdot e^{\beta \cdot \frac{x_1 - x_1^{target}}{x_1^{target}}}} - \sum_{n=2}^{3} \left(max\left(1, \frac{x_n - x_n^{limit}}{x_n^{limit}}\right)^{\gamma_n} - 1 \right) \right)$$

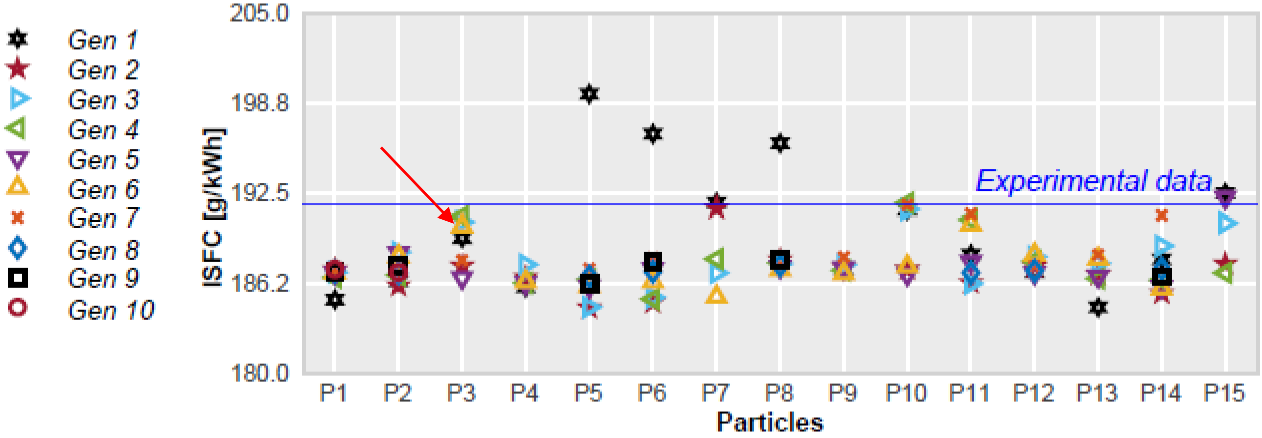
$x_1 \longrightarrow$ ISFC

$x_2 \longrightarrow$ NOx

$x_3 \longrightarrow$ soot

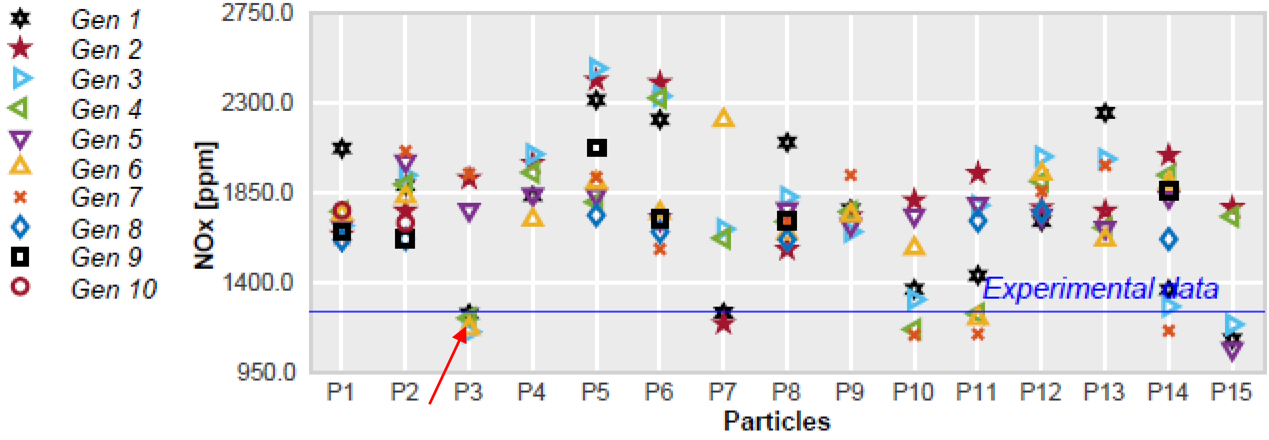
Results: Merit function for all particles of generations

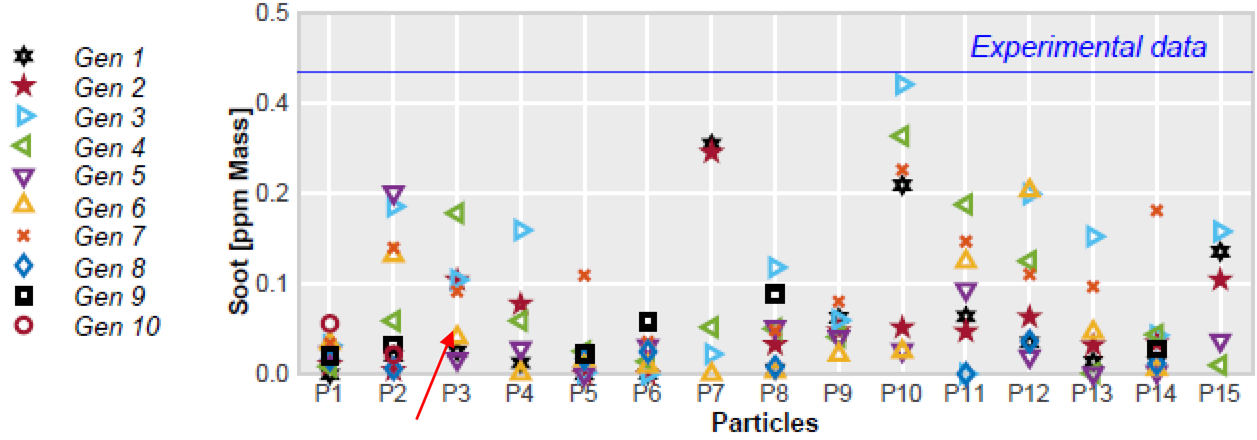




Results: NOx and soot comparison

- Emissions comparison between the experimental data (baseline case) and the results obtained to each simulation from the new geometries.

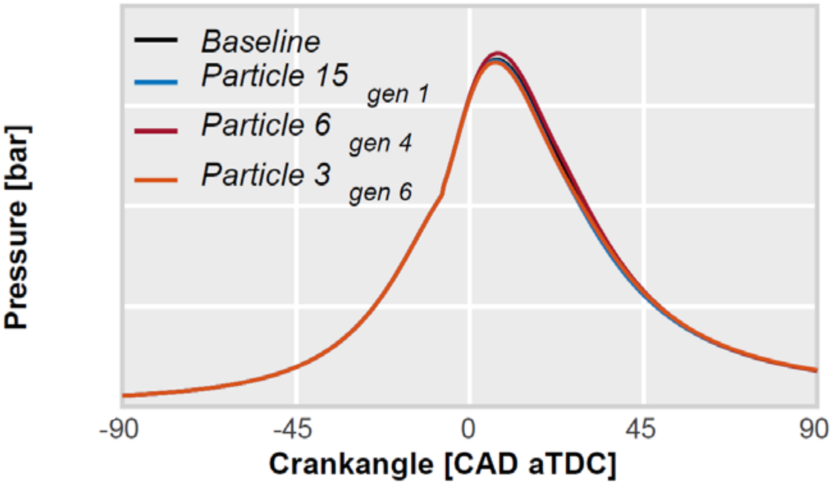


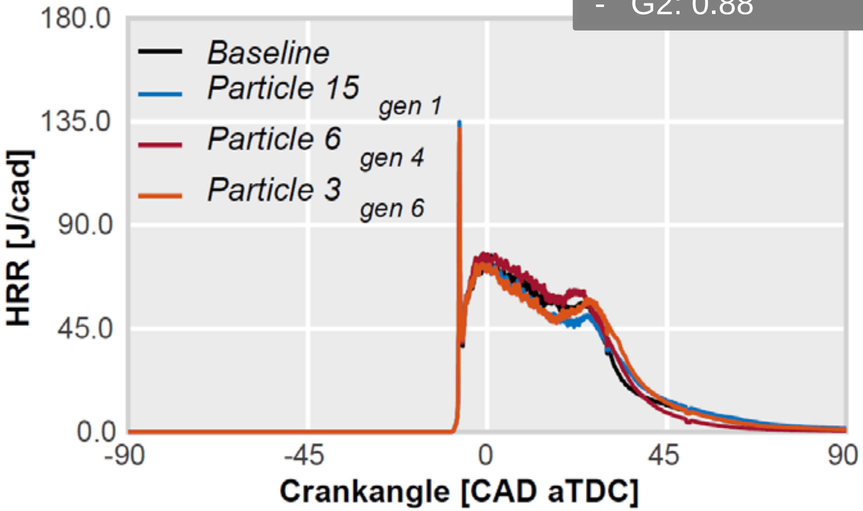


Results: in-Cylinder Pressure and Heat Release Rate

- Comparison of baseline and best case predicted

Particle 3 – Gen 6:
- 10 holes
- Swirl 2.1
- G1: 1.11
- G2: 0.88

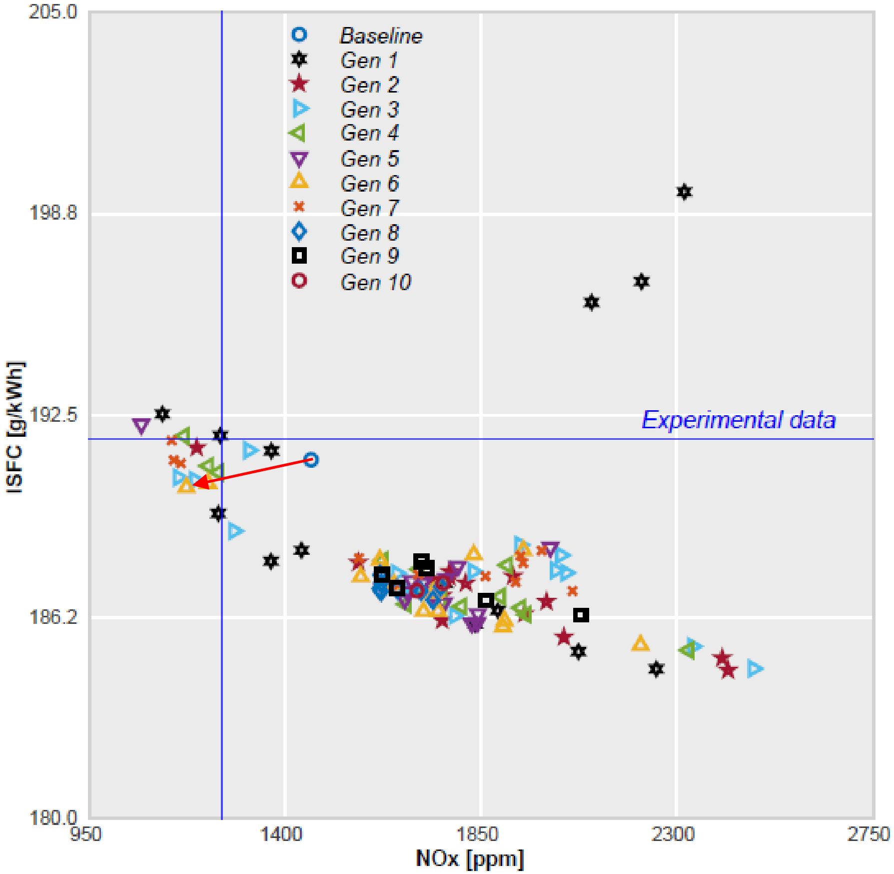




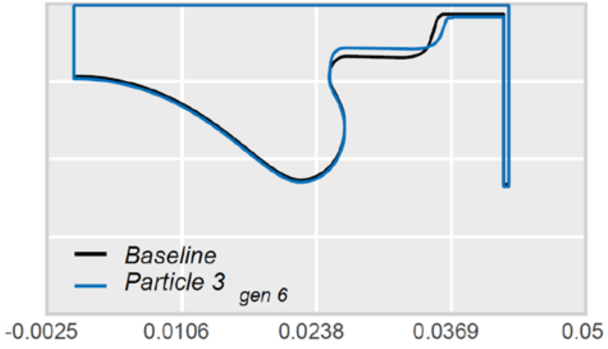
	IMEP [bar]	ISFC [g/KWh]	NOx [ppm]	YSoot [-]
Coarse mesh	22.45	191.12	1459.97	2.10E-06
Part. 15 gen. 1	22.46	192.54 ☹	1118.82 ☺	2.41E-06 ☹
Part. 6 gen. 4	23.17	185.22 ☺	2326.19 ☹	1.79E-07 ☺
Part. 3 gen. 6	22.62	190.27 ☺	1173.79 ☺	5.12E-07 ☺

Results: NOx ISFC trade-off

- The favourable configuration is selected from the pareto front.



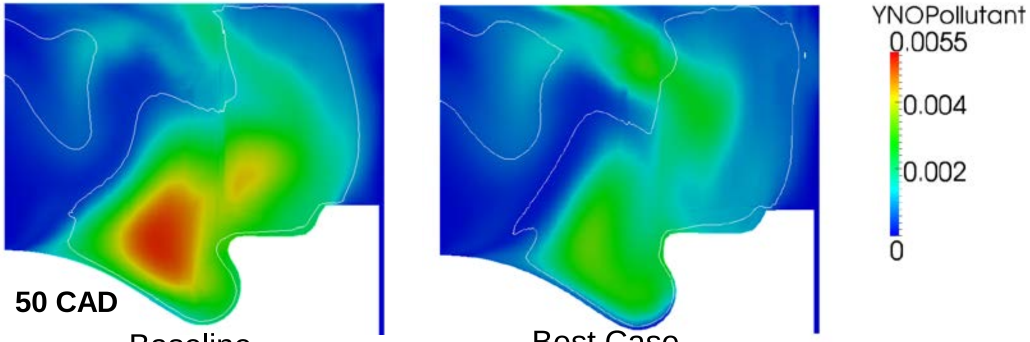
Particle 3 – Gen 6:
- 10 holes
- Swirl 2.1
- G1: 1.11
- G2: 0.88



Results:
Baseline – Best case comparison

- What is happening in the bowl?

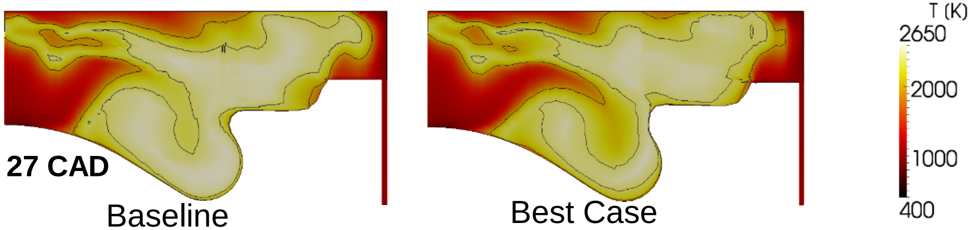
YNO



Baseline

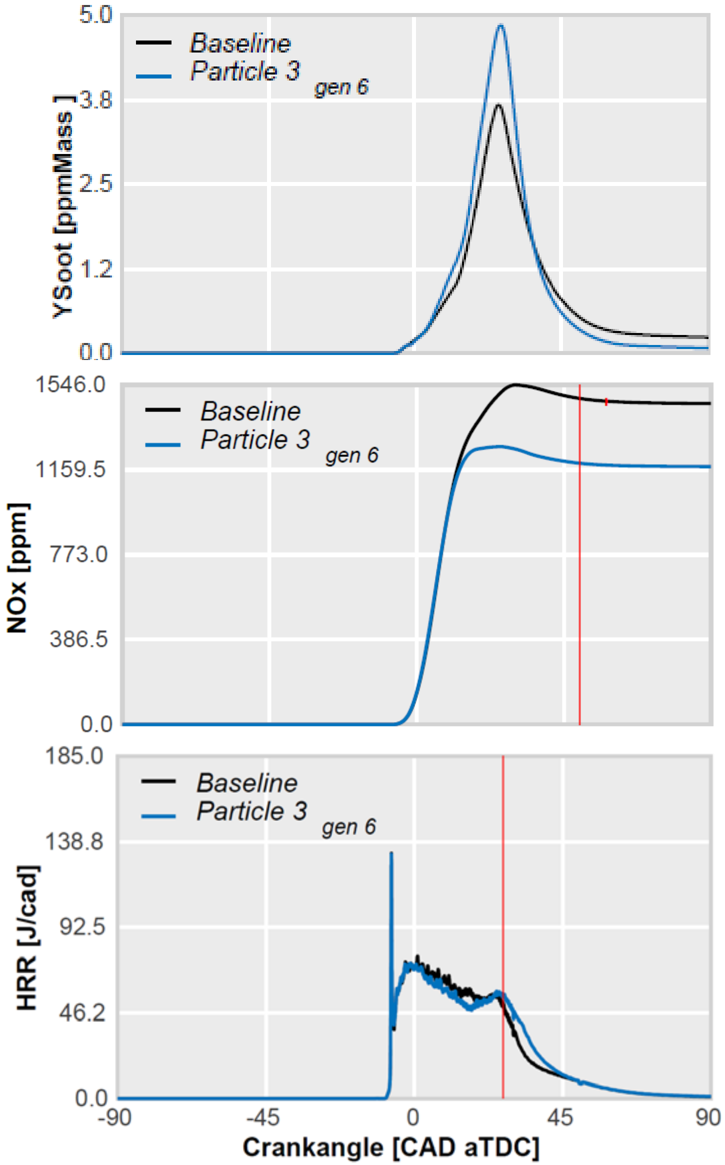
Best Case

Temperature



Baseline

Best Case



Conclusions

- In general, the CFD model setup provides a reliable prediction of combustion performance, in terms of in-cylinder pressure, RoHR and pollutant emissions, both for the fine and coarse meshes.

- Particle swarm optimization method has been coupled to the OpenFOAM Lib-ICE code and validated.

- An optimum configuration has been obtained that fulfills NOx and Soot restrictions improving slightly fuel consumption. However, further iterations will be performed to ensure that this optimum is the global best.
    - The best case predicted produced a 0,45% reduction in consumption and 24% in NOx levels.

- The main effects of the step bowl configuration have been confirmed → it enhances the late mixing process and deflects the flame, keeping it away from the cylinder wall.

Conclusions & Next steps

Next steps

- Increase the number of bowl related geometrical parameters to get more flexibility on the combustion system design (on going)

- Add the spray included angle to go for a full matching optimization → challenges on the oriented mesh automatic generation

- Extend the study including different operating conditions and engine settings (SOI, ROI, Inj Pressure,…) – Coupling with an in-house developed virtual injector model (ongoing)

- Apply the methodology to the optimization of the combustion system using substitutes of diesel fuel with significantly different physical and chemical properties like DME, OMEs

Acknowledgment

- This work was partly sponsored by FEDER and the Spanish “Ministerio de Economía y Competitividad” in the frame of the Project “Desarrollo de modelos de combustión y emisiones HPC para el análisis de plantas propulsivas de transporte sostenible (CHEST)”, reference TRA2017-89139-C2-1-R

- Authors would like to thank the ICE group at Polimi, specially Prof T. Lucchini and Dr. A. Della Torre for their kind and exhaustive support in the Lib-ICE code implementation

THANK YOU VERY MUCH !

ANY QUESTION ?

BIBLIOGRAPHY

[1] J. Kennedy and R. Eberhart, "Particle swarm optimization," *Proceedings of ICNN'95 - International Conference on Neural Networks*, Perth, WA, Australia, 1995, pp. 1942-1948 vol.4.

[2] Federico Marini, Beata Walczak, Particle swarm optimization (PSO). A tutorial. Chemometrics and Intelligent Laboratory Systems, Volume 149, Part B, 2015, Pages 153-165, ISSN 0169-7439.

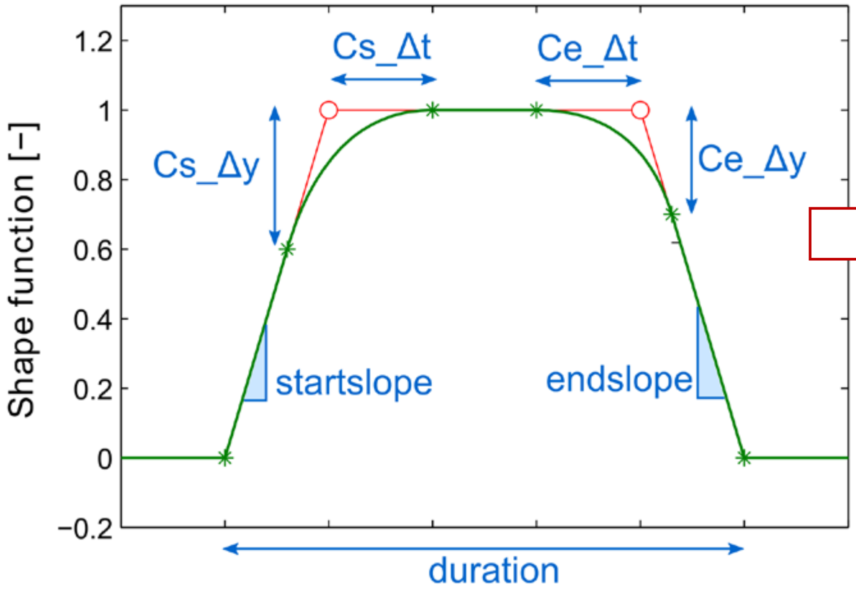
[3] J. Vesterstrom and R. Thomsen, "A comparative study of differential evolution, particle swarm optimization, and evolutionary algorithms on numerical benchmark problems," *Proceedings of the 2004 Congress on Evolutionary Computation (IEEE Cat. No.04TH8753)*, Portland, OR, USA, 2004, pp. 1980-1987 Vol.2.

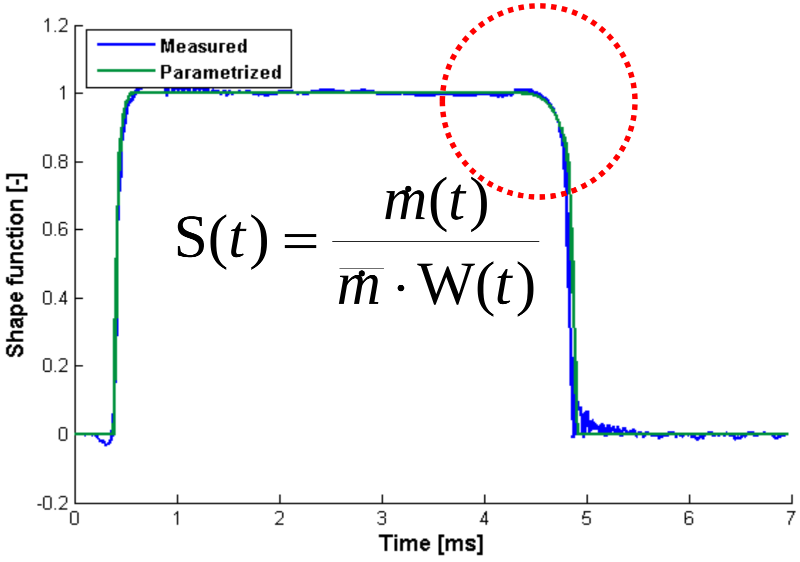
APPENDIX

Methodology – Injection rate profile generation

- This tool can generate the main injection and any number of pilot and post injection required
- Allows to modify the injection pressure, fuel mass or nozzle hole diameter
- Requires experimental data of the injector to be trained
- Keeps the start and end of injection slopes

$$y1 = \bar{\dot{m}} \cdot \left[1 + A_i \cdot exp\left(-\gamma_i \cdot t\right) \cdot cos(\omega_i \cdot t + \phi_i)\right]$$





$$S(t) = \frac{\dot{m}(t)}{\bar{\dot{m}} \cdot W(t)}$$