PROJECT: PARAMETER IDENTIFICATION OF THE GOLDAK HEAT SOURCE IN WELDING SIMULATIONS

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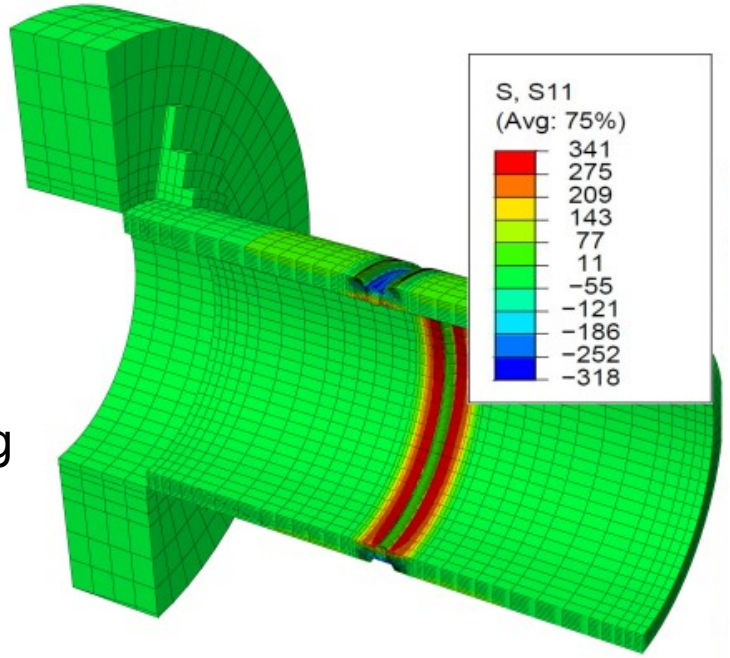

2021-01-28, Strasbourg

Context?

Where and What?

Organization Chart

Fraunhofer Institute for Mechanics of Materials IWM

Woehlerstraße 11, 79108 Freiburg, Germany

Executive Director: Prof. Dr. Peter Gumbsch (Assistant: Monika Ebling -200)
Deputy Directors: Dr. Rainer Kübler; Prof. Dr. Chris Eberl (Assistant: Emanuele Oppermann -486)
Strategy Staff: Thomas Götz -153, Prof. Dr. Christian Elsässer -286

Fraunhofer IWM

Date January 18, 2021

business units

Manufacturing Processes Dr. Dirk Helm -158	Tribology Prof. Dr. Matthias Scherge -206 +49 721 204327-12	Component Safety and Lightweight Construction Dr. Michael Luke -338 and Dr. Silke Sommer -266	Assessment of Materials and Lifetime Concepts Dr. Christoph Schweizer -382	Administrative Infrastructure Elke Schubert -124	Technical Infrastructure Dr. Rainer Kübler -213
groups					
Powder Technology and Fluid Dynamics Dr. Torsten Kraft -248	Wear Protection and Advanced Ceramics Dr. Andreas Kailer -247	Fatigue and Fracture Mechanics Dr. Michael Luke -338 and Dr. Igor Varfolomeev -210	Microstructure and Residual Stresses Dr. Johannes Preußner -101	Finances and Contracts Nina Halaczinsky -487	Mechanical Workshop Stefan Frei -345
Forming Processes Dr. Alexander Butz -369	Multiscale Modeling and Tribosimulation Prof. Dr. Michael Moseler -332	Crash Safety and Damage Mechanics Dr. Silke Sommer -266 and Frank Huberth -472	Lifetime Concepts and Thermomechanics Dr. Christoph Schweizer -382	Human Resources and Travel Management Kerstin A. Drüsedau -140	Facility Management Manuel Birkle -219
Glass Forming and Machining Tobias Rist -430	Polymer Tribology and Biomedical Materials Dr. Raimund Jaeger -284	Composite Materials PD Dr. Jörg Hohe -340	Materials Modeling Dr. Daniel Urban -378	Public Relations and Visitor Management Katharina Hien -154	IT Services Klaus Merkel -217
	Tribological and Functional Coatings Bernhard Blug -180	Meso- and Micromechanics Dr. Thomas Straub -537			Scientific IT Dr. Heiko Hafok -311
	Triboconditioning and -analytics (Location Karlsruhe) Prof. Dr. Matthias Scherge +49 721 204327-12				Occupational Safety Rainer Kübler -213

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Phone +49 761 5142-...

Development work is carried out on mechanism-based material models for a wide range of applications with which to describe the deformation and failure behavior of components under thermal and mechanical loads.

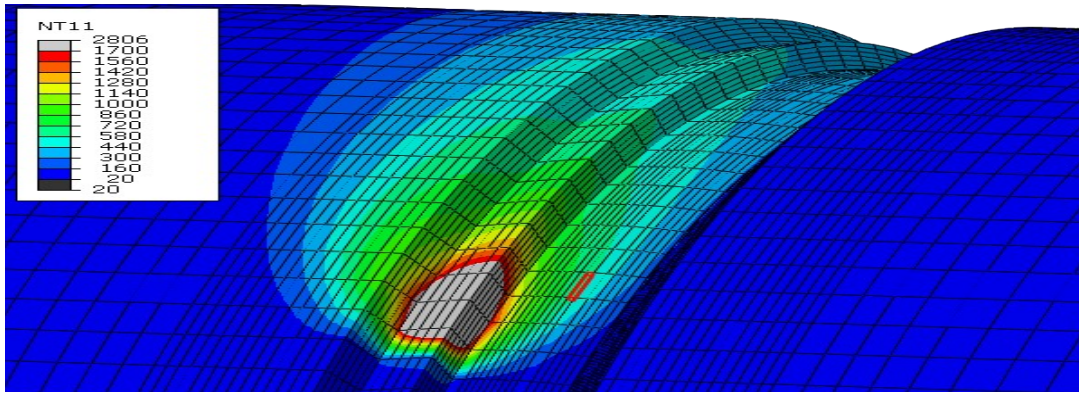
Why?

The Eschede **derailment** occurred on 3 June 1998, near the village of Eschede in the Celle district of Lower Saxony, **Germany**, when a high-speed **train** derailed and crashed into a road bridge. 101 people were killed and 88 were injured.

Welding process?

Definition

Welding is a fabrication **process** whereby two or more parts are fused together by means of heat, pressure or both forming a join as the parts cool. **Welding** is usually used on metals and thermoplastics but can also be used on wood.



$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} + \frac{\dot{q}}{k} = \frac{\rho C_p}{k} \frac{\partial T}{\partial t}$$

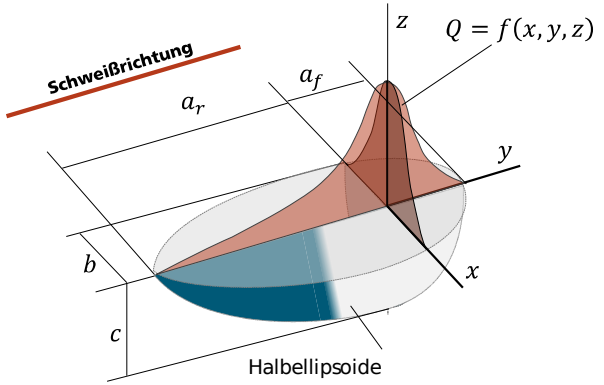
Moving heat sources is a topic in transient heat transfer that is applicable to engineering problems, particularly welding engineering. In the early 20th Century, welding engineers began studying moving heat sources, both empirically and theoretically.

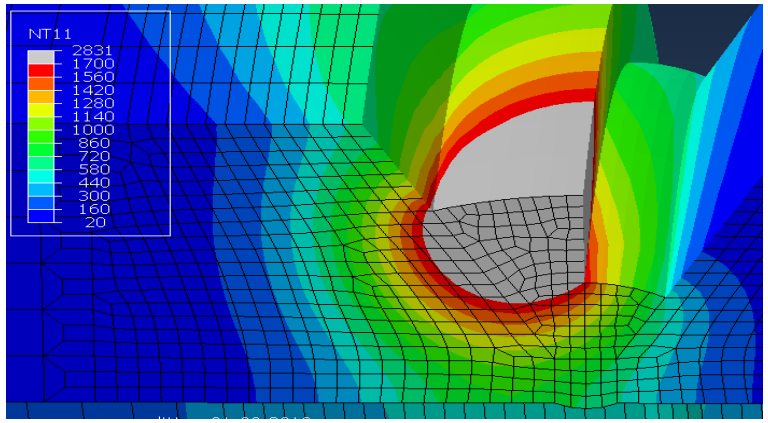
Goldak heat source model

Implemented to the Abaqus simulation via USER subroutine DFLUX Double-ellipsoidal heat source by Goldak .

Gaussian distribution of the power density $Q(x, y, z)$ where Q_0 is the maximum value of the power density at the center

$$Q(x,y,z) = \begin{cases} Q_0 exp\left(-\left(\frac{x^2}{b^2}+\frac{y^2}{c^2}+\frac{z^2}{a_f^2}\right)\right); x \geq 0 \\ Q_0 exp\left(-\left(\frac{x^2}{b^2}+\frac{y^2}{c^2}+\frac{z^2}{a_r^2}\right)\right); x < 0 \end{cases}$$





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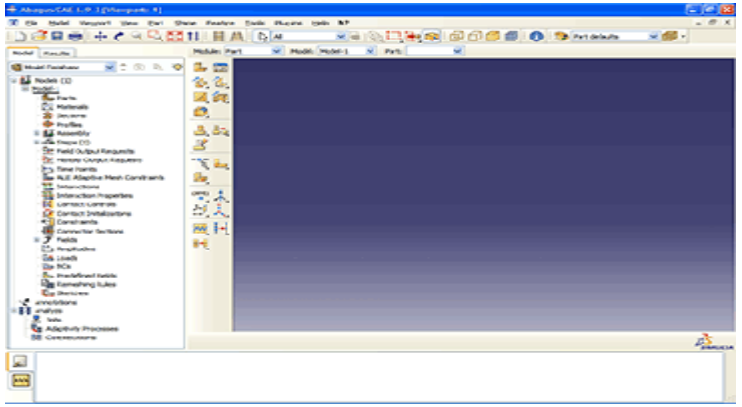
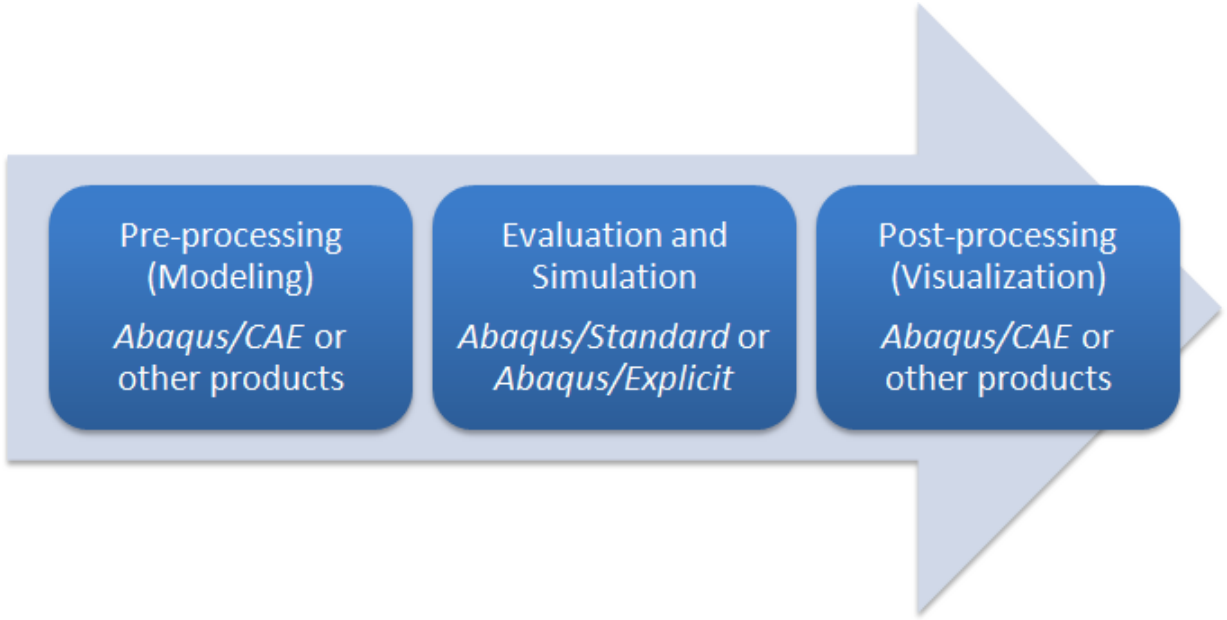
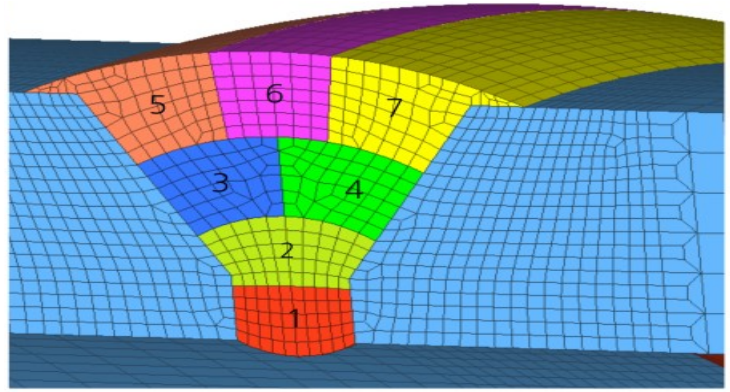
Abaqus software

Abaqus FEA is a software suite for finite element analysis and computer-aided engineering.







Problematic?

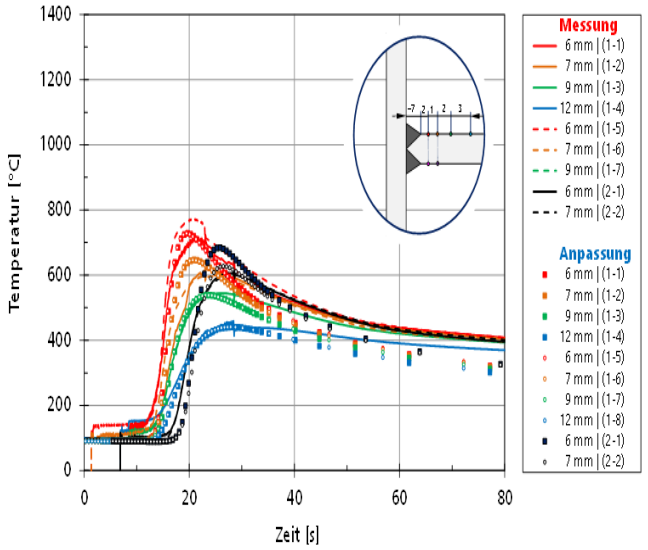
Abaqus simulation

$$Q(x,y,z) = \begin{cases} Q_0 exp\left(-\left(\frac{x^2}{b^2}+\frac{y^2}{c^2}+\frac{z^2}{a_f^2}\right)\right); x \geq 0 \\ Q_0 exp\left(-\left(\frac{x^2}{b^2}+\frac{y^2}{c^2}+\frac{z^2}{a_r^2}\right)\right); x < 0 \end{cases}$$

Pre-processing (Modeling)
Abaqus/CAE or other products

Evaluation and Simulation
Abaqus/Standard or *Abaqus/Explicit*

Post-processing (Visualization)
Abaqus/CAE or other products

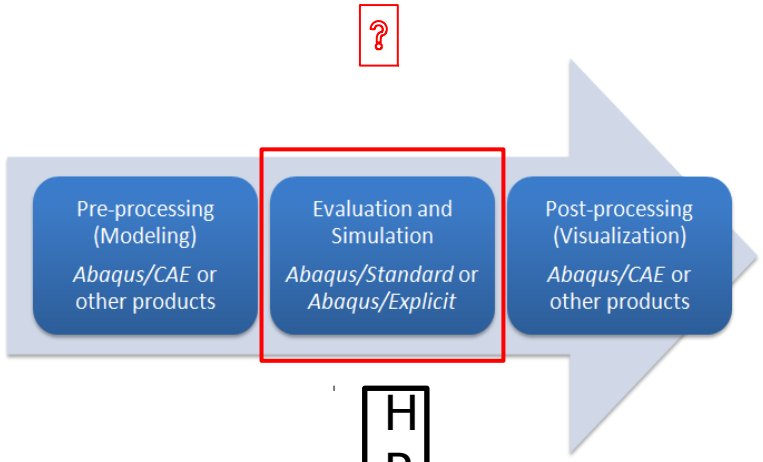


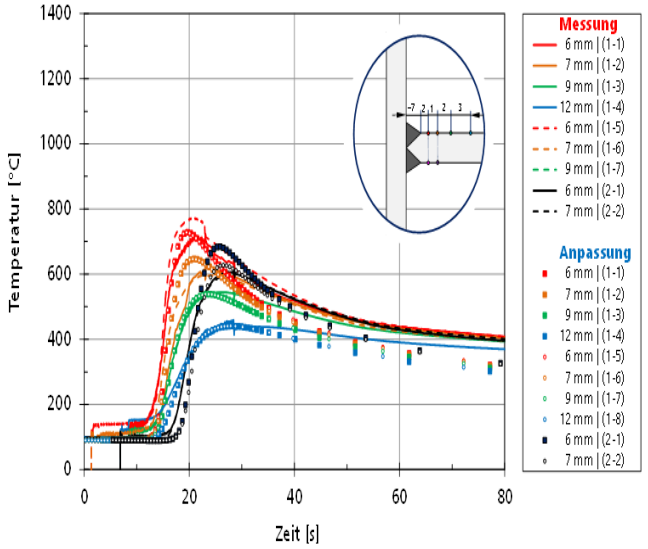

```
C
      SUBROUTINE DFLUX(FLUX,SOL,JSTEP,JINC,TIME,NOEL,NPT,COORDS,JLTYP,
     1 TEMP,PRESS,SNAME)
C
      INCLUDE 'ABA_PARAM.INC'
C
      DIMENSION COORDS(3),FLUX(2),TIME(2)
      CHARACTER*80 SNAME
C
C The total absorbed power needs to be calibrated
C with an intensity function QT
C
C
      XX = COORDS(2)
      YY = COORDS(3)
      ZZ = COORDS(1)
      TT = TIME(1)
C
C
C
C
C    Start angele phi [rad]
      phi_start = 0.0
C
      IF ((JSTEP.EQ.1).OR.(JSTEP.EQ.2)) THEN
C
C       1. Lage
          QT = 1.6*14.0e3
C    speed of weld sorurce [mm/sek]
          speed = 5.0
C
C    Radius of welding circle [mm]
```

Parameters are estimated and modified manually on the Abaqus inputfile**.f** USER subroutine DFLUX written in Fortran.

Abaqus simulation

$$Q(x,y,z) = \begin{cases} Q_0 exp\left(-\left(\frac{x^2}{b^2}+\frac{y^2}{c^2}+\frac{z^2}{a_f^2}\right)\right); x \geq 0 \\ Q_0 exp\left(-\left(\frac{x^2}{b^2}+\frac{y^2}{c^2}+\frac{z^2}{a_r^2}\right)\right); x < 0 \end{cases}$$

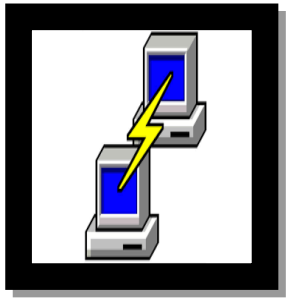




.inp

```
**************************************
**      STEP 1:                     **
**************************************
*STEP, INC=10000
*HEAT TRANSFER
 0.532, 196.84, ,
**
*MODEL CHANGE, REMOVE
 W2_3d, W3_3d, W4_3d, W5_3d, W6_3d, W7_3d
**
*SRADIATE, OP=NEW
 AIR_HEAT_EXCHANGE_1, R, 20.0, 0.8
**
*SFILM, OP=NEW
 AIR_HEAT_EXCHANGE_1, F, 20.0, 25.0e-3
**
*DFLUX, OP=NEW
 Rohr_3d, BFNU, 1.0
 Rohr_HAZ_3d, BFNU, 1.0
 W1_3d, BFNU, 1.0
**
*OUTPUT, FIELD, FREQ=1
*NODE OUTPUT
 NT,
**
*END STEP
**
**************************************
**      STEP 2:                     **
**************************************
*STEP, INC=50000
*HEAT TRANSFER, DELTMX=1000
 0.1, 4803.16, 0.001, 200.0
```

H P C



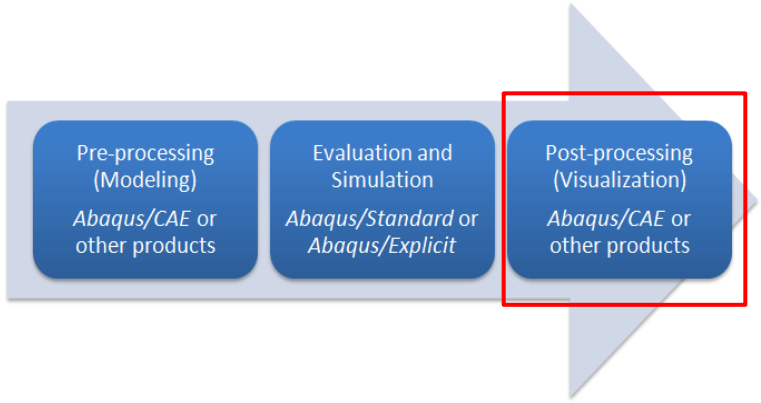
Time consuming

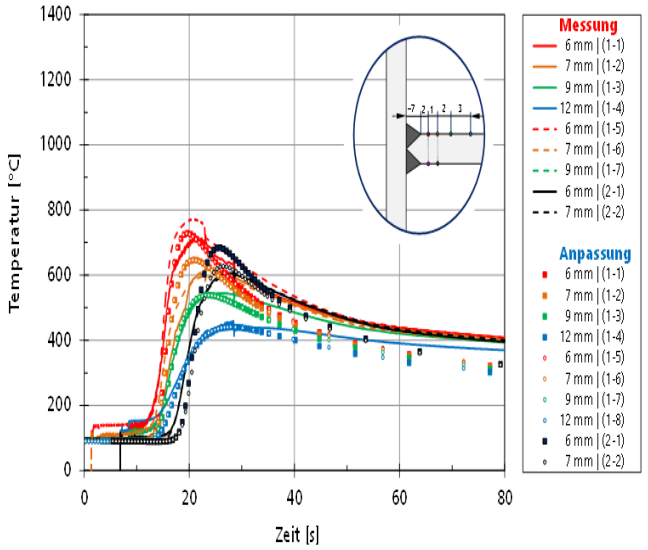
.odb

Fraunhofer IWM

Abaqus simulation

$$Q(x,y,z) = \begin{cases} Q_0 exp\left(-\left(\frac{x^2}{b^2}+\frac{y^2}{c^2}+\frac{z^2}{a_f^2}\right)\right); x \geq 0 \\ Q_0 exp\left(-\left(\frac{x^2}{b^2}+\frac{y^2}{c^2}+\frac{z^2}{a_r^2}\right)\right); x < 0 \end{cases}$$





.odb

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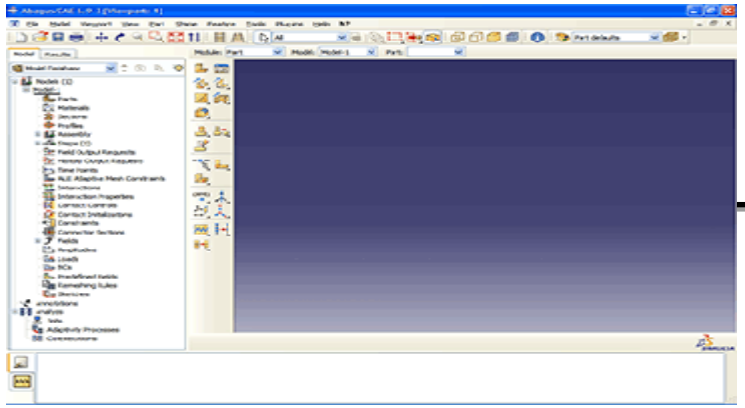
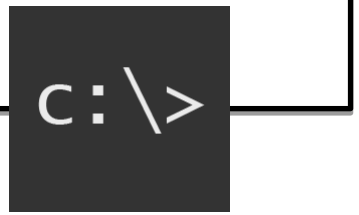
Path

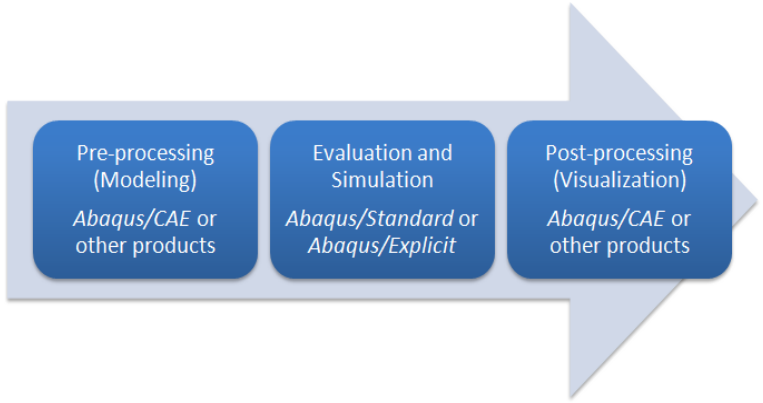


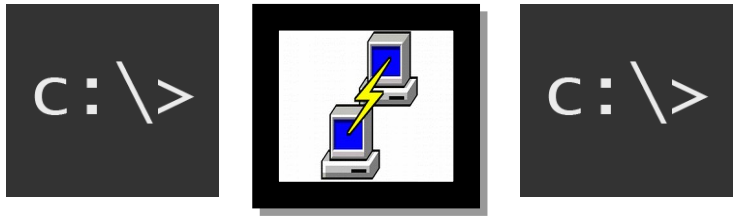


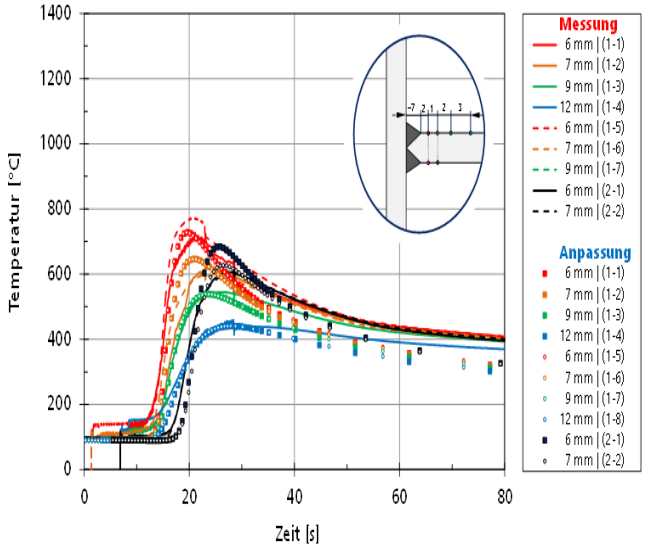
Fraunhofer IWM

Objective

$$Q(x,y,z) = \begin{cases} Q_0 exp\left(-\left(\frac{x^2}{b^2}+\frac{y^2}{c^2}+\frac{z^2}{a_f^2}\right)\right); x \geq 0 \\ Q_0 exp\left(-\left(\frac{x^2}{b^2}+\frac{y^2}{c^2}+\frac{z^2}{a_r^2}\right)\right); x < 0 \end{cases}$$

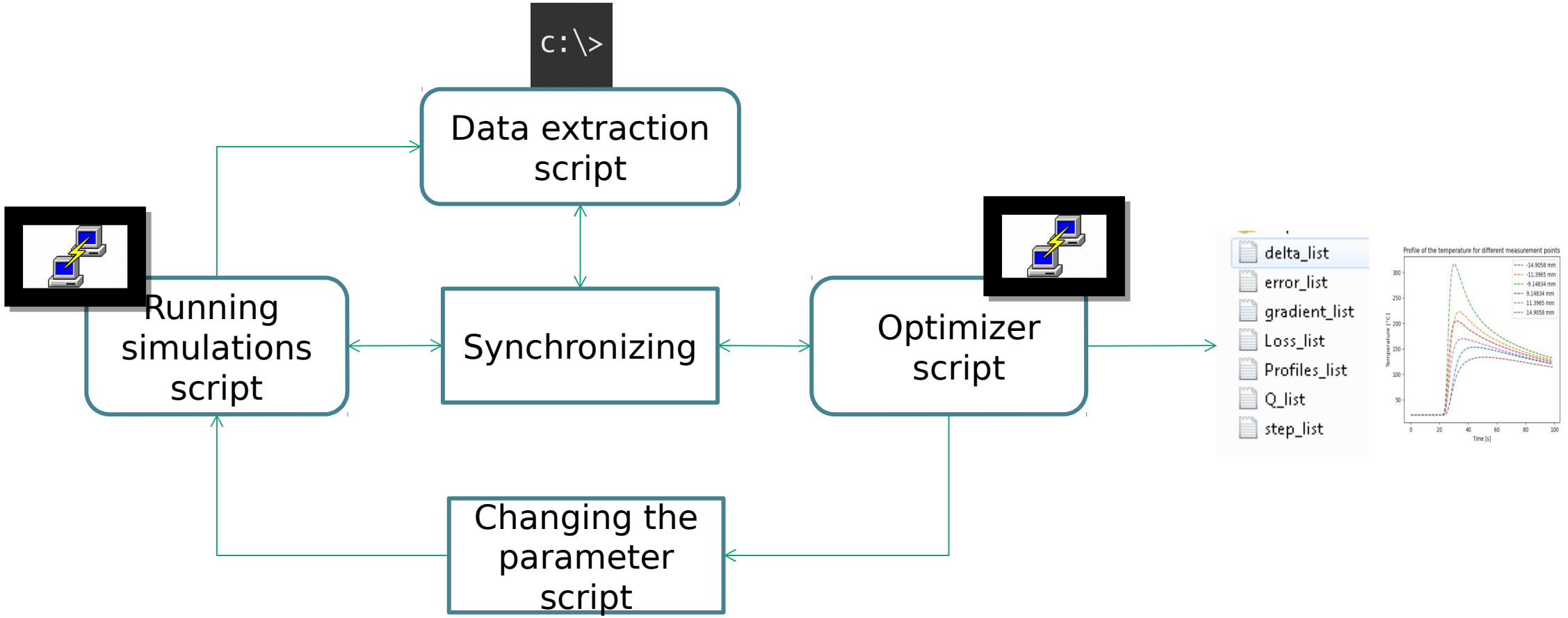




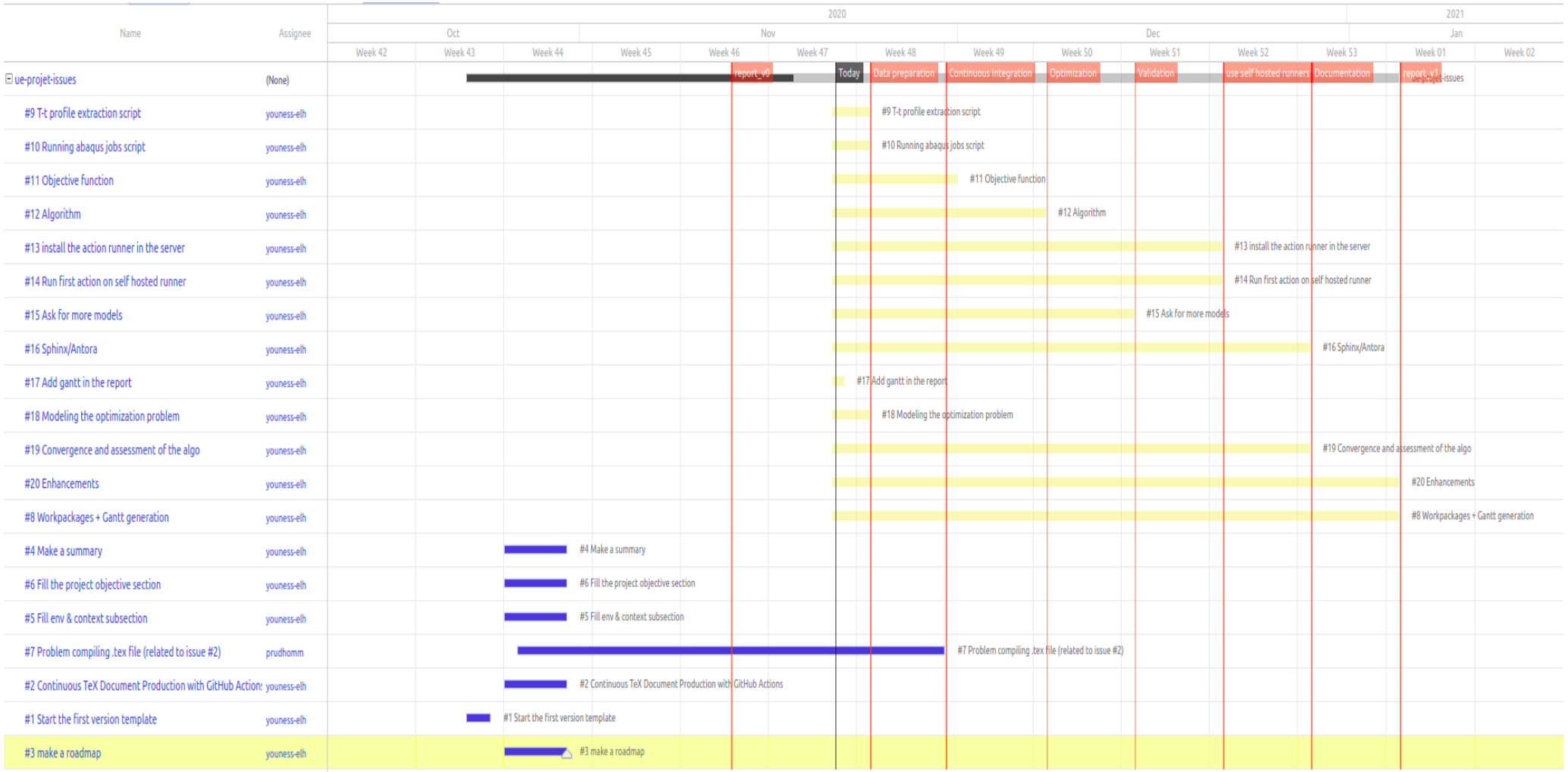


How to run this iterative approach automatically?

Work packages



Github project management



Optimization algorithm

The cost function

The cost function of our optimization problem is:

$$\boldsymbol{Minimize_v\ Loss(Q)}$$

$$\text{With Loss(Q)} = \frac{1}{2}|Tsim - Tref|_{L^2}{}^2 + \frac{\alpha}{2}|Q|_{L^2}{}^2$$

- ✓ Is a regulation and penalization parameter.
- ✓ Tref is the reference temperature profile.
- ✓ Tsim is the simulation profile dependent on Q.

The algorithm

The chosen algorithm is based on the gradient descent method with the following key parameters:

```
#########################################################################
#################### Algorithm of gradient descent  ####################
#########################################################################

delta = L2-L1
error = 1.
tol = 1.e-6
max_iter = 12 # (~three hours per cycle)
max_iter_step = 12 #
step = 25.
```

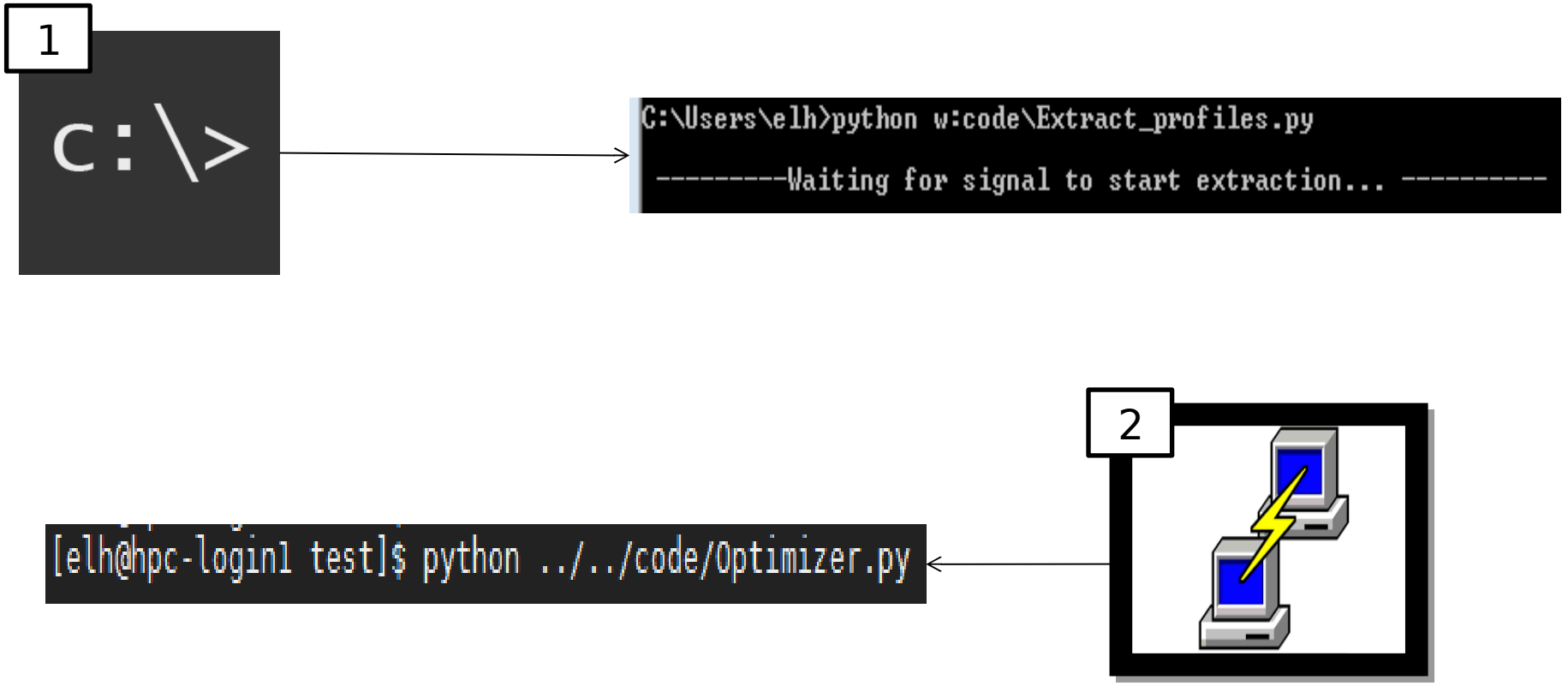
- α is taken around e^{-16}.
- Gradient is approximated as $\nabla Loss(Q) = \frac{L(Q)^1 - L(Q)^o}{Q^1 - Q^0}$

The algorithm

The following sub loop was used to find the descent direction:

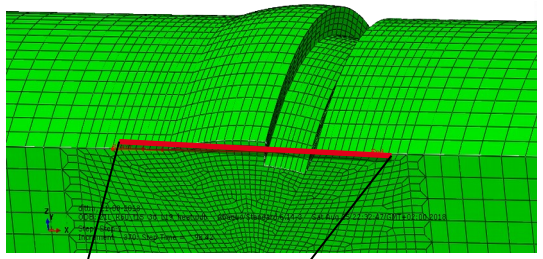
```
while ((count < max_iter_step)  and (delta >=0)):
    print('------------------------------------------------------------')
    print('-----Looking for descent direction for iteration '+str(count+1)+'------')
    print('------------------------------------------------------------\n')
    step /= 2.3
    Q = max(Q_old - step*gradient,0)
    profiles = Abaqus(Q)
    L_new = Loss(Q,profiles,Targets)
    delta = L_new - Loss_list[-1]
    count +=1
    #save
    Q_list.append(Q)
    Loss_list.append(L_new)
    delta_list.append(delta)
    step_list.append(step)
    Profiles_list.append(profiles)
```

How to use:

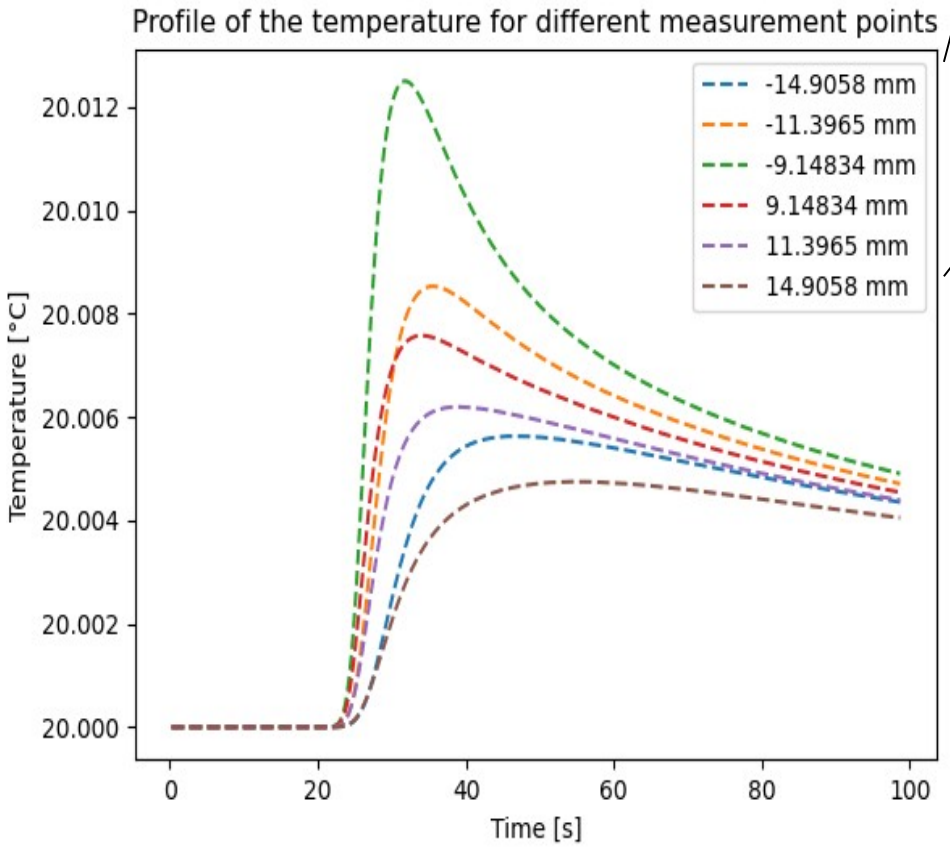


Some results

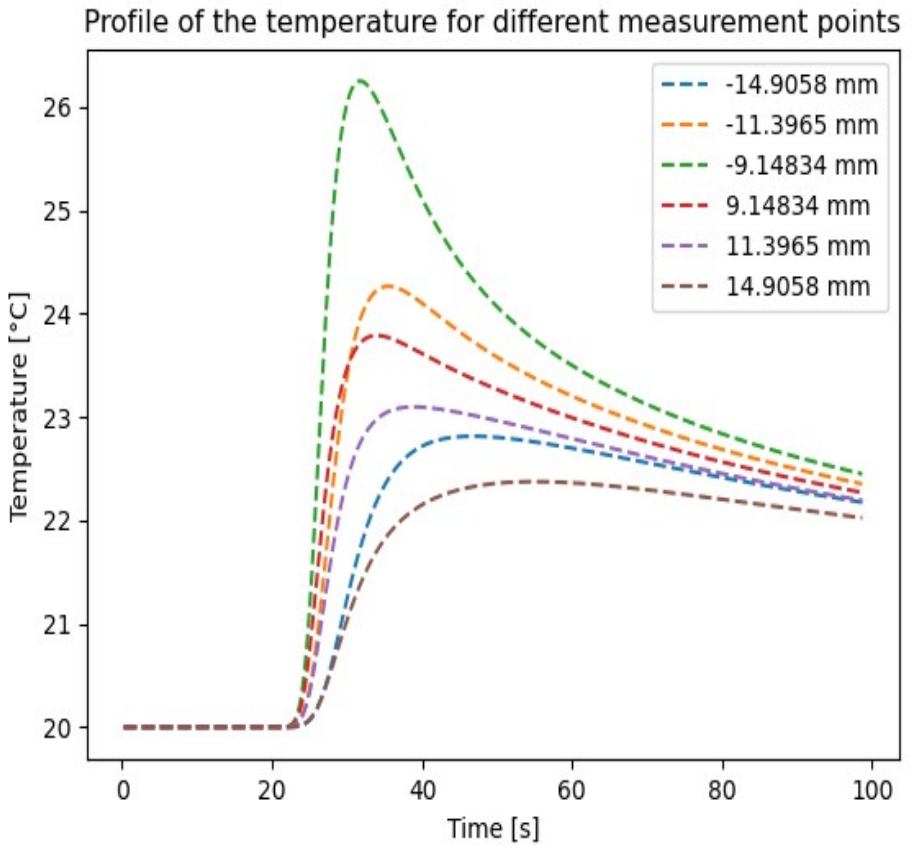
Examples



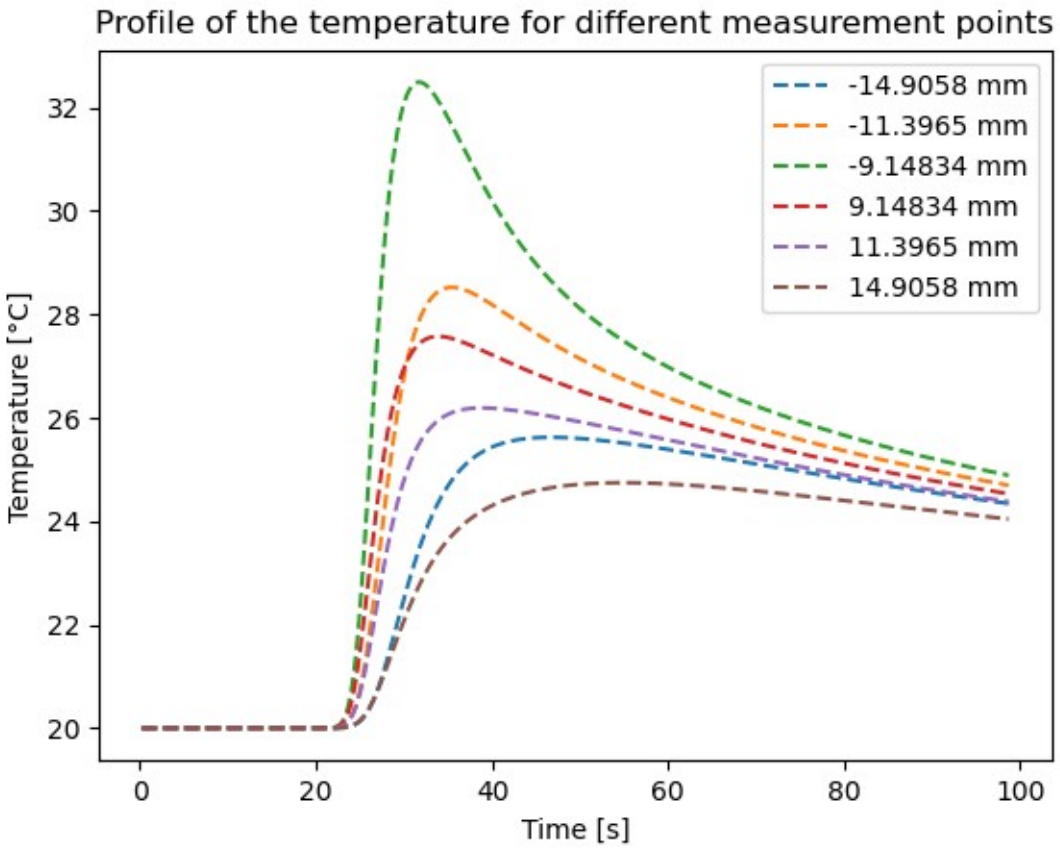
Q = 1



Q = 500

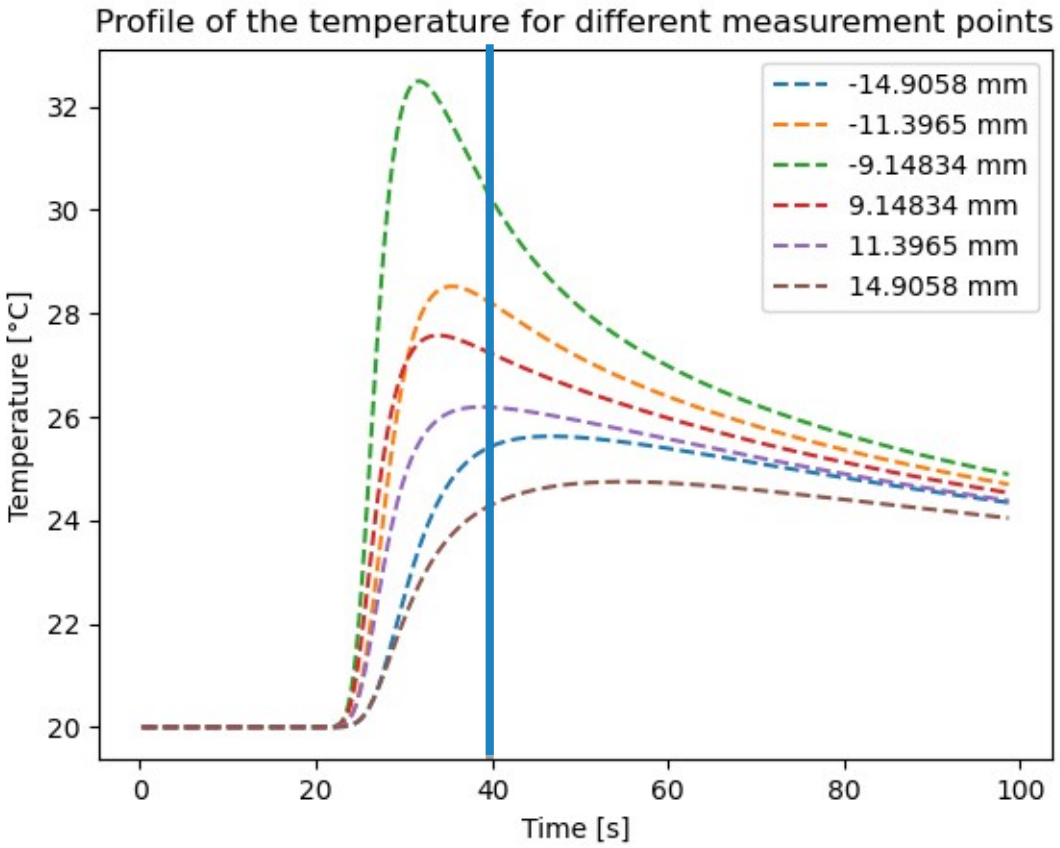


Simulation time:



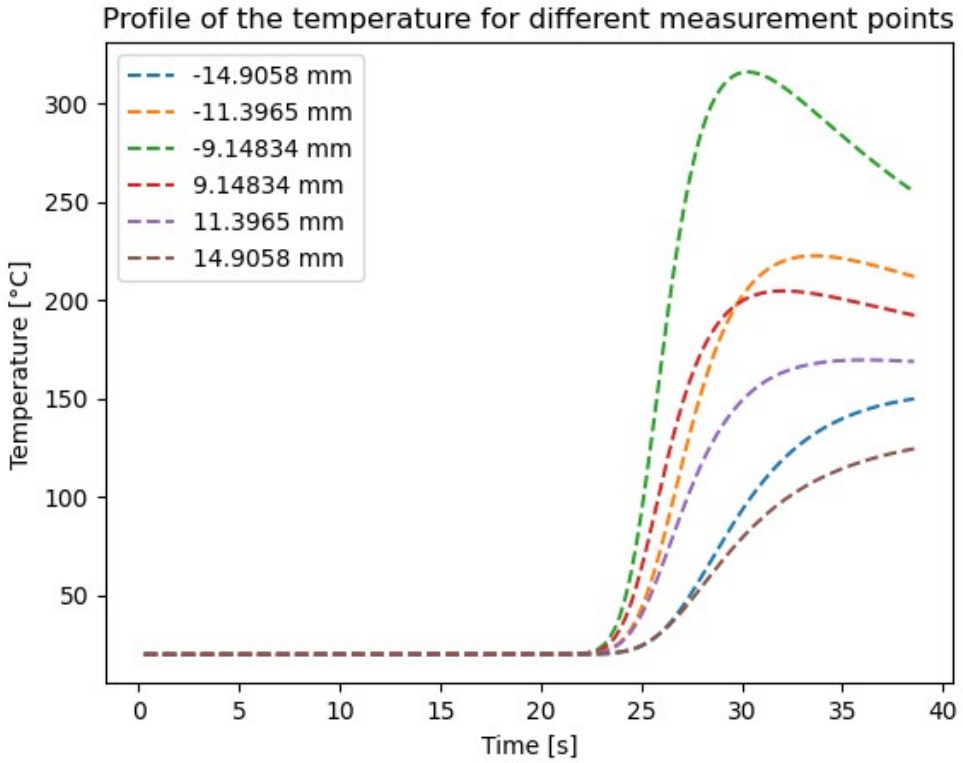
~ 3 hours

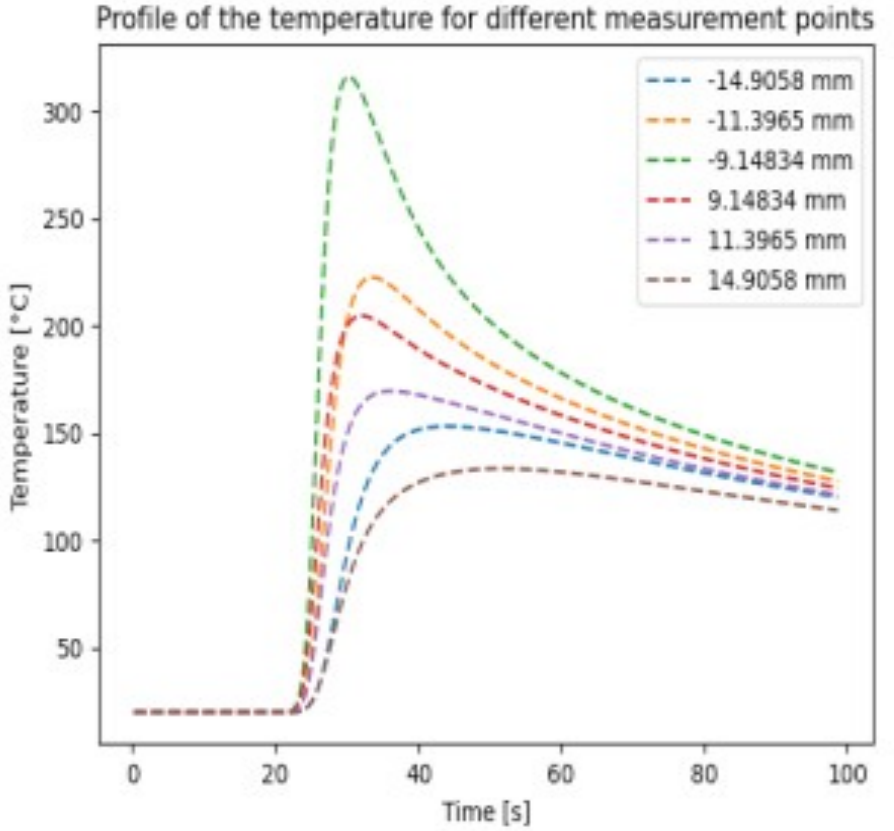
Simulation time



~ 1.5 hour

Reference profile:





First try

- $step = 20$ then step = step/10.3 .
- $Q° = 7321\ which\ goes\ to\ 18321\ in\ the\ first\ step.$
- $\nabla Loss(Q)° \sim -550$

Loss evolution over iterations:

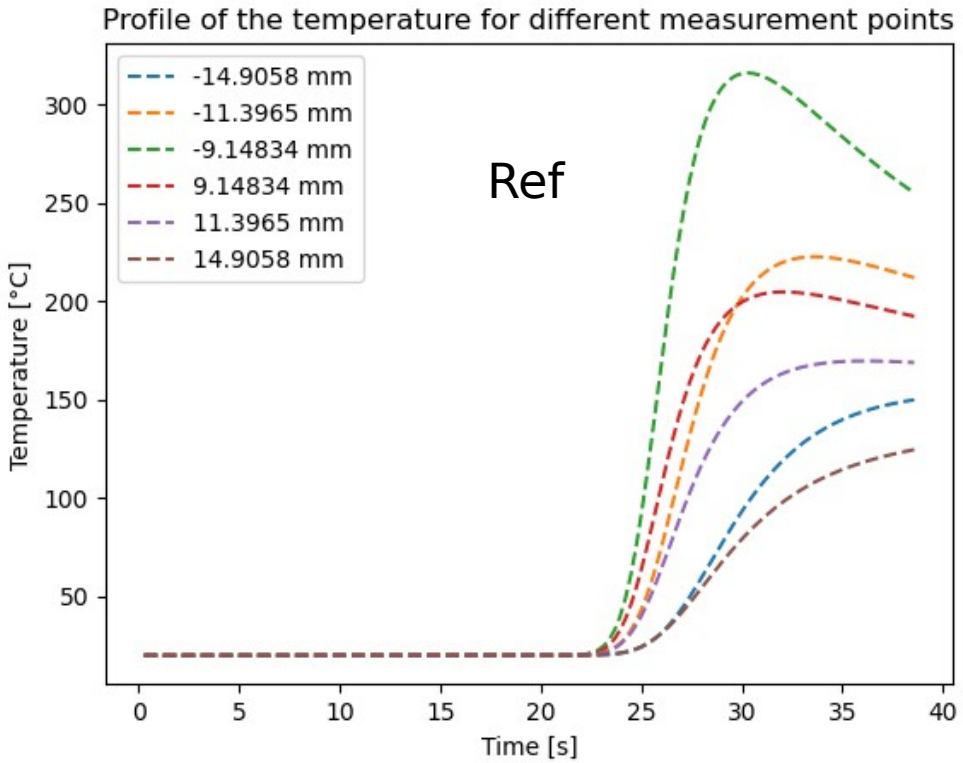
```
7.939960101075110026e+06
3.913946736285572872e+06
3.401935196144585498e+06
5.450714358963172417e+05
4.048547164426437812e+05
2.153708858484998718e+07
2.151098746989504620e+07
2.150845797562927380e+07
2.073616695963315293e+07
2.073592287261193991e+07
7.940604837914695032e+06
```

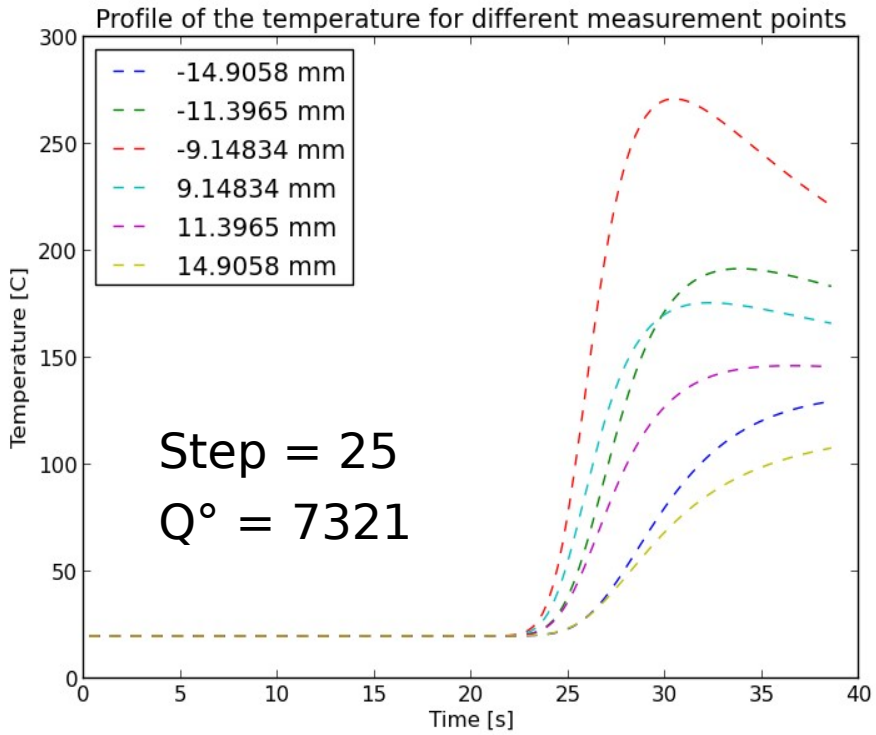
Loss evolution over iterations:

```
1.000000000000000000e+00
7.321000000000000000e+03
1.832103651581840677e+04
1.925196349847832607e+04
8.062871620759859798e+04
8.063315217826582375e+04
8.062914688436240249e+04
7.940063258435850730e+04
7.940024442592239939e+04
0.000000000000000000e+00
0.000000000000000000e+00
```

Best so far:

Relative loss error of: 9.51e-01





Outlook

Enhancement:

Using the tool to generate enough data to build:

- **Regression model for one single use**
- **ANN model for versatile use (e.g the initial guess)**
- **To build a reduced basis out of the FE model**

Programming:

- **Using Gitlab runners instead of shared folders**
- **Enhancing the optimizer packages**

Perspectives:

- **Having a reliable model for more models**
- **Possibility of taking into account several parameters**
- **Including the mechanical behavior to the model.**

Thank you for your attention