ESAFORM Conference, Toulouse, France
26.04.2024

Surrogate Modeling for Multi-Objective Optimization in the High-Precision Production of LiDAR Glass Optics

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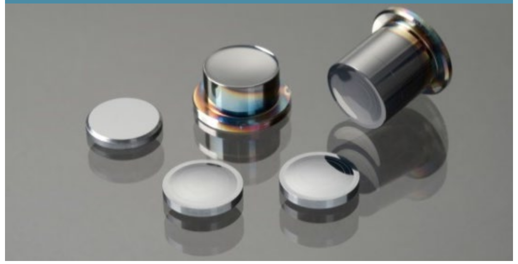
doi: 10.24406/publica-3093

Introduction & Motivation

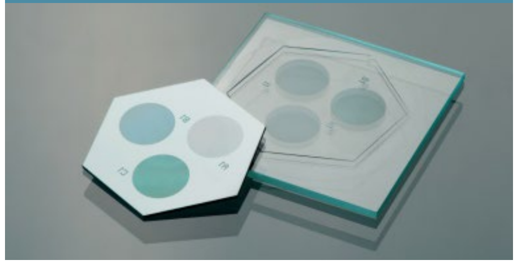
Why replicative optics production?

LIDAR optics

Infrared optics



Microstructured optics

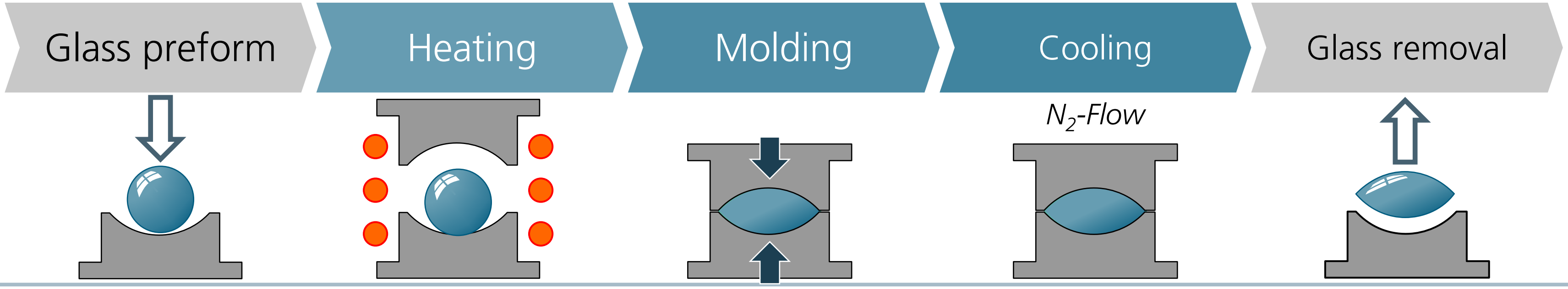


Sensors

Replicative Glass Molding

- **Complex geometries**
  - 3D bended freeform surfaces, Sharp edges
- **High form accuracy**
  - Form deviation of Submicron
- **Low surface roughness**
  - Ra < 5 nm
- **Defect-free**
  - Ripples, bubbles, contaminations
- **Mass & low-cost production**

Replicative manufacturing of glass optics (E.g. isothermal Precision Glass Molding)



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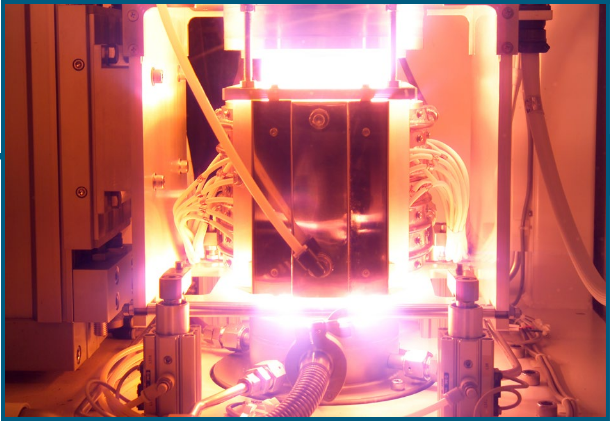
Introduction & Motivation

Replicative glass molding process parameters

Process parameters

- Molds temperature
- Glass temperature
- Heating time & rate
- Pressing force & time
- Annealing time

Replicative Glass Molding



Final product

Inputs

Black box

- Closed chamber process
- Limited physical model for input/output interactions

Outputs

- Form accuracy
- Center thickness
- Optical properties
- Energy consumption
- Overall production time

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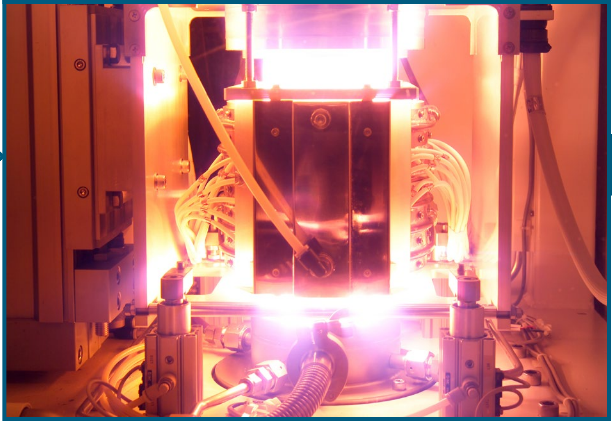
Introduction & Motivation

Replicative glass molding process parameter optimization

Process parameters

- Molds temperature
- Glass temperature
- Heating time & rate
- Pressing force & time
- Annealing time

Replicative Glass Molding



Final product

How to achieve optimum output(s)?

Finite element method ✓

ML-based optimization ?

Introduction & Motivation

Previous Methods

Finite element method

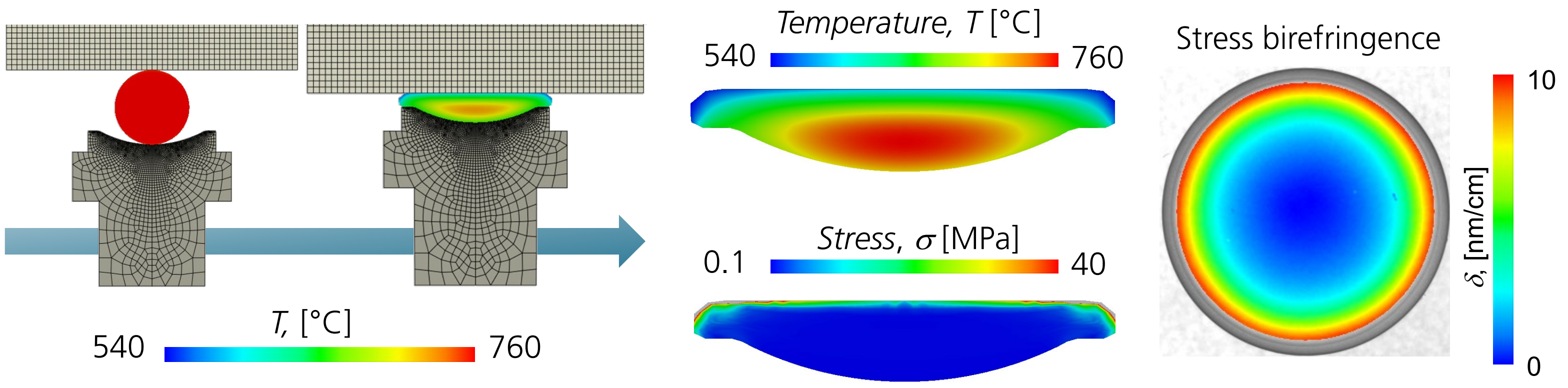
- Thermo-structural coupling analysis
- Viscoelastic material modeling
- Boundary condition simplifications

Advantages

- Fundamental understanding
- Early detection of defects
- temperature and stress distribution

Disadvantages

- Sophisticated characterizations
- Thermal and mechanical calibration
- High computational effort (3D model)



- **Vu et. al. (2020), Thermo-viscoelastic Modeling of Nonequilibrium Material Behavior of Glass in Non-isothermal Glass Molding. Proc. Manuf. 47, 1561-1568.**
- **Vu et.al. (2022), Modeling non equilibrium thermoviscoelastic material behaviors of glass in non-isothermal glass molding. JACER 105(11), 6799-6815.**
- **Vu (2024), Modeling relaxation nature of nonequilibrium glass in non-isothermal glass molding. RWTH Aachen Dissertation.**

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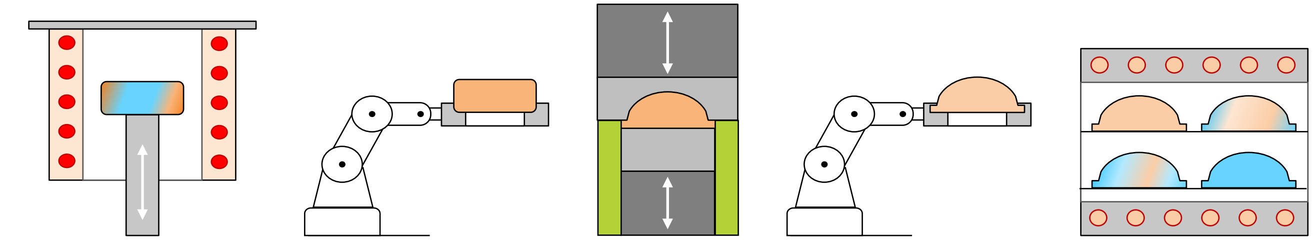
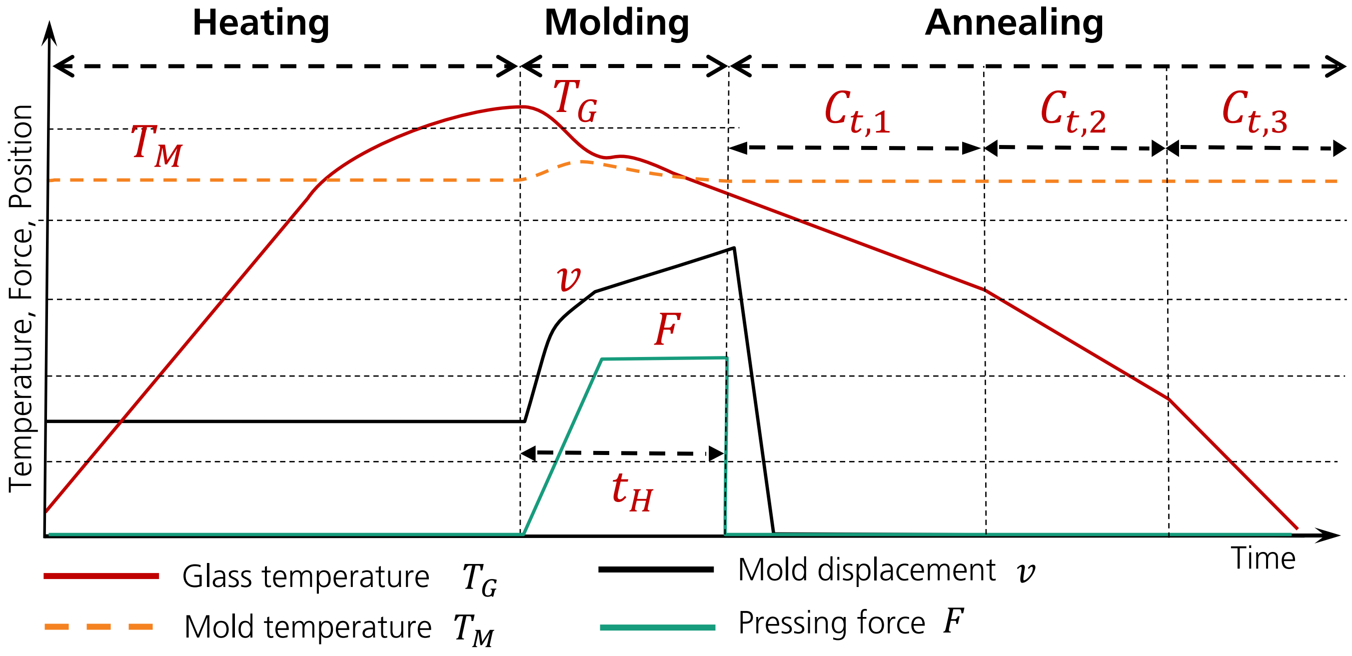
Introduction & Motivation

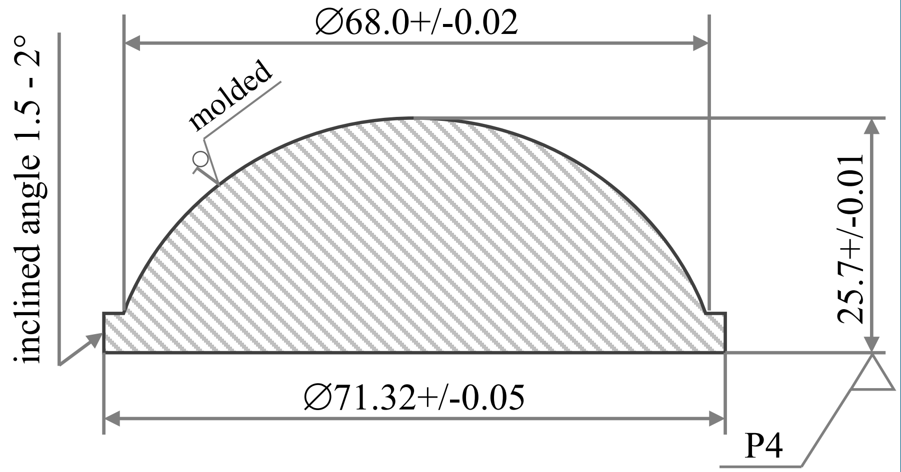
Non-isothermal Glass Molding (NGM) to produce LIDAR lenses

Heating → Transport → **Molding** → Transport → **Annealing**





Final lense requirements



Lense output parameters to optimize

1. Lense form accuracy
2. Lense center thickness

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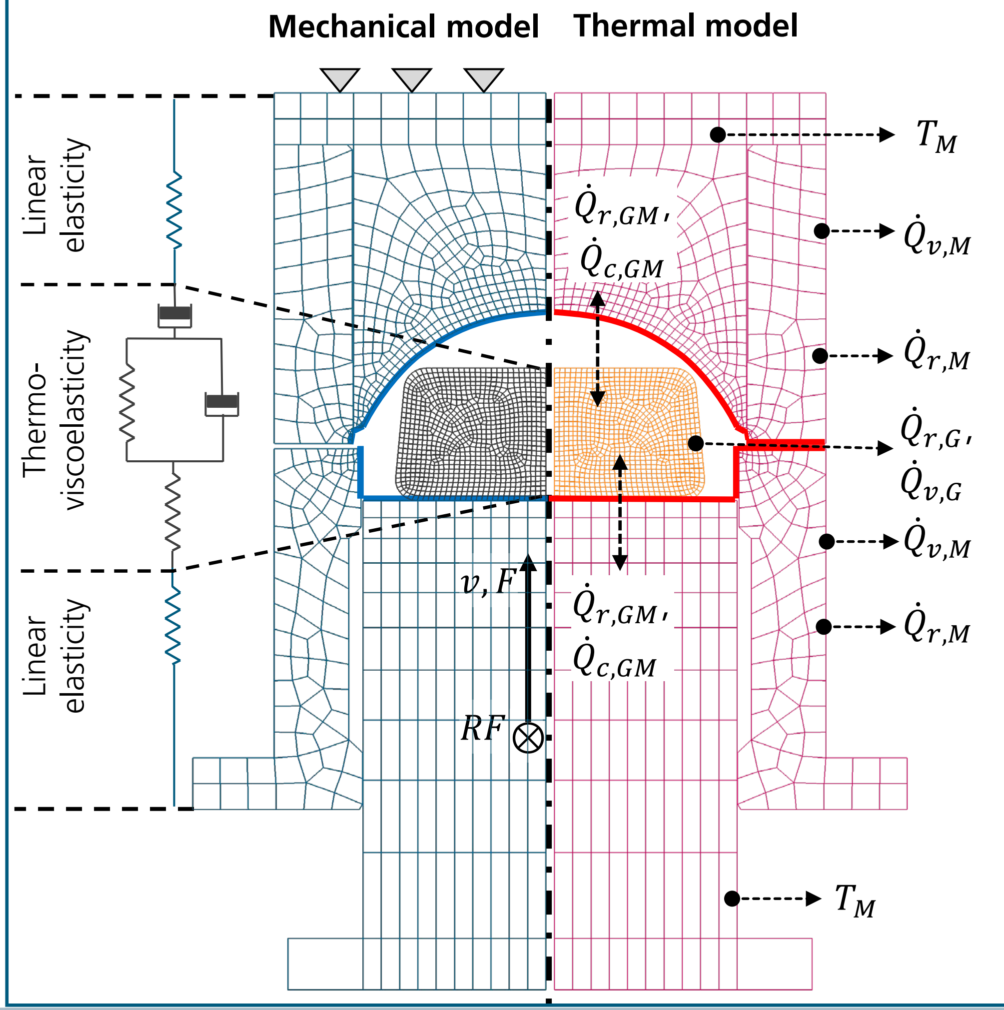
Introduction & Motivation

FEM simulation model of NGM process



Heat transfers at boundaries

Convection heat transfers

$\dot{Q}_{v,G}$ Glass-environment convection

$\dot{Q}_{v,M}$ Molds-environment convection

Radiation heat transfers

$\dot{Q}_{r,G}$ Glass-environment radiation

$\dot{Q}_{r,M}$ Molds-environment radiation

$\dot{Q}_{r,GM}$ Glass-molds radiation

Contact heat transfers

$\dot{Q}_{c,GM}$ Glass-molds conductance

Other boundary conditions

Fixed mech. BC, $u = 0$

Reference point RF, v

Friction interfaces, $\mu(T, p, v)$

Thermal conductance, $h_c(T, p, R_a)$

Process parameters

1. Glass temperature
2. Molds temperature
3. Molding velocity
4. Pressing force
5. Pressing time
6. Cooling time1
7. Cooling time2
8. Cooling time3

Black box

Non-isothermal Glass Molding (FEM Simulation)

Outputs

1. Glass form accuracy
2. Glass center thickness

Introduction & Motivation

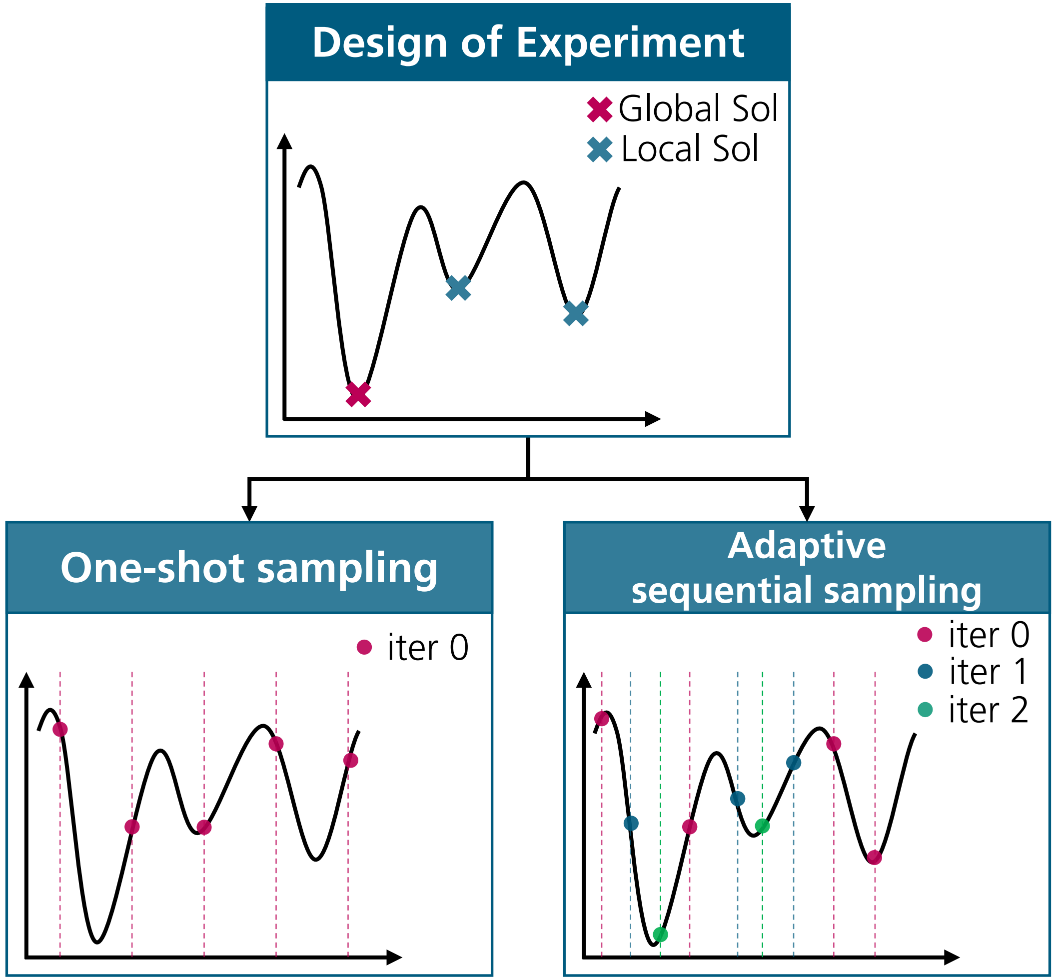
Motivation

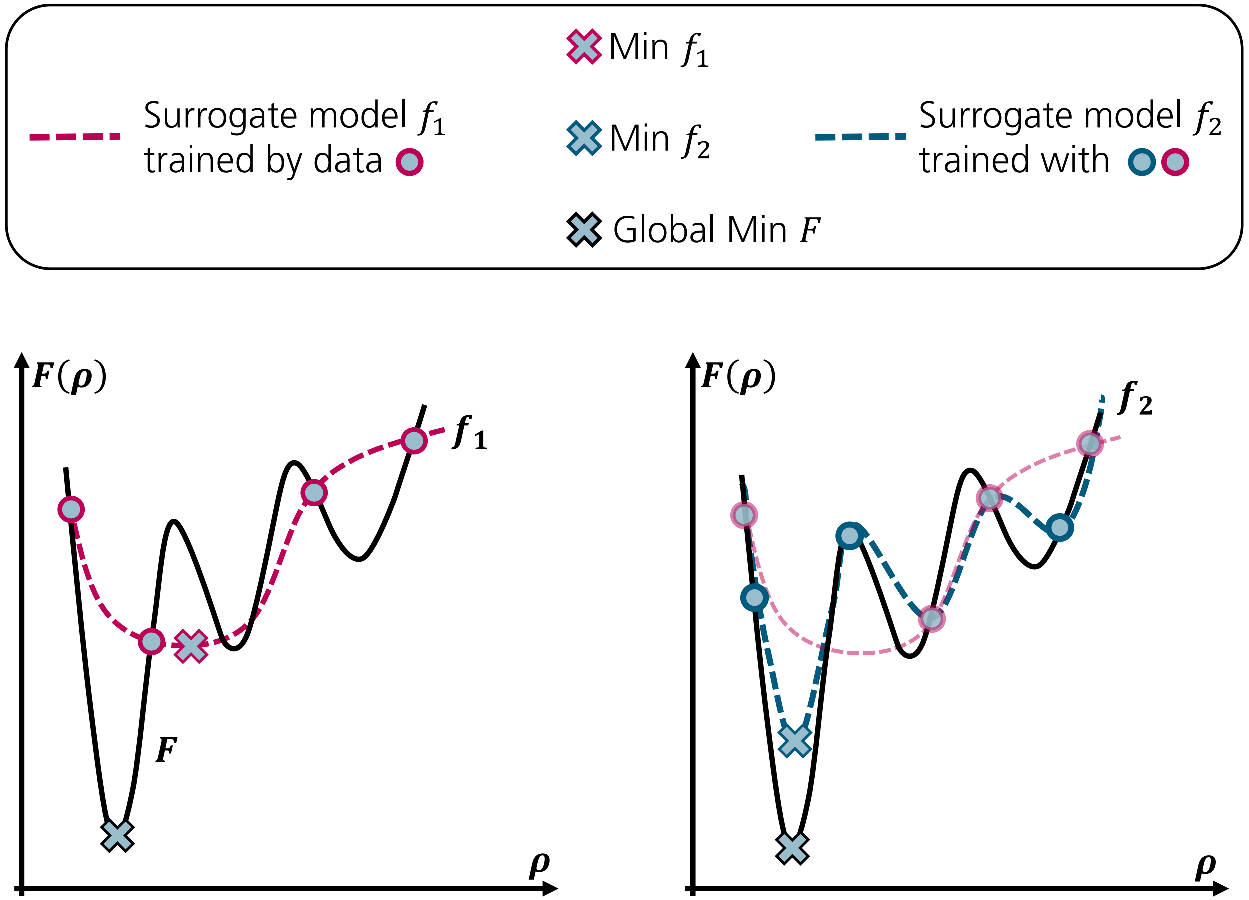
Motivation

- Developing an automatic machine learning based optimization algorithm
- Improving multiple features of produced optics at the same time
- Industry mostly rely only on sparse experimental data, not FEM simulation
- Compatible algorithm with both experiment and simulation
- Compatible algorithm with sparse dataset → minimization of experimental effort

Methodology & Results

How can an experiment be designed for machine learning & optimization?





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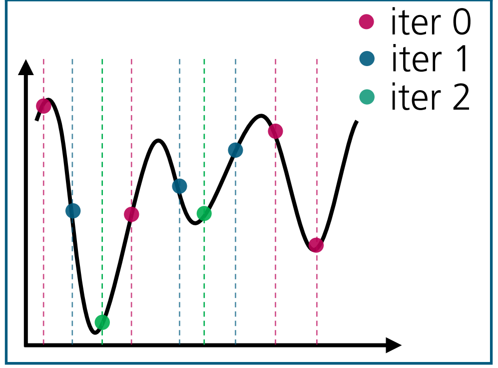
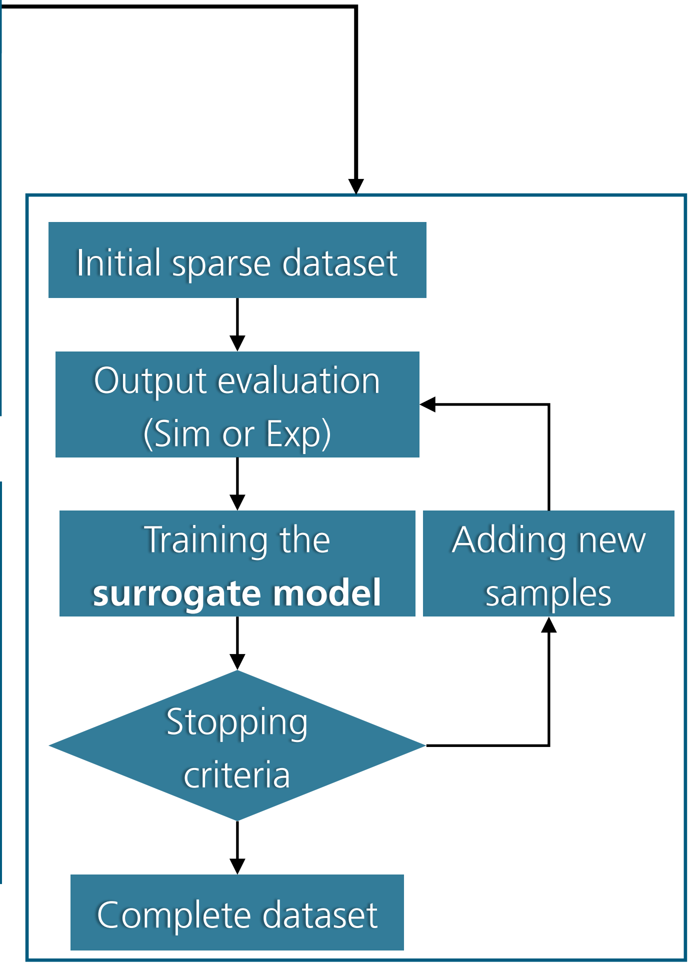
Methodology & Results

Which surrogate models are suitable for sparse data set?

Adaptive sequential sampling



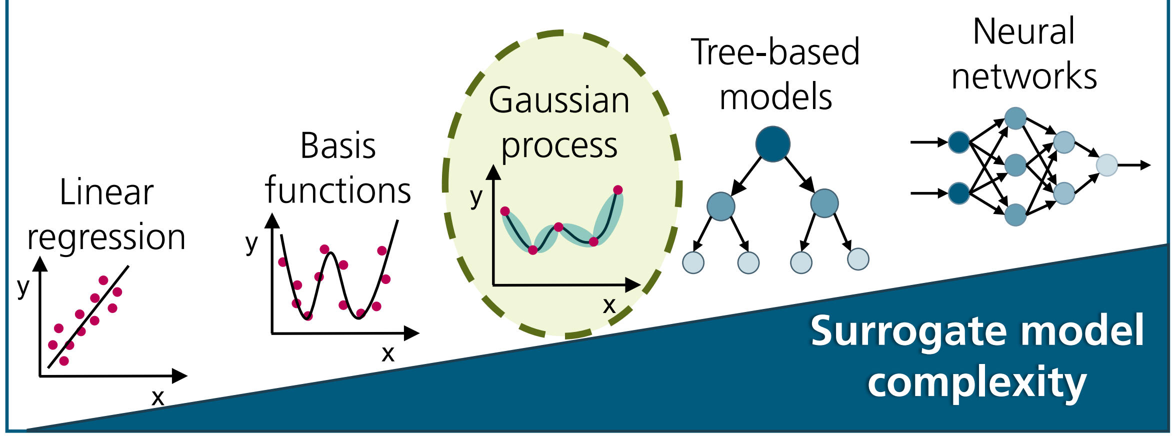


Surrogate model

- Supervised machine learning
- Compensation for expensive black box

Which surrogate model?

- Complex models require more data (Hyperparameter tuning)
- Sparse dataset (<30) requires simpler surrogate model
- Highly simple models work poorly



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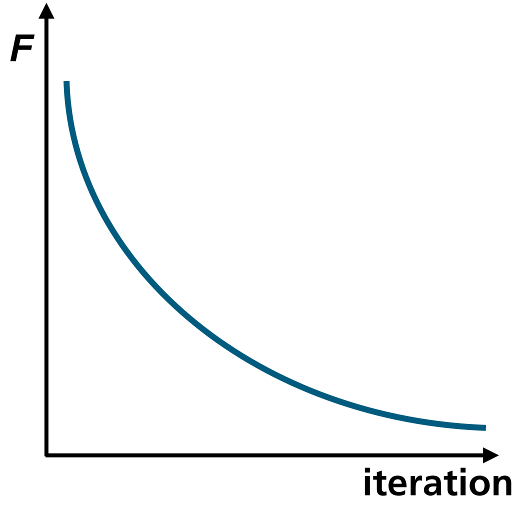
Methodology & Results

Definitions: Hypervolume & Selection strategy

Optimization

Single-objective

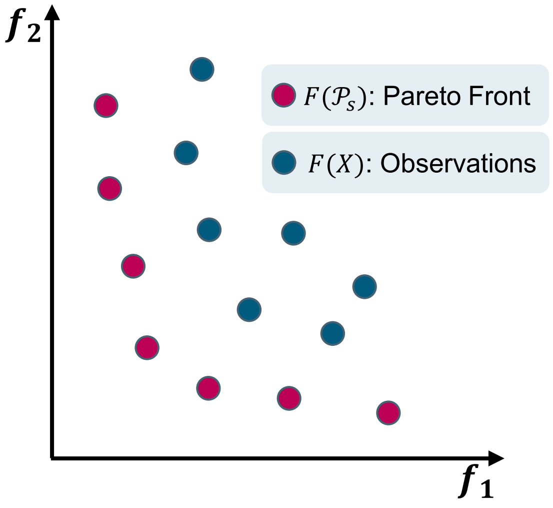
Convergence plot



- One single solution

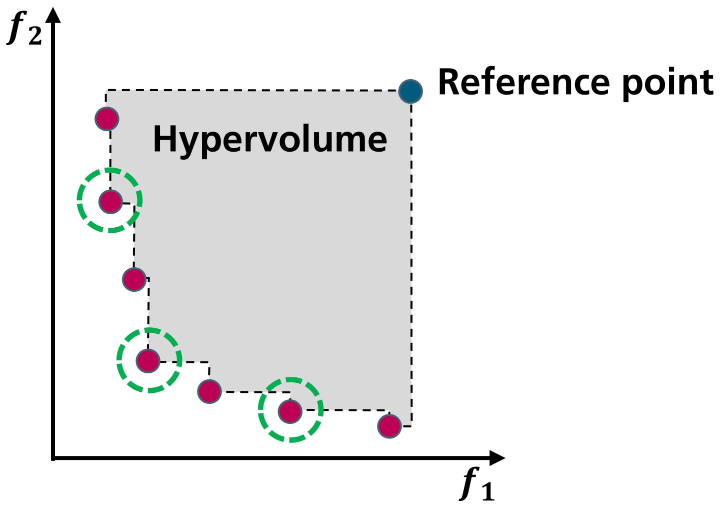
Multi-objectives

Performance space



- Pareto front optimal solutions
- Trade-off between objectives

Hypervolume & Selection strategy



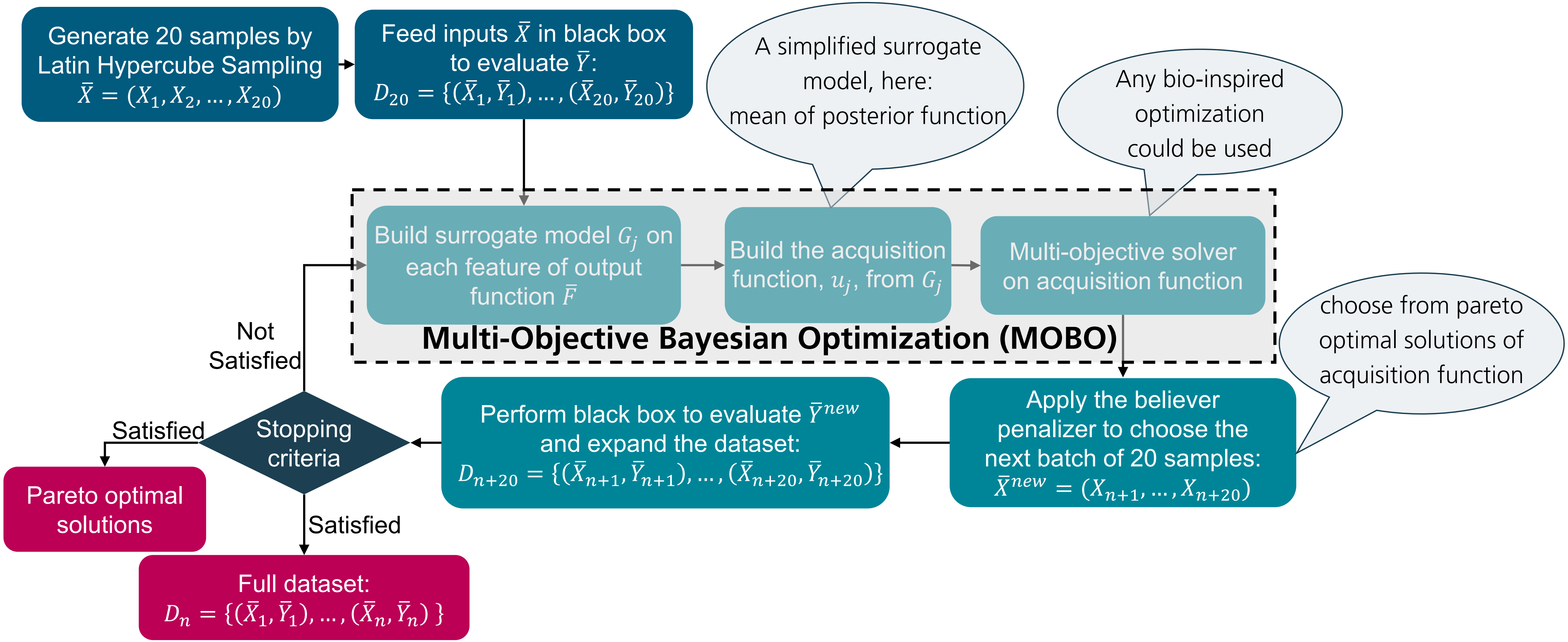
- Hypervolume indicator for convergence of multi-objectives
- **Selection strategy (Adaptive sampling)**

Instead of <u>**one**</u> new sample, <u>**a batch of**</u> samples are suggested

- Kriging believer
- Local penalization
- Believer penalizer

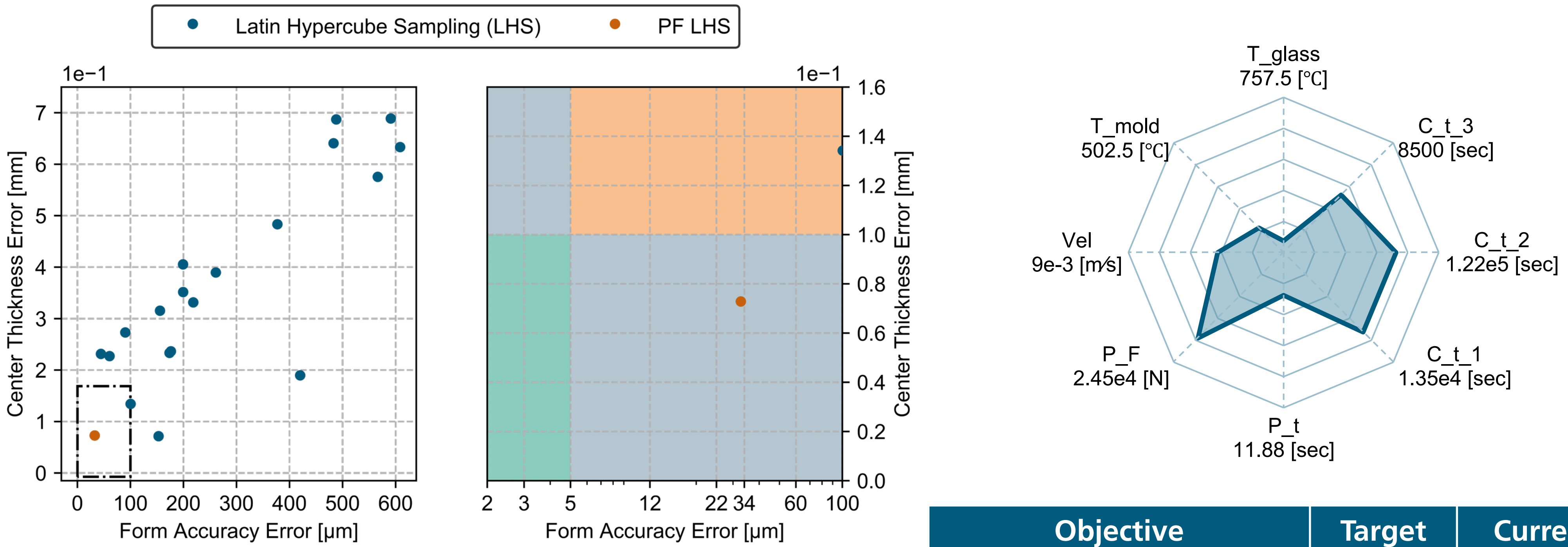
Methodology & Results

How can the ML-based optimization be implemented in manufacturing process?



Methodology & Results

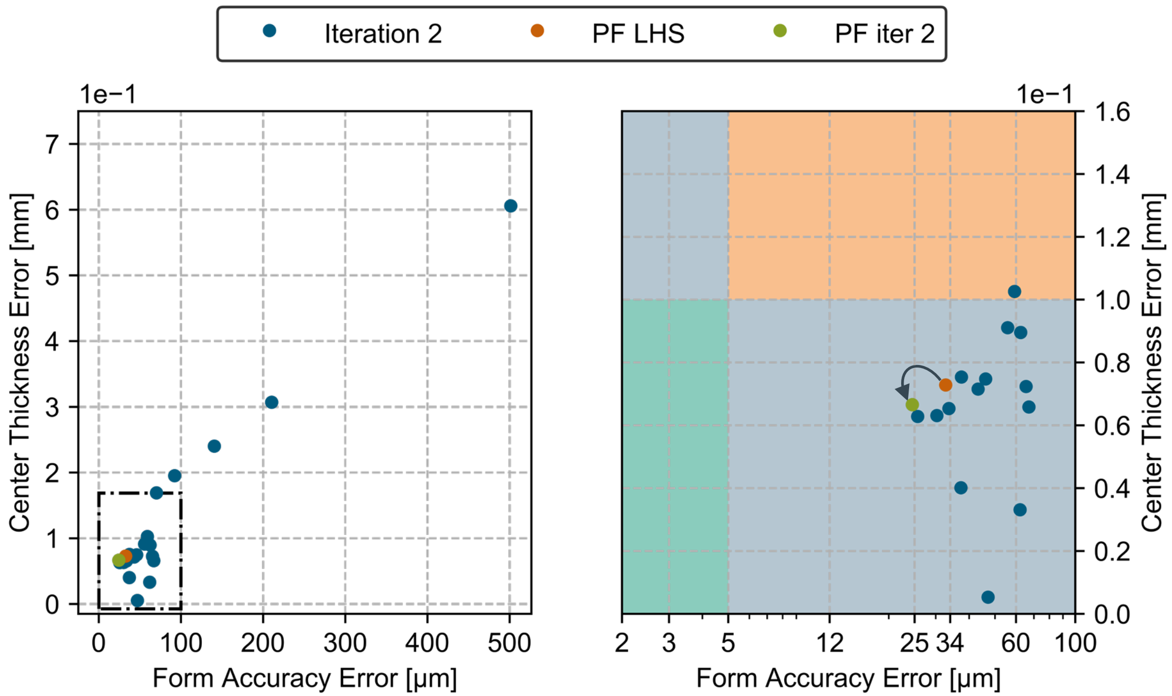
Results of NGM Process

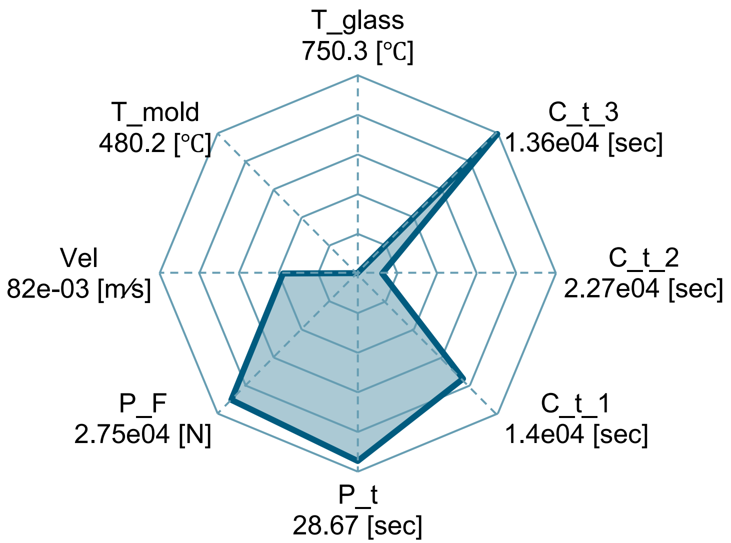


Objective	Target	Current best
Form accuracy error (μm)	5	33
Center thickness error (mm)	1.0	0.78

Methodology & Results

Results of NGM Process

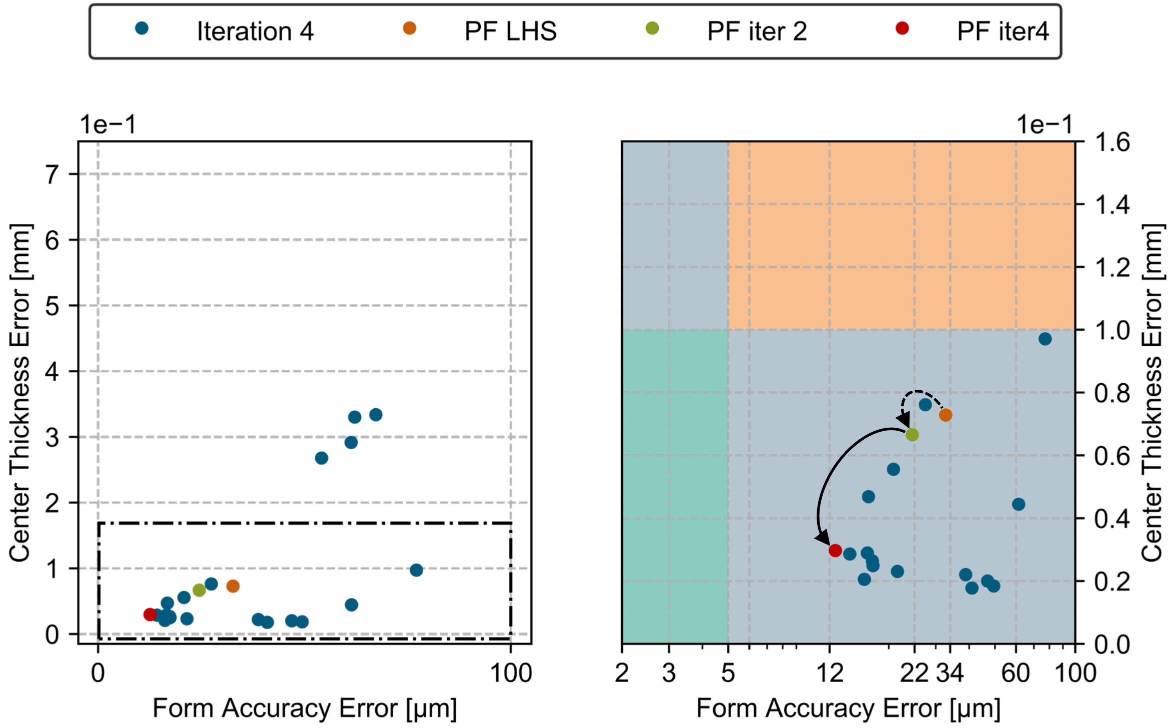


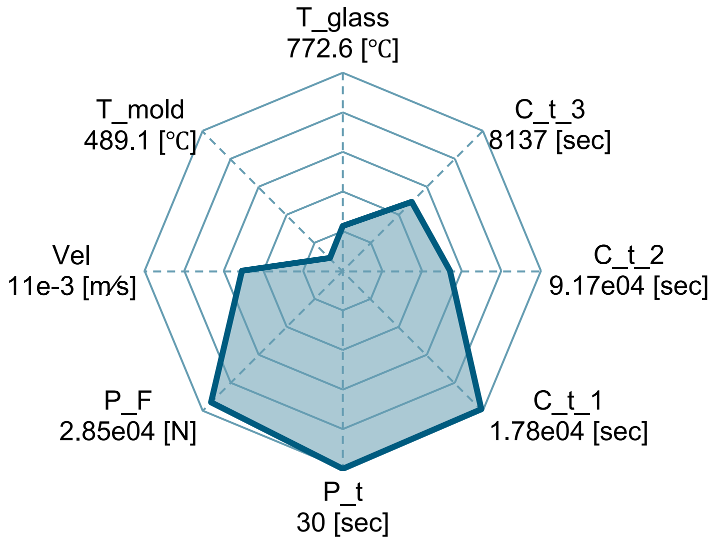


Objective	Target	Current best
Form accuracy error (μm)	5	25
Center thickness error (mm)	1.0	0.65

Methodology & Results

Results of NGM Process

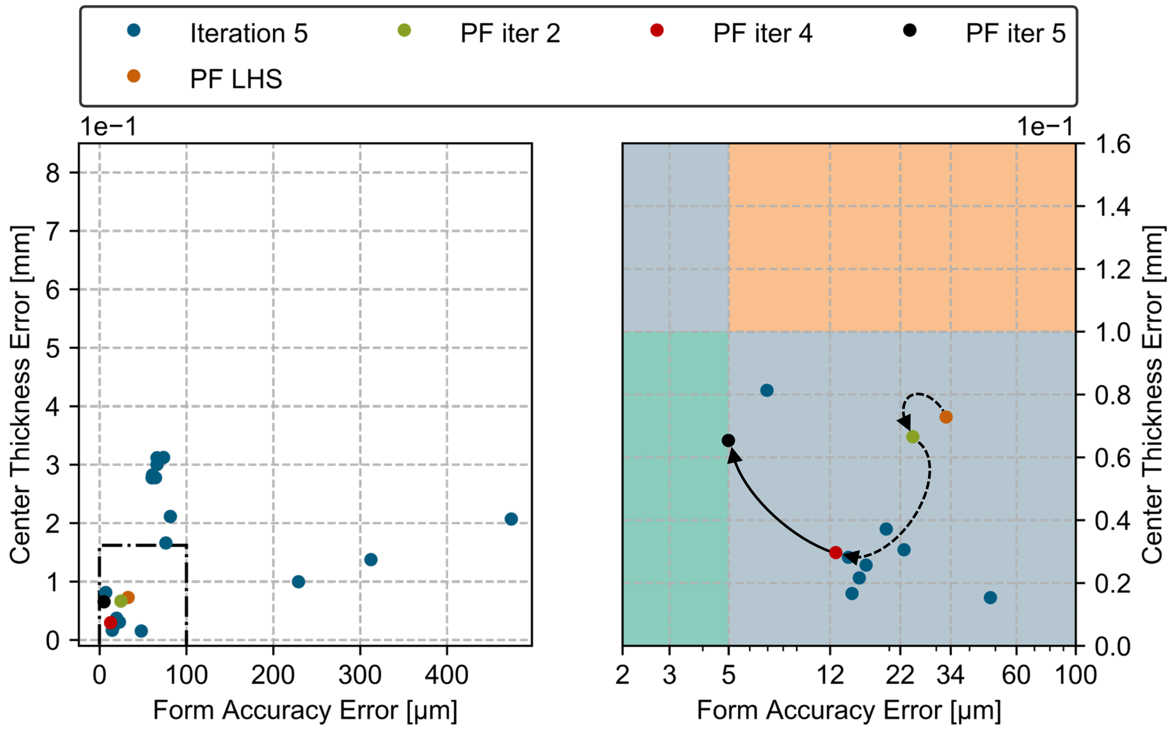


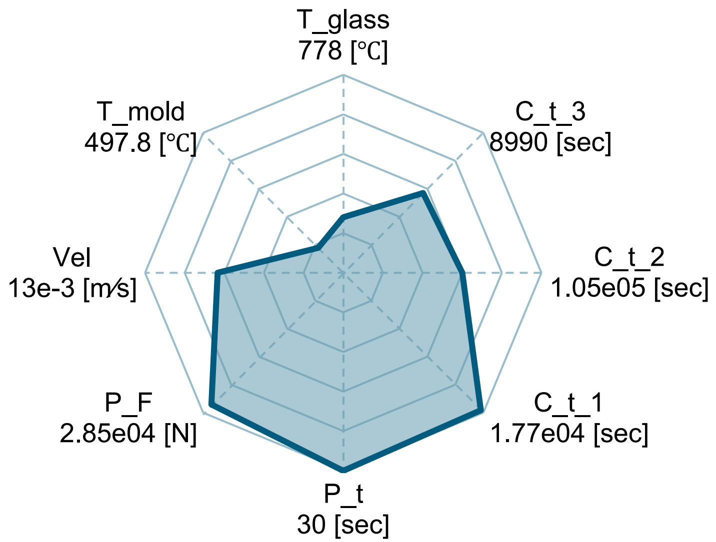


Objective	Target	Current best
Form accuracy error (μm)	5	12
Center thickness error (mm)	1.0	0.3

Methodology & Results

Results of NGM Process





Objective	Target	Current best
Form accuracy error (μm)	5	5
Center thickness error (mm)	1.0	0.65

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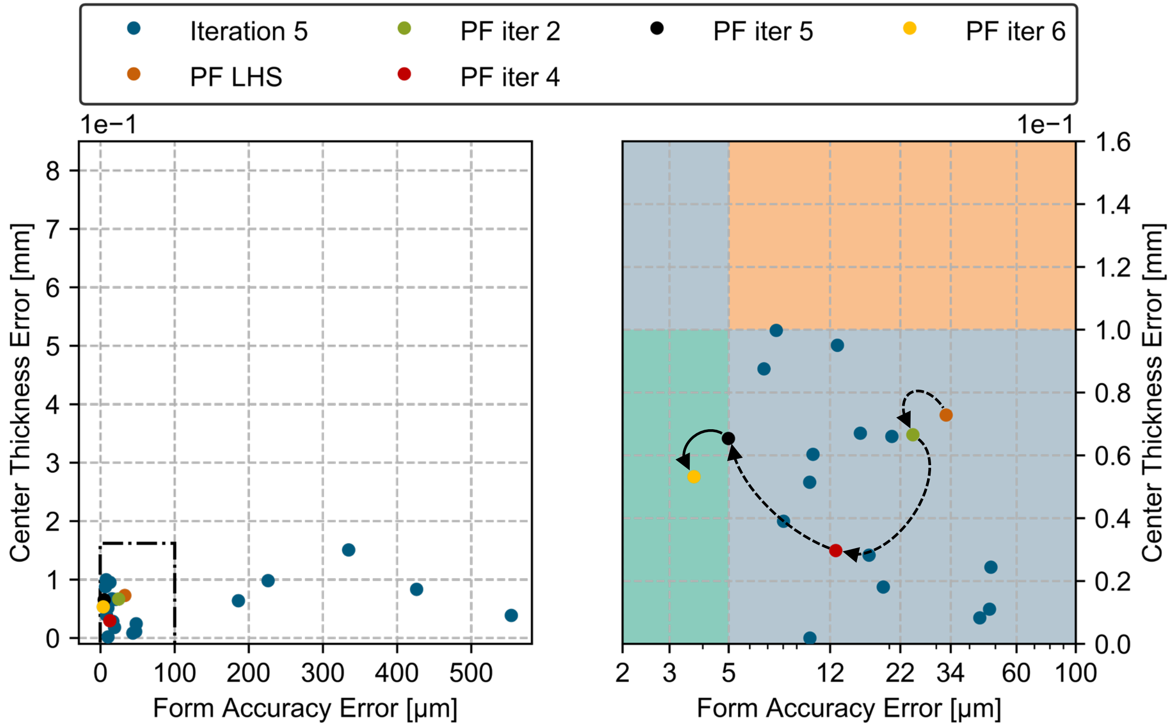
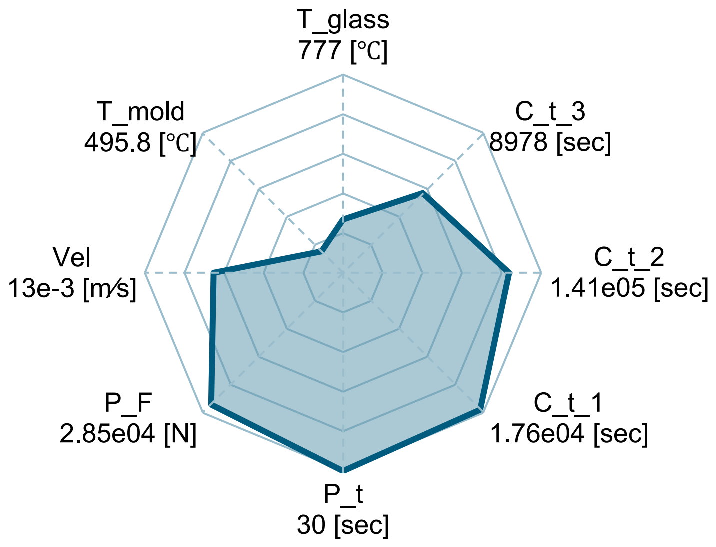
Methodology & Results

Results of NGM Process





Objective	Target	Current best
Form accuracy error (μm)	5	4
Center thickness error (mm)	1.0	0.5

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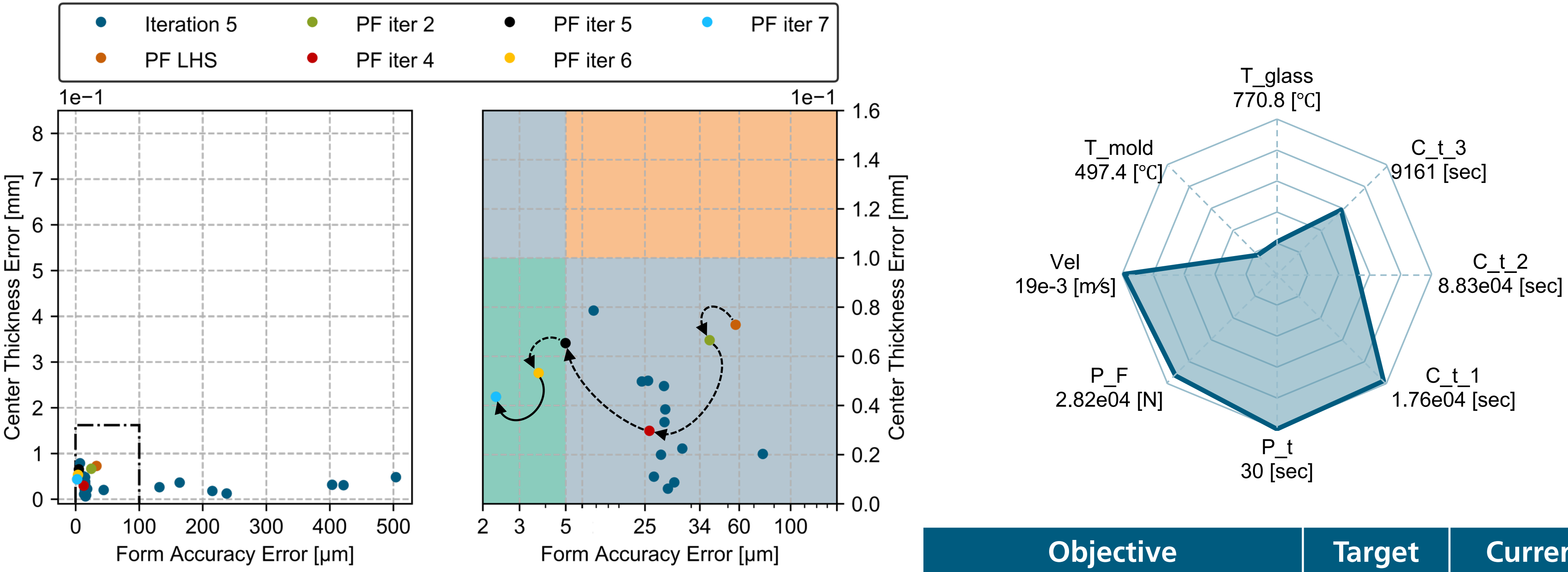
Methodology & Results

Results of NGM Process

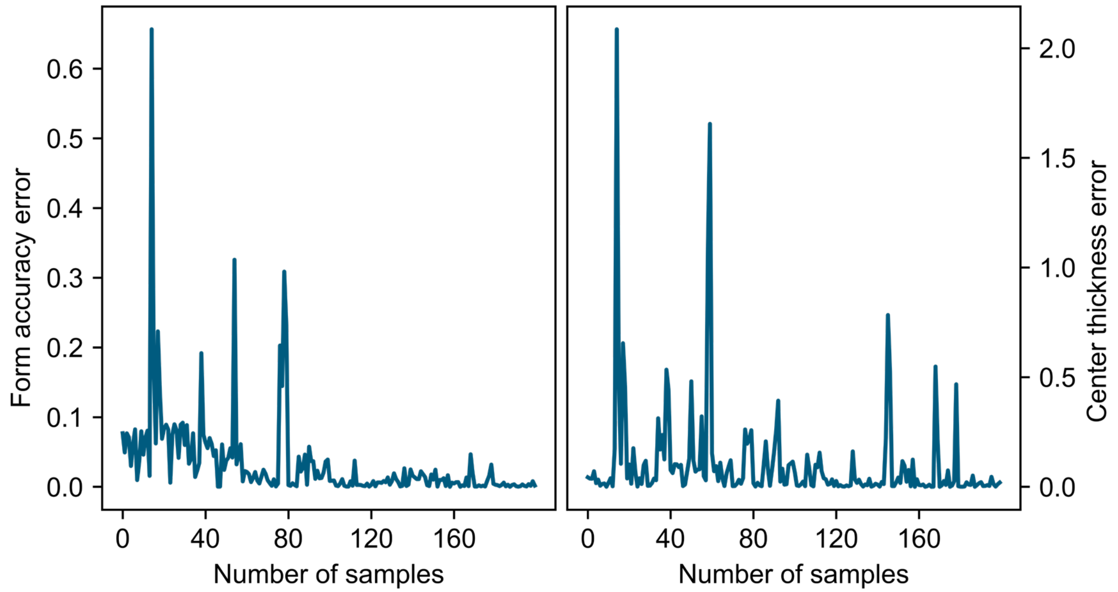


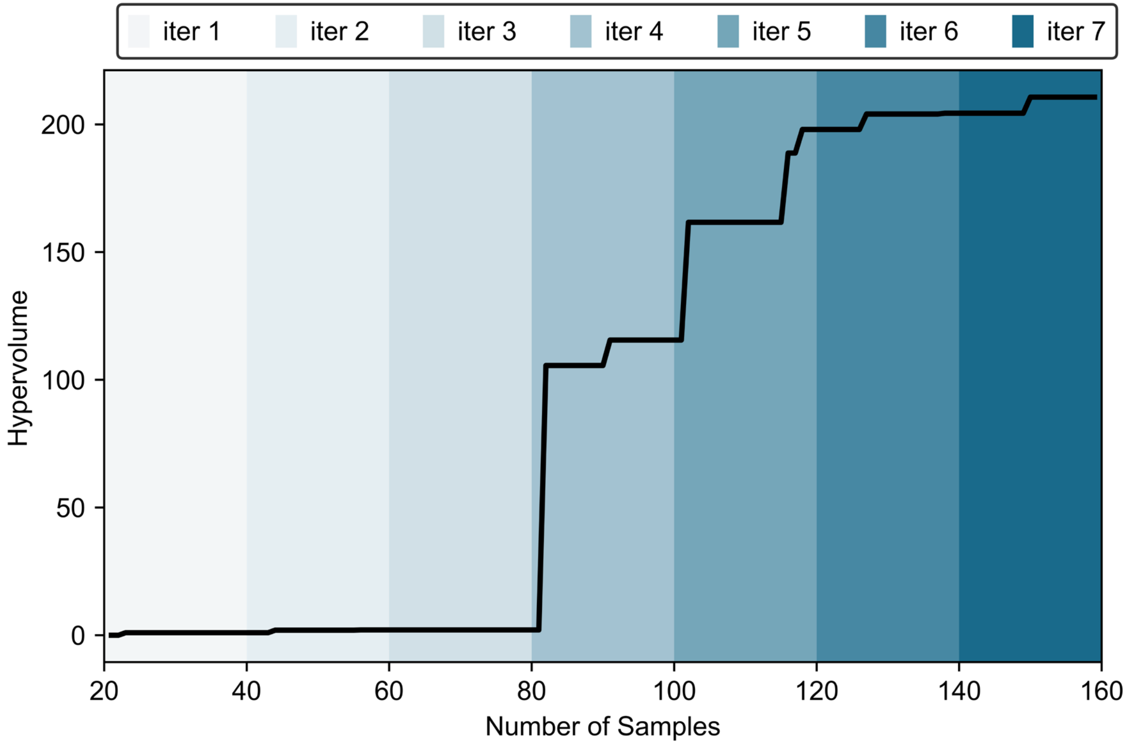
Objective	Target	Current best
Form accuracy error (μm)	5	2.3
Center thickness error (mm)	1.0	0.4

Methodology & Results

Results of NGM Process

Mean squared error of GP as surrogate model v.s. black box NGM model





Summary & Outlook

Summary

- Various methods for Design of Experiments
- Adaptive sampling method & Surrogate model in manufacturing
- Suggesting batch of samples instead of one sample
- MLOPT as an intelligent & effective way for Design of Experiment
- MLOPT as a suitable method for multi-objective optimization with sparse dataset

Outlook

- Further output features can be added to the model
  - Glass properties
  - Energy consumption
  - Whole process time
  - Mold wear
  - …
- Optimum initial and iterative batch size could be further studied
- More complex surrogate models can be added to the model after certain number of iterations

THANKS FOR YOUR ATTENTION!

Contact

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Project »Glass4AutoFuture« sponsored by the German Research Foundation DFG and Fraunhofer Society under the Trilateral Transfer Projects is gratefully acknowledged.