Optimization of Tooling Design for Hot Mandrel Bending of Pipe Elbows

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Agenda

Introduction

- What is a Pipe Elbow ?
- How it is made ?

Objectives

- Resource efficiency and productivity
- New tools for SME

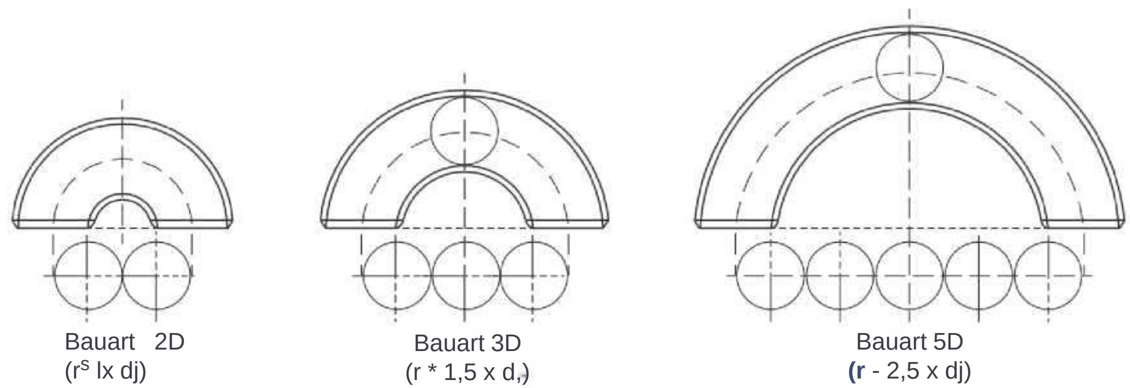
Performed work and selected results

- FEM Modelling
- Materials Modelling
- Meta-Modelling

Summary and Outlook

Elbows from seamless or ERW pipes

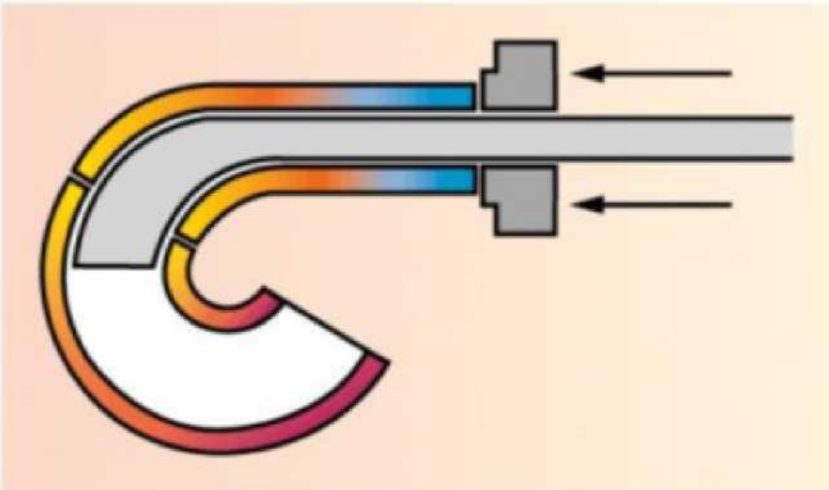
Outside diameter:	**17.2 -610.0 mm**
Wall thickness:	**1.8 - 32.0 mm**
Radius:	**2D / 3D / 5D**



Challenge

- **Broad range of dimensions**
- **Broad range of tools (mandrels)**

Production of Elbows by Hot Mandrel Bending



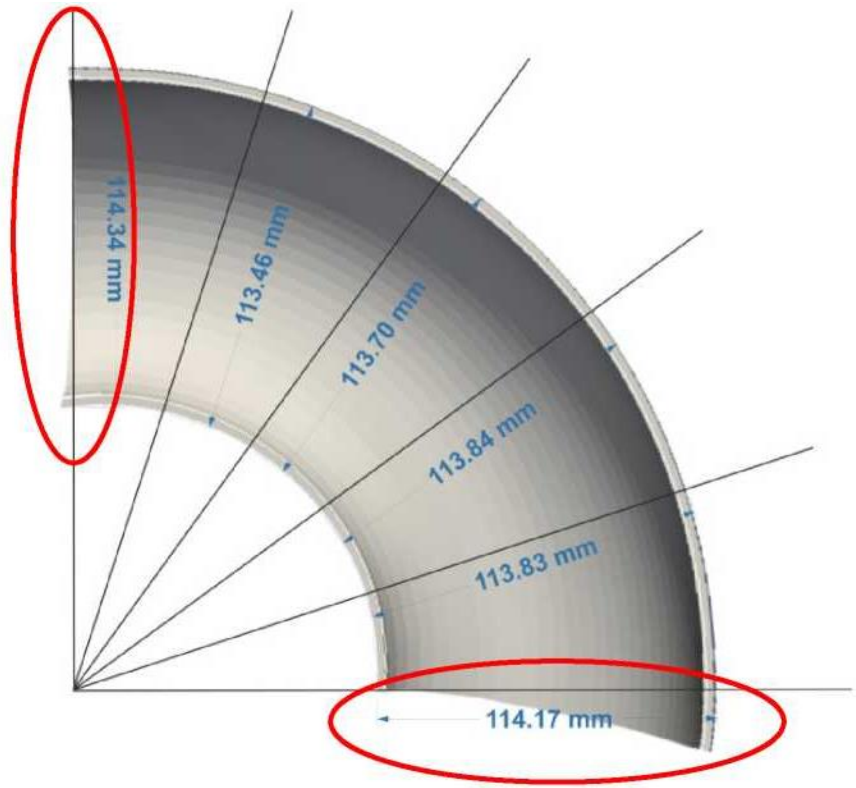
1. (Seamless) Tubes/Pipes are cut to sections
2. Pipe sections are placed on a tool/mandrel
3. Simultaneous inductive heating (~ 800 °C) and forming
4. Forming consists of simultaneous widening and bending
5. Result are elbows showing homogeneous wall thickness (inside and outside)

Challenges:

- Quality, Resource efficiency, Productivity

1. Optimization of the process

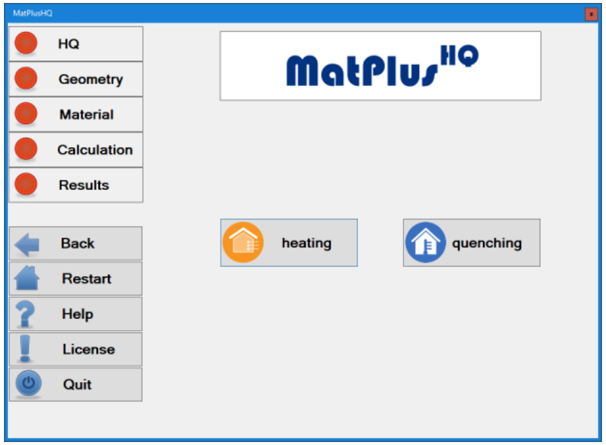
- Reduction of material losses
    - starting from 8 – 25%
- Reduction of energy consumption
- Decrease of production time
- Increase in productivity

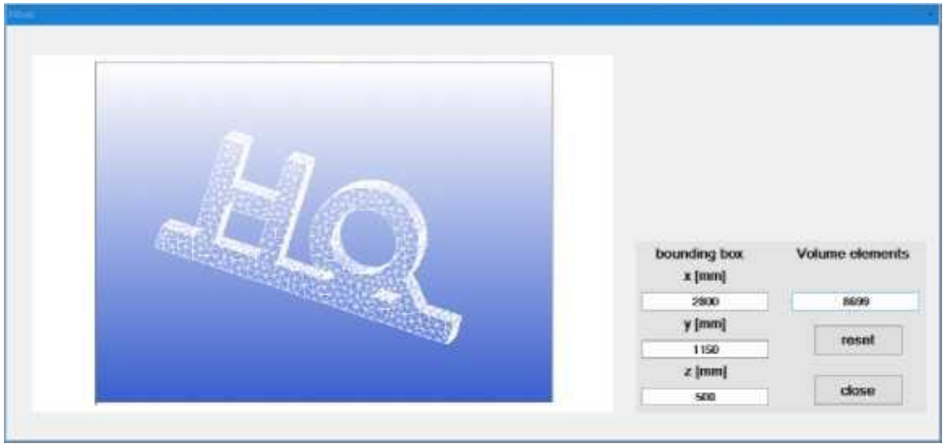


2. Creation of software tools for SME:

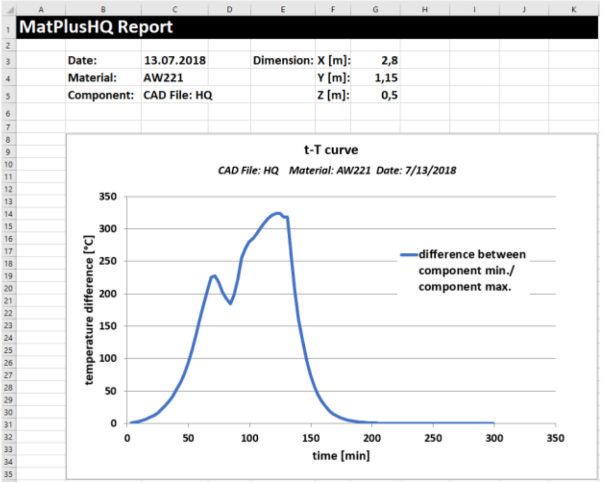
- Easy to use tools for optimization of processes and tool design
- Transfer of technology to other SME concerning hot forming

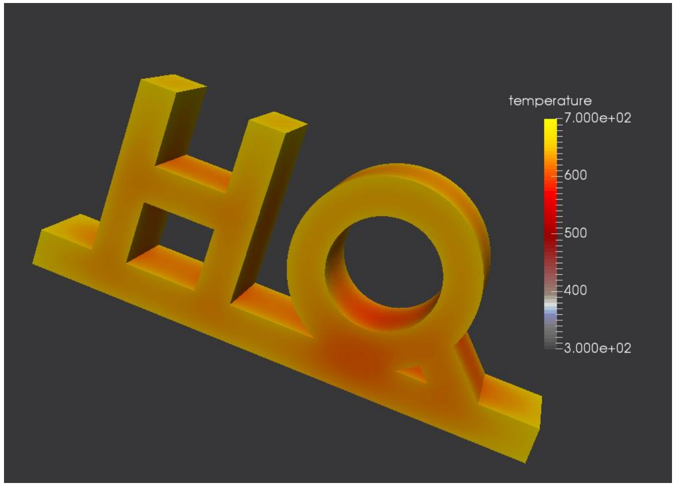
Example MatPlus HQ – shop floor App



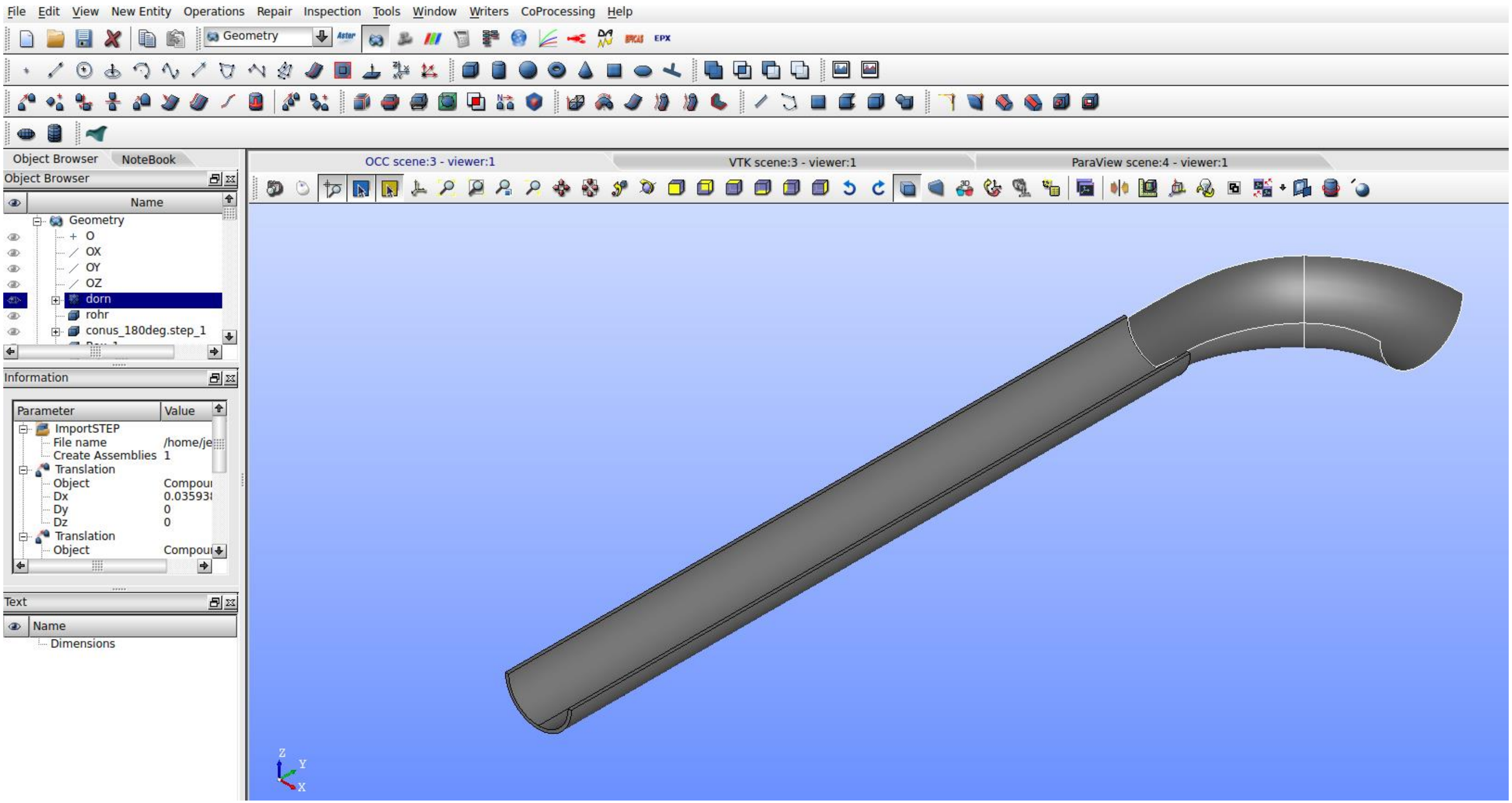


FEM-Calculation

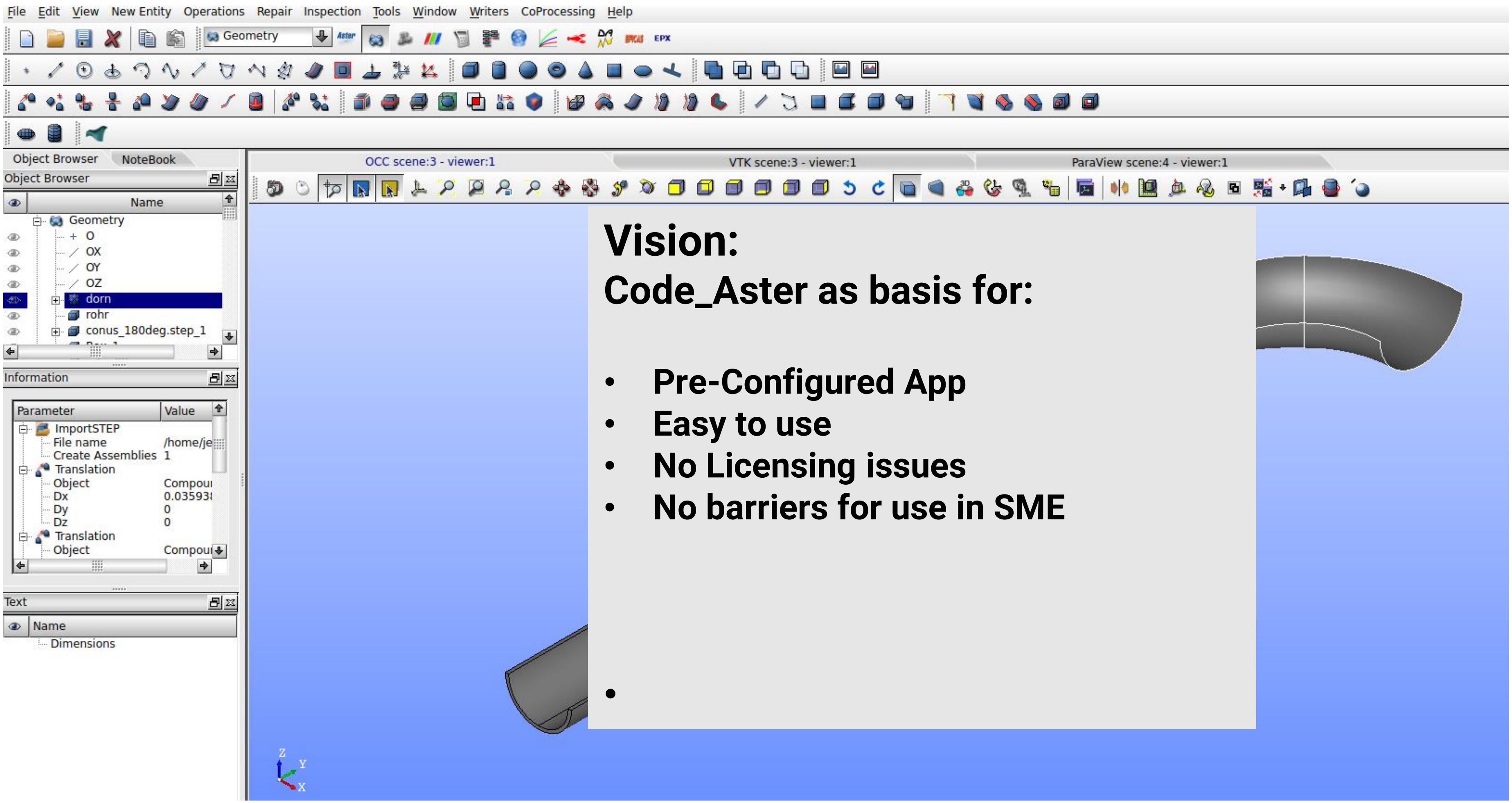




Initial Idea - Customize a free 3D FEA System



Initial Idea - Customize a free 3D FEA System

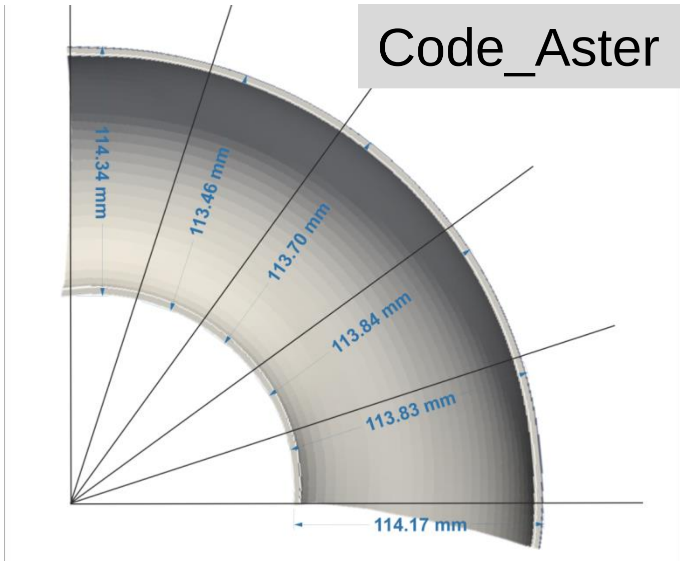


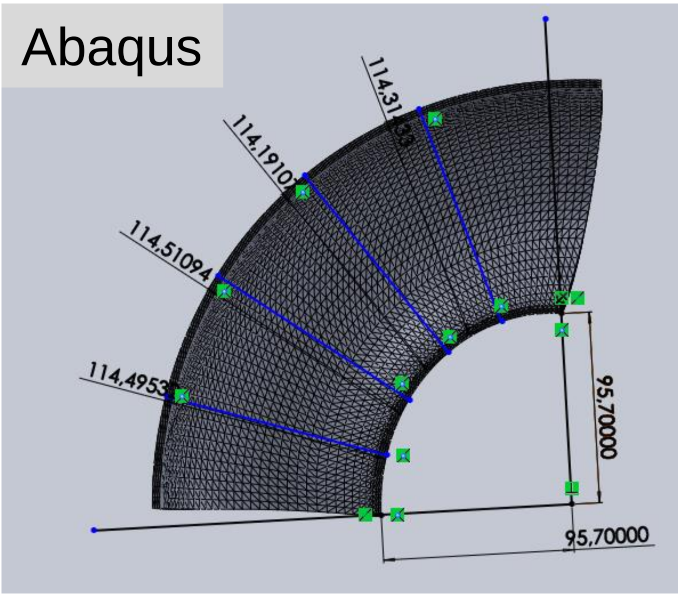
Vision:

Code_Aster as basis for:

- **Pre-Configured App**
- **Easy to use**
- **No Licensing issues**
- **No barriers for use in SME**
-

Code_Aster seemed to be powerful





..but was finally not suitable for our complex system

- **Contact conditions**
- **Damage modeling for hot forming**
- **Robustness and performance**

Final Workflow of the project

- **Determination of boundary conditions**
  - Materials properties
  - Friction coefficients
  - Temperature fields

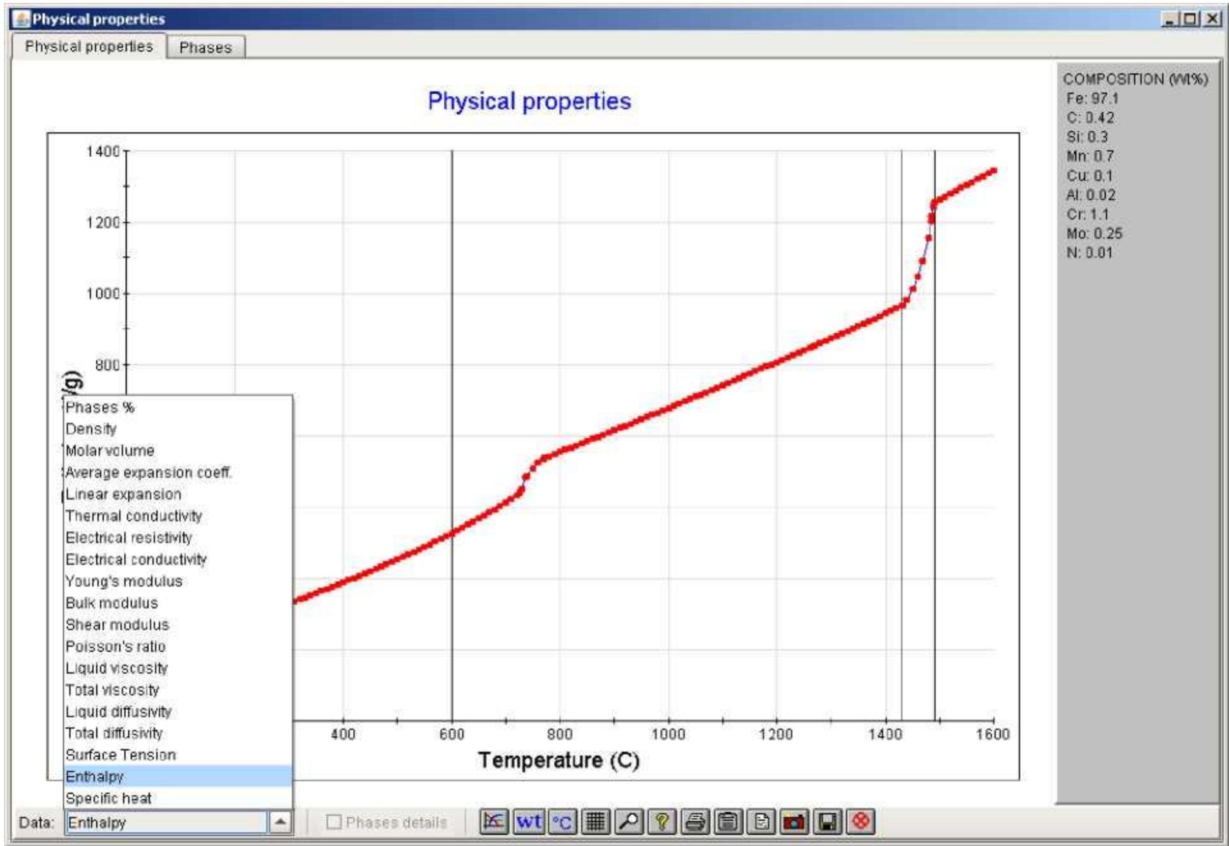
- **Generation of automated calculations**
  - Pre-Processing including parametric modelling of geometries
  - Batch processing of many calculations (> 2.500)
  - using a multi-processor cluster with LS DYNA
  - Automated post processing of the required features

- **Meta-Modelling**
  - Evaluate calculations using different methods like neural networks, random forest
  - Optimization runs using meta-models

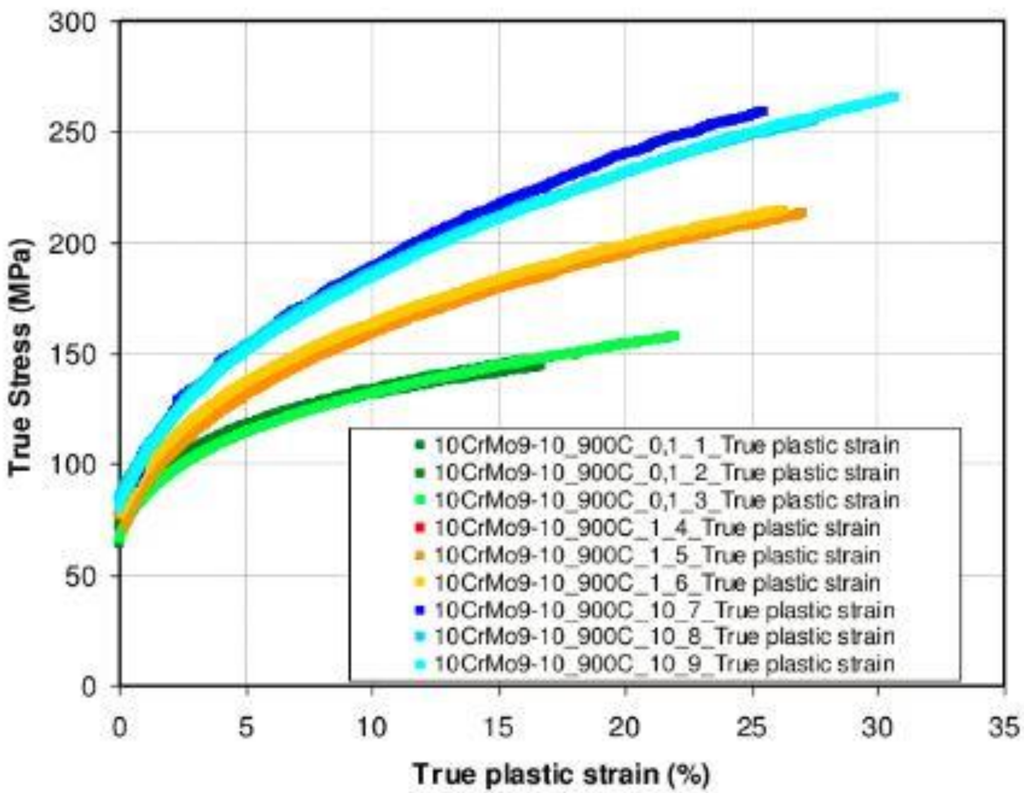
Calculation of materials properties using JMatPro

Generation of consistent material cards for forming simulations

- **Thermo-Physical Properties**
- **Flow curves**



Hot Tensile Testing EN ISO 6892-2



Materials:
- P235,
- 1.4541,
- 10CrMo9-10

Temperature:
- 700 °C
- 900 °C

Strain Rates:
- 0.1/s,
- 1/s,
- 10/s

Damage Modelling using simplified Johnson Cook model

Simplified Johnson Cock model

$$\sigma = (A + B\exp(n\epsilon))$$

no influence of strain rate and temperature

area of reduction

Tab. 2 Results of tensile tests, 1.4541

Specimen	Temp. °C	D_0 mm	a_0 mm	b_0 mm	a_u mm	b_U mm	L_0 mm	L_U mm	$R_{p0,2}$ MPa	R_m MPa	A_g %	A_5 %	Z %	Strain rate 1/s
T_700C_0,1_1	700	89,60	3,15	12,50	0,69	9,08	10,00	15,82	130,2	298,7	29,5	58,2	84,1	0,1
T_700C_0,1_2	700	89,60	3,15	12,50	0,64	8,94	10,00	16,36	140,9	296,4	29,6	63,6	85,5	0,1
T_700C_0,1_3	700	89,60	3,15	12,50	0,74	9,05	10,00	16,29	157,0	298,6	30,5	62,9	83,1	0,1
average	**700**								**142,7**	**297,9**	**29,9**	**61,6**	**84,2**	**0,1**

Tab. 3 Results of tensile tests, P235

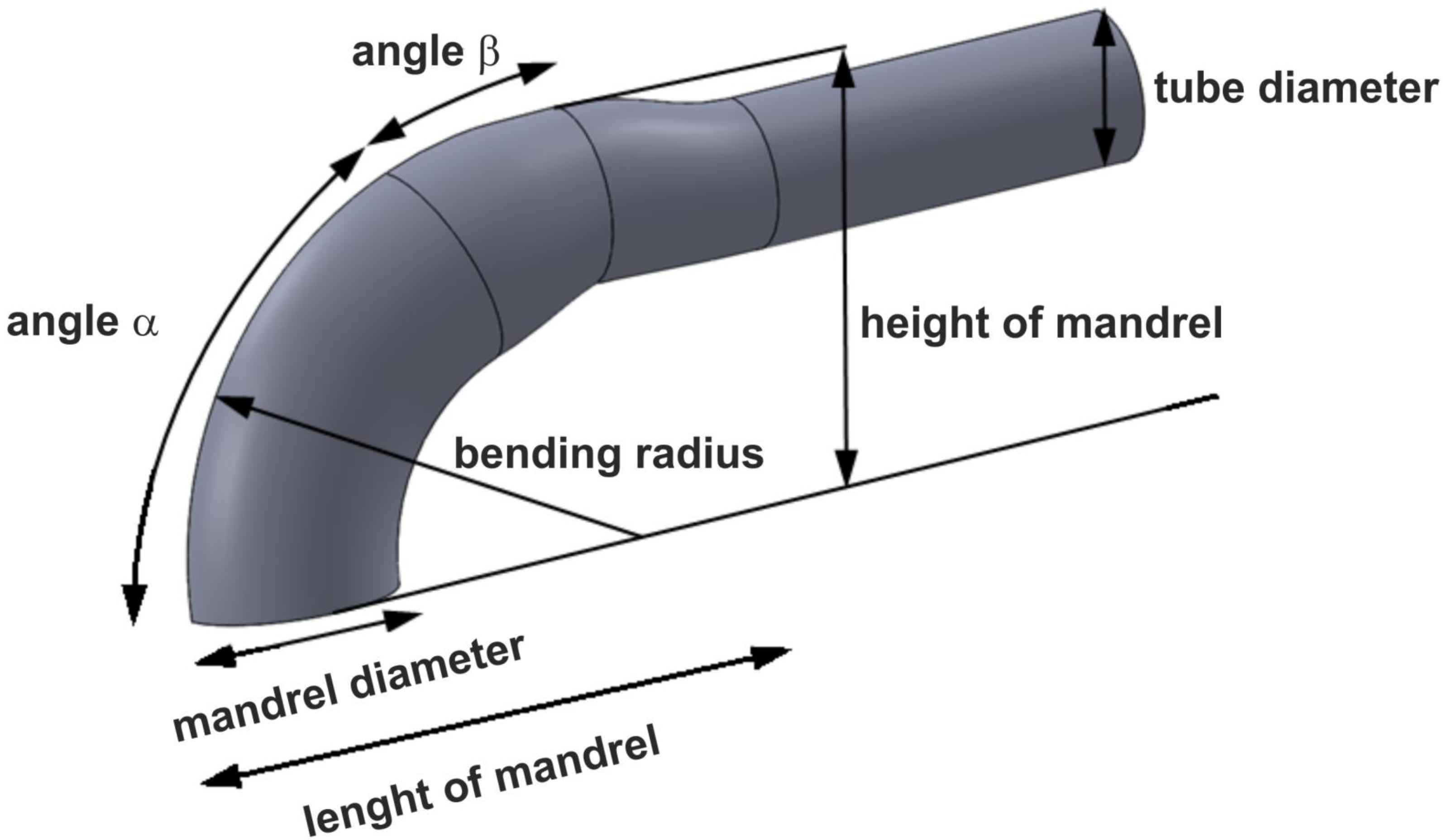
Specimen	Temp. °C	D_0 mm	a_0 mm	b_0 mm	D_u mm	b_U mm	L_0 mm	L_U mm	$R_{p0,2}$ MPa	R_m MPa	A_g %	A_5 %	Z %	Strain rate 1/s
T_700C_0,1_1	700	82,50	3,81	12,50	0,17	5,40	10,00	21,61	73,7	117,7	21,5	116,1	98,1	0,1
T_700C_0,1_2	700	82,50	3,81	12,50	0,15	5,38	10,00	21,88	80,3	120,8	17,7	118,8	98,3	0,1
T_700C_0,1_3	700	82,50	3,81	12,50	0,14	5,53	10,00	21,11	75,6	118,0	19,6	111,1	98,4	0,1
average	**700**								**76,5**	**118,8**	**19,6**	**115,3**	**98,3**	**0,1**

$$\epsilon_{fail} = \ln \frac{100}{100 - Z}$$

P235: $\epsilon fail$**=4.07**

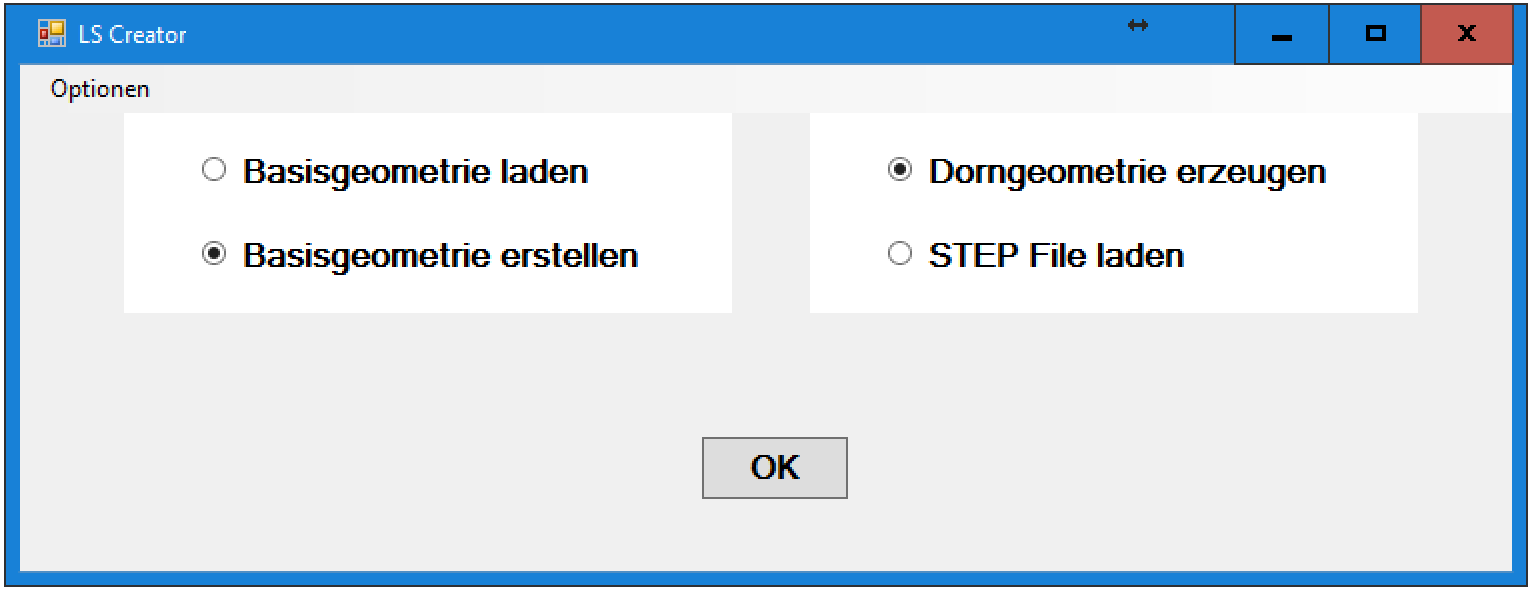
1.4541: $\epsilon fail$**=1.83**

Parameters/Variation of Tool Geometry



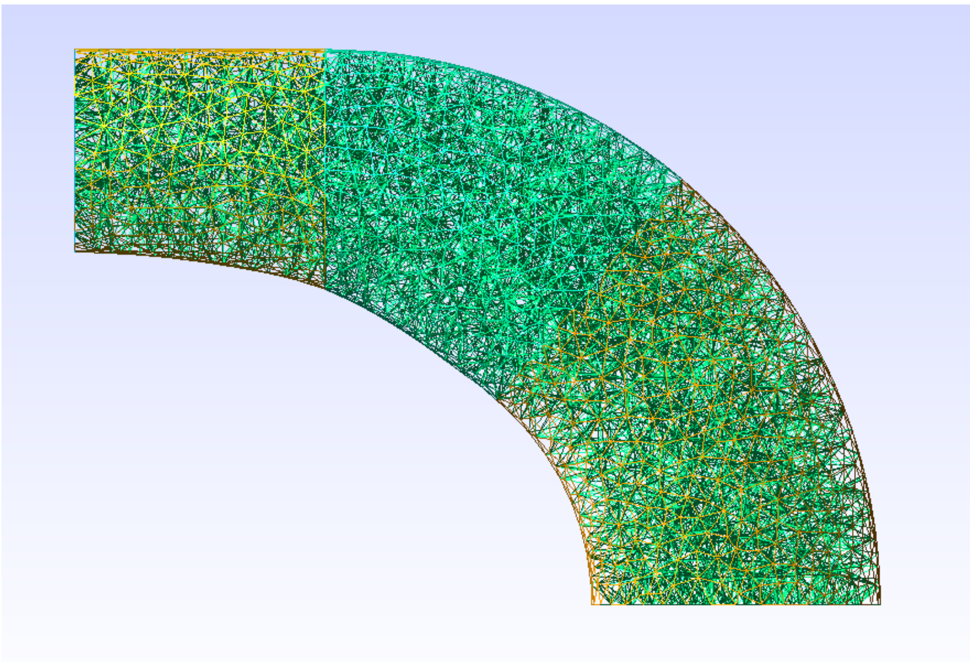
Resulting Geometry

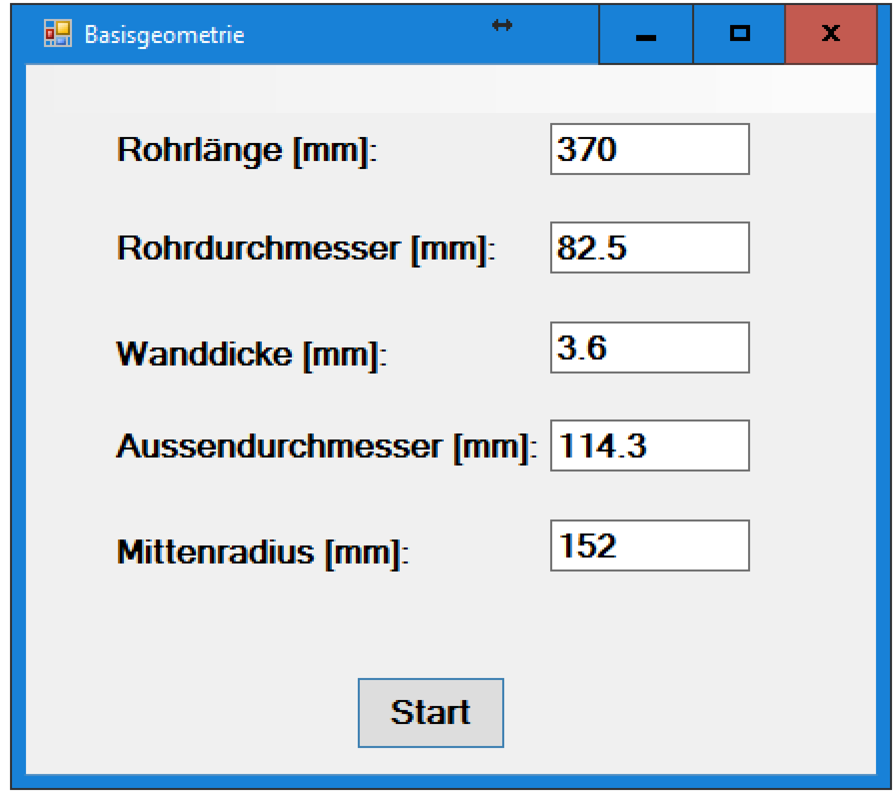
App for Parametric Design of Mandrel Geometry



Tool for automatic generation of Input-Files

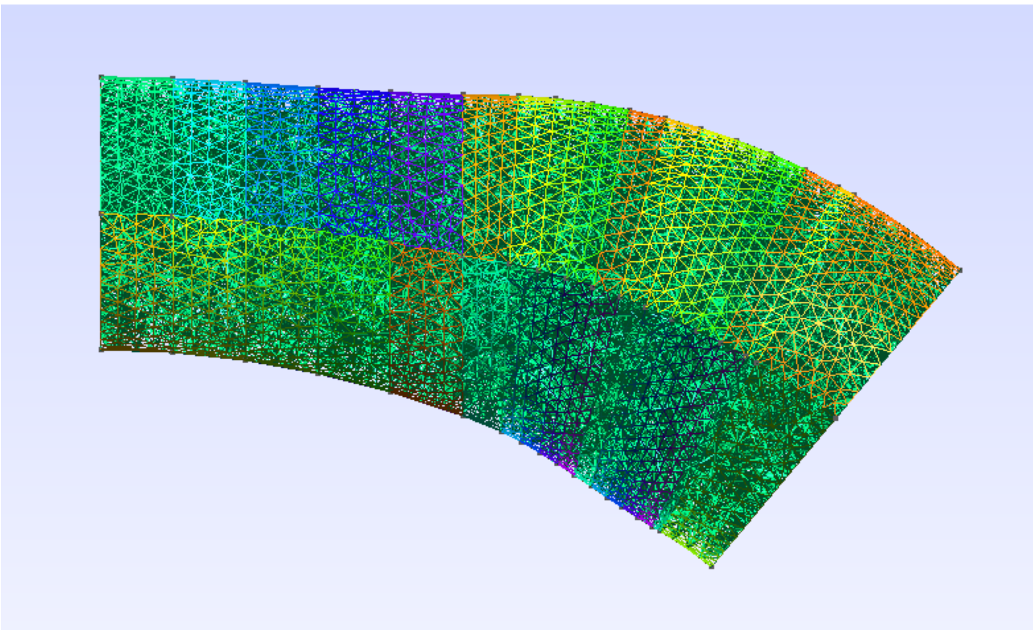
App for Parametric Design of Mandrel Geometry

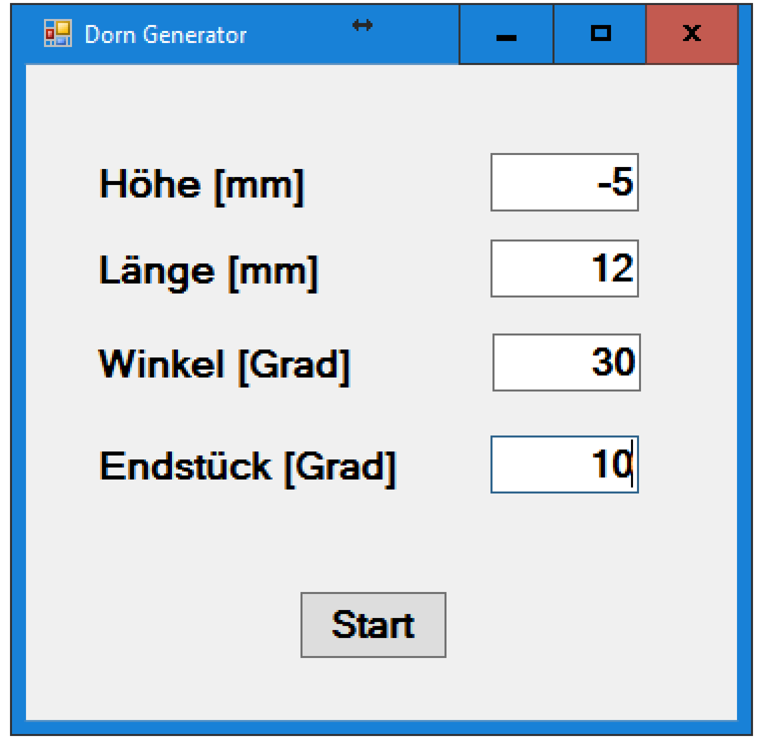




Fixed parameters for a certain dimension

App for Parametric Design of Mandrel Geometry





parameters for optimization
can be processed in batch mode

Computation Metrics

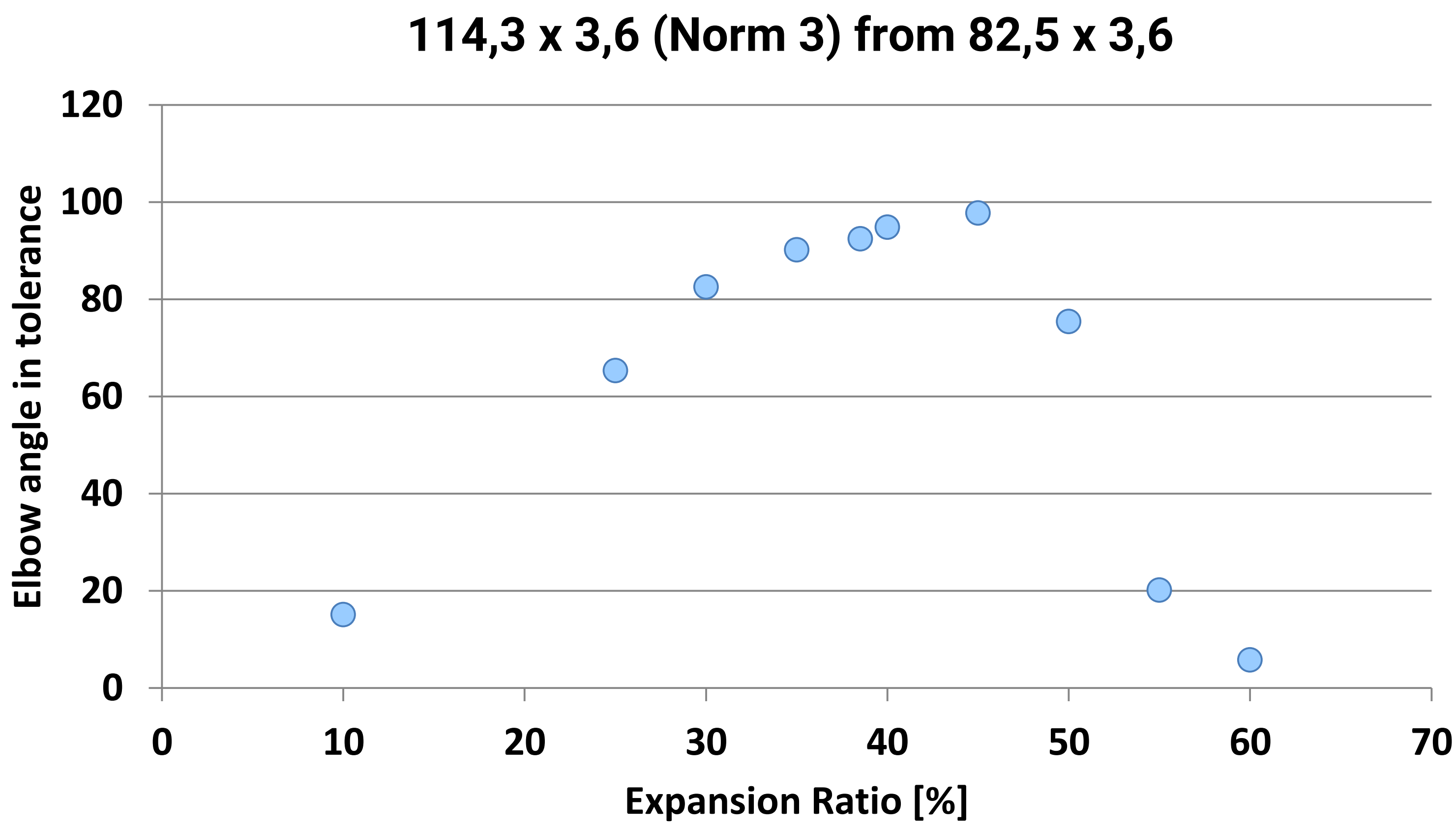
>2500 Calculations using LS-DYNA

- **8 from ~1000 dimensions of elbows**
- **Variation of parameters (material, radius, diameter, wall thickness, length, height, angle, expansion)**

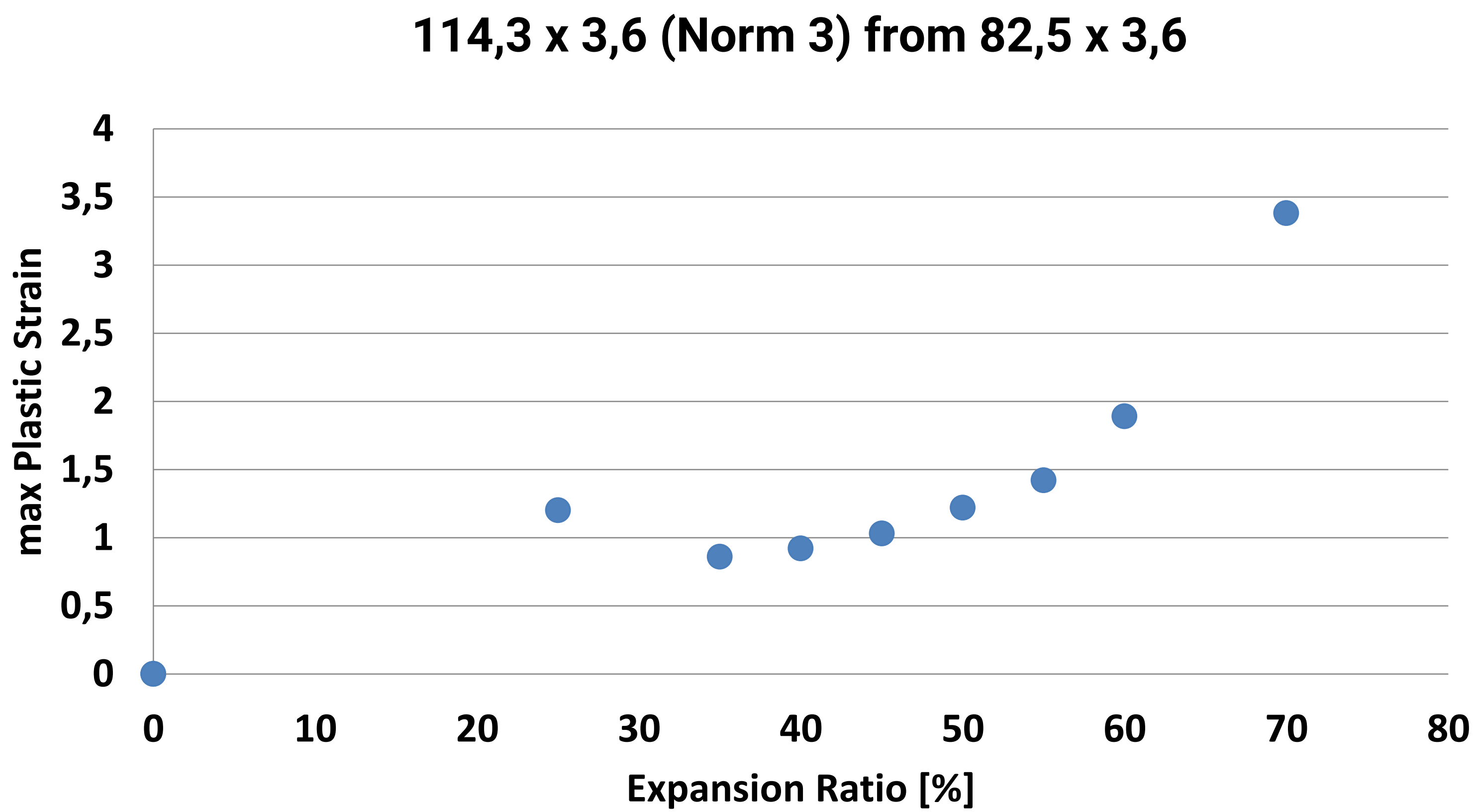
Computation time using an 8 Core, CPU: Intel Xeon E5-2670

- **456 days, 14 hours, 20 minutes**
- **was reduced by using a bigger university cluster**

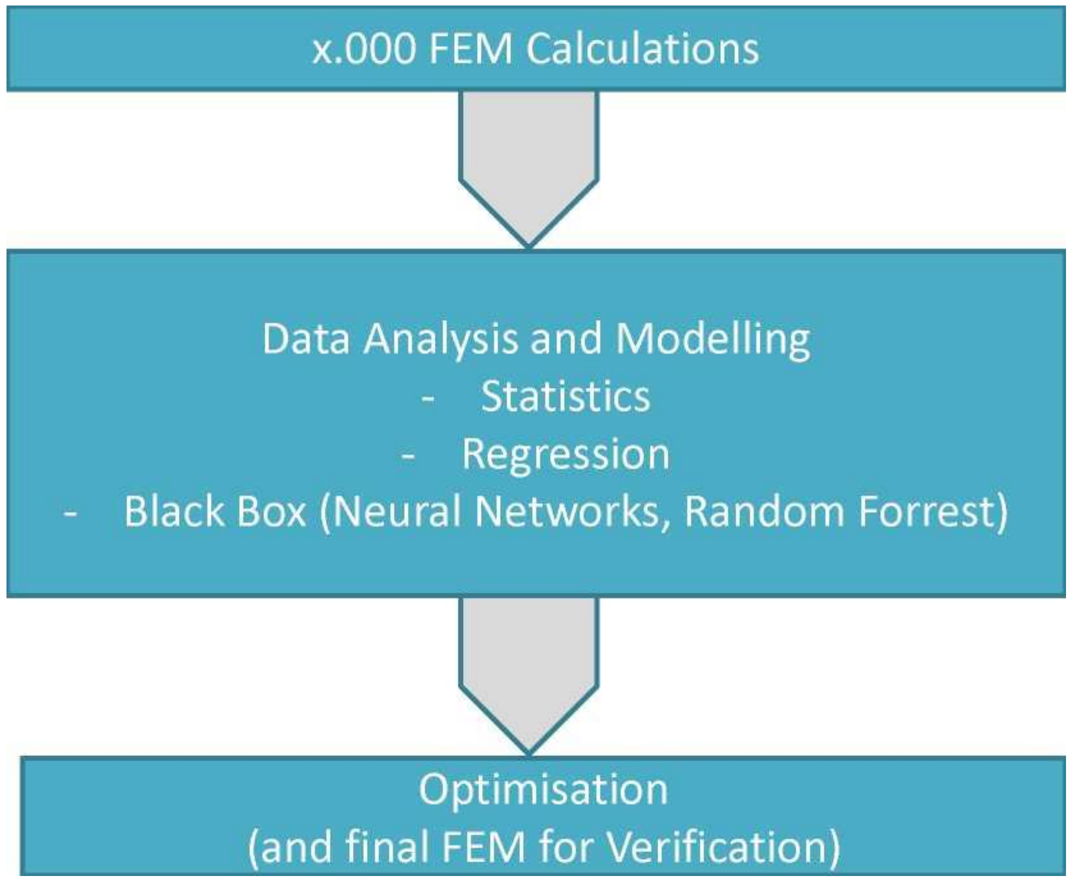
Influence of Expansion Ratio on Angle in Tolerance



Influence of Expansion Ratio on Plastic strain



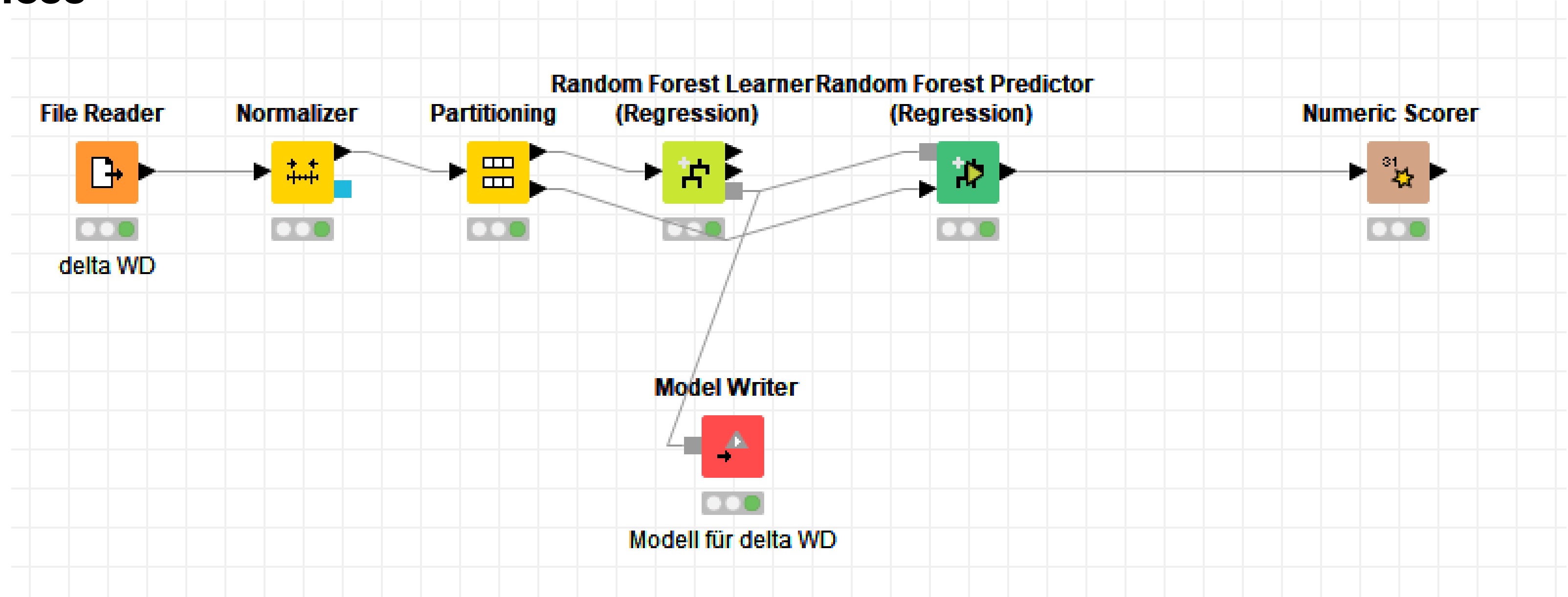
Meta-Modelling for Multi-Variate Optimization



Example KNIME (Konstanz Information Miner)

Random Forest Workspace:

Here: model for variation of wall thickness

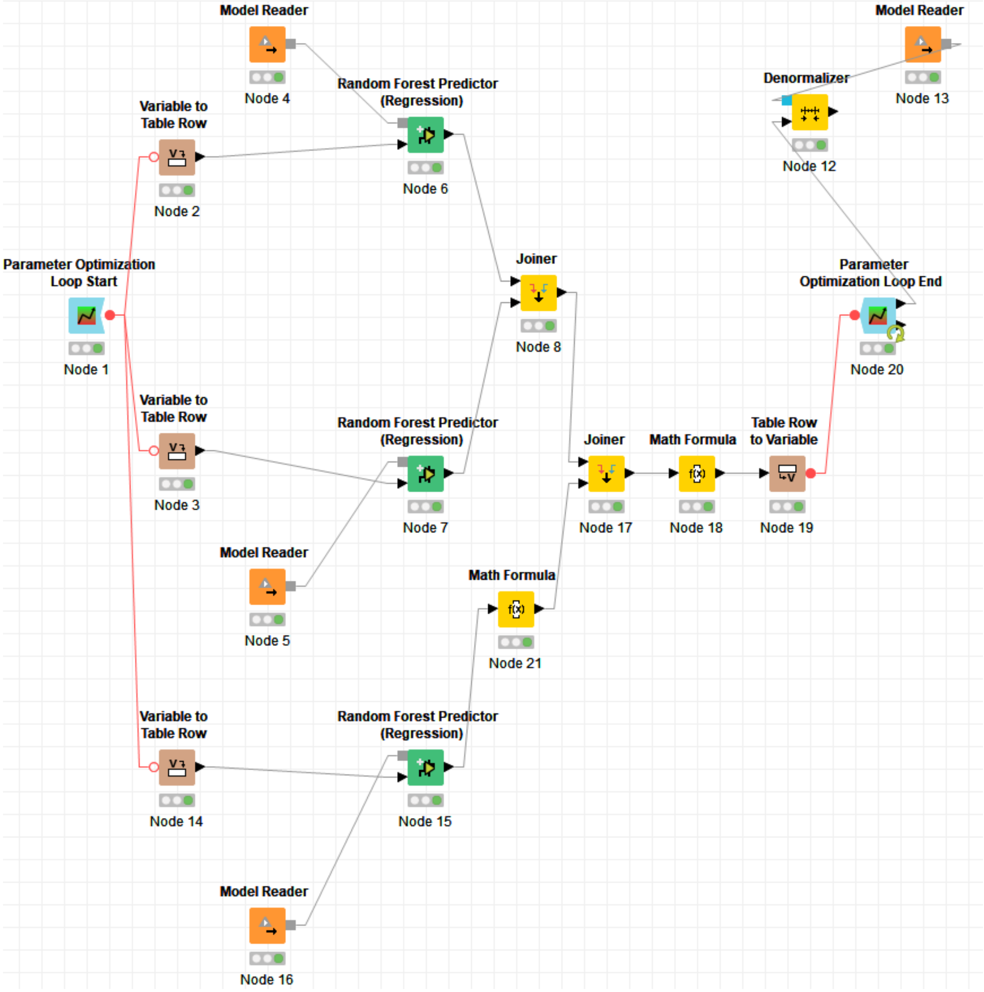


Input parameters:

- Tool lengths
- Tool height
- Expansion angle

Example KNIME (Konstanz Information Miner)

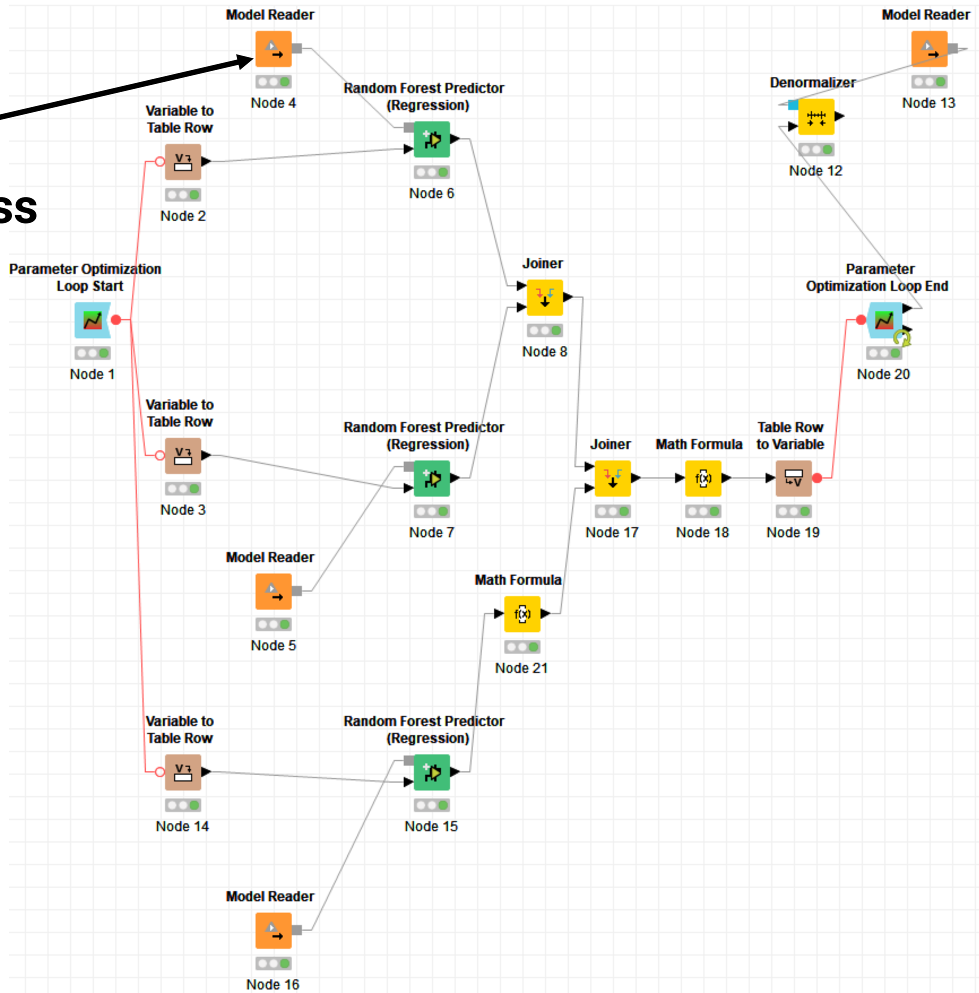
Combination of all models to optimize the target values:



Example KNIME (Konstanz Information Miner)

Combination of all models to optimize the target values:

Delta wall thickness

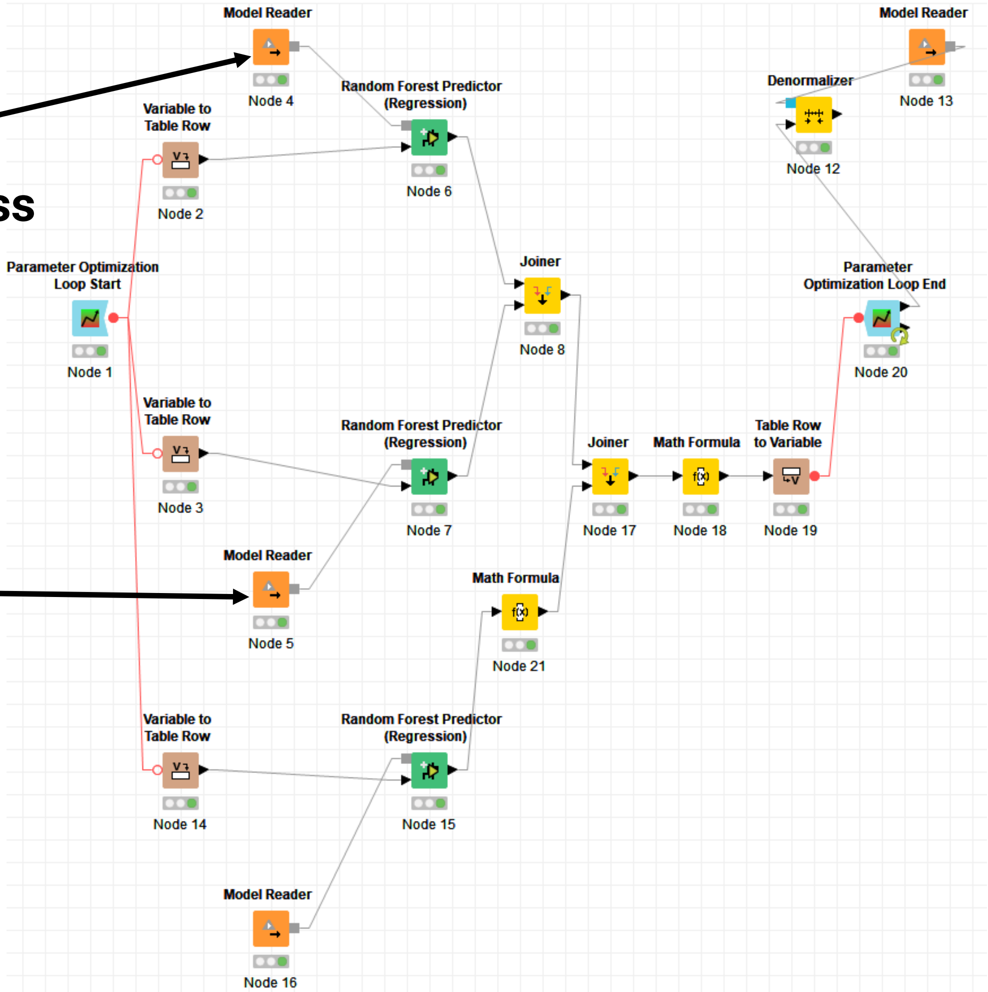


Example KNIME (Konstanz Information Miner)

Combination of all models to optimize the target values:

Delta wall thickness

Delta outer diameter



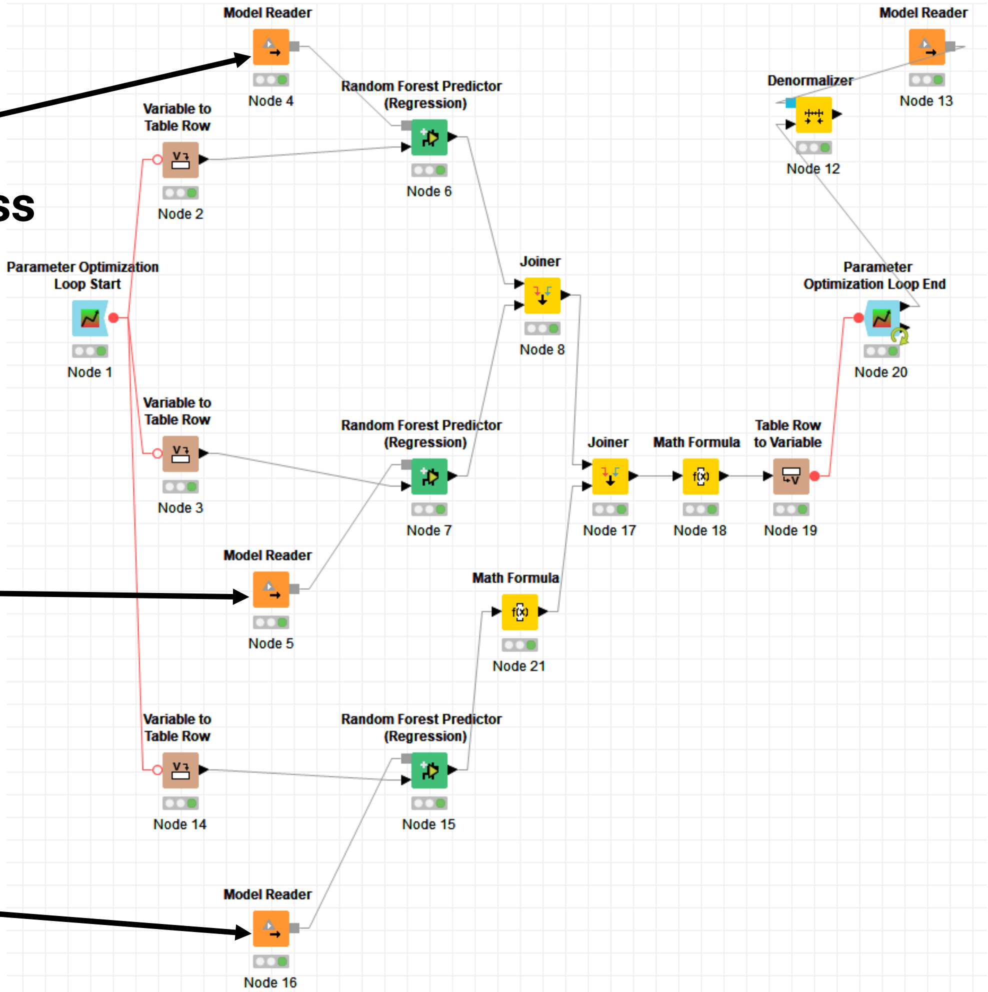
Example KNIME (Konstanz Information Miner)

Combination of all models to optimize the target values:

Delta wall thickness

Delta outer diameter

max. angle in norm



Example KNIME (Konstanz Information Miner)

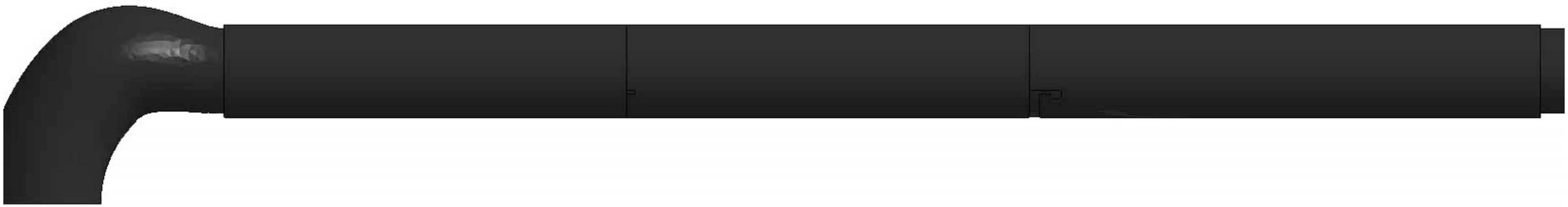
Results of a meta-model:

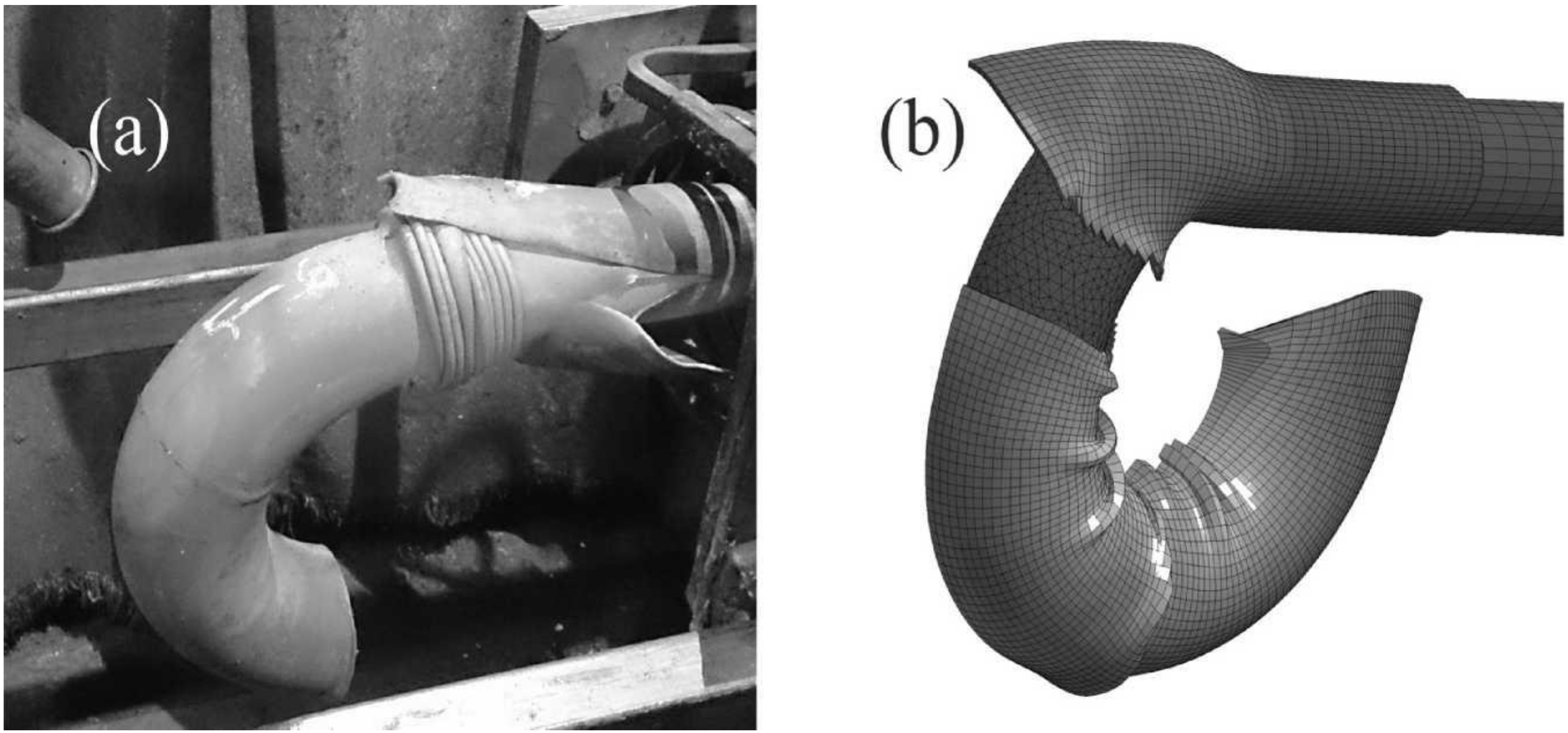
Knime Model				
Best Value	**Tool angle_const [°]**	**Tool height [mm]**	**Tool_length [mm]**	**Objective value**
1	60	205.6	224.55	0.24160192
2	60	205.6	230.05	0.241961948
3	60	206.15	224.55	0.242608664
4	60	206.15	230.05	0.242728537
5	57.75	205.6	224.55	0.247997124
6	57.75	205.6	230.05	0.249123411
7	57.75	206.15	224.55	0.249582874
8	57.75	206.15	230.05	0.250483848
9	55.5	205.6	230.05	0.258777058
10	55.5	205.6	224.55	0.258832455

Good agreement with FEM calculation

Production of elbows with optimized tool

- **Higher production yield: + 14%**
- **Higher production speed: + x**




(a)
(b)

Verification

New tooling design leads to:

- Increased materials efficiency: Losses can be reduced significantly
- Increased productivity: Production speed can be increased significantly
- Increased energy efficiency by higher speed of production and less material
- Findings were validated in practical tests at Lindemann
  –but not yet in industrial production

New software and tools help to reduce complexity:

- easy to use
- to automatically perform many calculations
- Meta-modelling can be used for optimisation, saves time and reduces number of FE-computations

Software will be further developed to help other SME improving their production processes

EFRE.NRW
Investitionen in Wachstum und Beschäftigung
EUROPÄISCHE UNION
Investition in unsere Zukunft
Europäischer Fonds für regionale Entwicklung