

▼ BPL_TEST2_Batch_calibration script with FMPy ver 0.3.15

The key library FMPy ver 0.3.15 and scipy and more are installed.

After the installation a small application BPL_TEST2_Batch_calibration is loaded and run. You can continue with this example if you like.

```

!lsb_release -a # Actual VM Ubuntu version used by Google

No LSB modules are available.
Distributor ID: Ubuntu
Description:    Ubuntu 20.04.5 LTS
Release:        20.04
Codename:       focal

%env PYTHONPATH=

env: PYTHONPATH=

!wget https://repo.anaconda.com/miniconda/Miniconda3-py39_23.1.0-1-Linux-x86_64.sh
!chmod +x Miniconda3-py39_23.1.0-1-Linux-x86_64.sh
!bash ./Miniconda3-py39_23.1.0-1-Linux-x86_64.sh -b -f -p /usr/local
import sys
sys.path.append('/usr/local/lib/python3.9/site-packages/')

--2023-04-21 07:08:51--  https://repo.anaconda.com/miniconda/Miniconda3-py39_23.1.0-1-Linux-
Resolving repo.anaconda.com (repo.anaconda.com)... 104.16.131.3, 104.16.130.3, 2606:4700::68
Connecting to repo.anaconda.com (repo.anaconda.com)|104.16.131.3|:443... connected.
HTTP request sent, awaiting response... 200 OK
Length: 69888122 (67M) [application/x-sh]
Saving to: 'Miniconda3-py39_23.1.0-1-Linux-x86_64.sh'

Miniconda3-py39_23. 100%[=====>] 66.65M  170MB/s   in 0.4s

2023-04-21 07:08:52 (170 MB/s) - 'Miniconda3-py39_23.1.0-1-Linux-x86_64.sh' saved [69888122/

PREFIX=/usr/local
Unpacking payload ...

Installing base environment...

Downloading and Extracting Packages

Downloading and Extracting Packages


Preparing transaction: done
Executing transaction: done
installation finished.

!conda update -n base -c defaults conda --yes

```

```
Preparing transaction: done  
Verifying transaction: done  
Executing transaction: done
```

```
!conda --version  
!python --version
```

```
 conda 23.3.1  
Python 3.9.16
```

```
!conda install -c conda-forge fmpy --yes # Install the key package
```

```
Preparing transaction: done
Verifying transaction: done
Executing transaction: done
```

```
!conda install matplotlib --yes
```

```
Collecting package metadata (current_repodata.json): done
Solving environment: done
```

```
## Package Plan ##
```

```
environment location: /usr/local
```

```
added / updated specs:
- matplotlib
```

The following packages will be downloaded:

package	build	
-----	-----	
brotli-1.0.9	h5eee18b_7	18 KB
brotli-bin-1.0.9	h5eee18b_7	19 KB
contourpy-1.0.5	py39hdb19cb5_0	204 KB
fonttools-4.25.0	pyhd3eb1b0_0	632 KB
libbrotlicommon-1.0.9	h5eee18b_7	70 KB

libbrotlidec-1.0.9		h5eee18b_7	31 KB
libbrotlienc-1.0.9		h5eee18b_7	264 KB
matplotlib-3.7.1		py39h06a4308_1	8 KB
matplotlib-base-3.7.1		py39h417a72b_1	6.7 MB
munkres-1.1.4		py_0	13 KB

Total:			7.9 MB

The following NEW packages will be INSTALLED:

brotili	pkgs/main/linux-64::brotili-1.0.9-h5eee18b_7
brotili-bin	pkgs/main/linux-64::brotili-bin-1.0.9-h5eee18b_7
contourpy	pkgs/main/linux-64::contourpy-1.0.5-py39hdb19cb5_0
fonttools	pkgs/main/noarch::fonttools-4.25.0-pyhd3eb1b0_0
libbrotlicommon	pkgs/main/linux-64::libbrotlicommon-1.0.9-h5eee18b_7
libbrotlidec	pkgs/main/linux-64::libbrotlidec-1.0.9-h5eee18b_7
libbrotlienc	pkgs/main/linux-64::libbrotlienc-1.0.9-h5eee18b_7
matplotlib	pkgs/main/linux-64::matplotlib-3.7.1-py39h06a4308_1
munkres	pkgs/main/noarch::munkres-1.1.4-py_0

The following packages will be UPDATED:

ca-certificates	conda-forge::ca-certificates-2022.12.~ --> pkgs/main::ca-certificates-2
matplotlib-base	conda-forge::matplotlib-base-3.4.3-py~ --> pkgs/main::matplotlib-base-3

The following packages will be SUPERSEDED by a higher-priority channel:

certifi	conda-forge/noarch::certifi-2022.12.7~ --> pkgs/main/linux-64::certifi-
conda	conda-forge::conda-23.3.1-py39hf3d152~ --> pkgs/main::conda-23.3.1-py39

Downloading and Extracting Packages

matplotlib-3.7.1	8 KB	:	0% 0/1 [00:00<?, ?it/s]
contourpy-1.0.5	204 KB	:	0% 0/1 [00:00<?, ?it/s]
munkres-1.1.4	13 KB	:	0% 0/1 [00:00<?, ?it/s]

```
!conda install scipy --yes
```

Total: 25.2 MB

The following NEW packages will be INSTALLED:

appdirs	pkgs/main/noarch::appdirs-1.4.4-pyhd3eb1b0_0
libgfortran-ng	pkgs/main/linux-64::libgfortran-ng-11.2.0-h00389a5_1
libgfortran5	pkgs/main/linux-64::libgfortran5-11.2.0-h1234567_1
pooch	pkgs/main/noarch::pooch-1.4.0-pyhd3eb1b0_0

```
21/04/2023,09:16 BPL_TEST2_Batch_calibration_fmipy_colab.ipynb - Colaboratory
libgfortran-ng-11.2. | 20 KB | : 81% 0.8104070831478458/1 [00:00<00:00, 4.09it/s]

appdirs-1.4.4 | 12 KB | : 100% 1.0/1 [00:00<00:00, 5.85it/s]

pooch-1.4.0 | 41 KB | : 39% 0.389594331098112/1 [00:00<00:00, 1.87it/s]

scipy-1.10.1 | 23.1 MB | : 8% 0.08037809153482604/1 [00:00<00:02, 2.88s/it]

scipy-1.10.1 | 23.1 MB | : 32% 0.3201614738446012/1 [00:00<00:00, 1.13it/s]
libgfortran5-11.2.0 | 2.0 MB | : 100% 1.0/1 [00:00<00:00, 2.55it/s]
```

Preparing transaction: done
Verifying transaction: done
Executing transaction: done

```
!conda install xldr --yes

Collecting package metadata (current_repodata.json): done
Solving environment: done

## Package Plan ##

environment location: /usr/local

added / updated specs:
- xldr
```

The following packages will be downloaded:

package	build	
xldr-2.0.1	pyhd3eb1b0_0	90 KB
Total:		90 KB

The following NEW packages will be INSTALLED:

```
xldr pkgs/main/noarch::xldr-2.0.1-pyhd3eb1b0_0
```

Downloading and Extracting Packages

Preparing transaction: done
Verifying transaction: done
Executing transaction: done

```
!conda install openpyxl --yes

Collecting package metadata (current_repodata.json): done
Solving environment: done

## Package Plan ##
```

```
environment location: /usr/local
```

```
added / updated specs:
- openpyxl
```

The following packages will be downloaded:

package	build	
et_xmlfile-1.1.0	py39h06a4308_0	10 KB
openpyxl-3.0.10	py39h5eee18b_0	537 KB
Total:		546 KB

The following NEW packages will be INSTALLED:

```
et_xmlfile      pkgs/main/linux-64::et_xmlfile-1.1.0-py39h06a4308_0
openpyxl        pkgs/main/linux-64::openpyxl-3.0.10-py39h5eee18b_0
```

Downloading and Extracting Packages

```
openpyxl-3.0.10      | 537 KB | : 0% 0/1 [00:00<?, ?it/s]
openpyxl-3.0.10      | 537 KB | : 3% 0.029819832445448308/1 [00:00<00:07, 7.92s/it]
et_xmlfile-1.1.0     | 10 KB  | : 100% 1.0/1 [00:00<00:00, 3.87it/s]
```

```
Preparing transaction: done
Verifying transaction: done
Executing transaction: done
```

Now specific installation and the run simulations. Start with connecting to Github. Then upload the four files:

- FMU - BPL_TEST2_Batch_linux_om_me.fmu
- Setup-file - BPL_TEST2_Batch_fmipy_explore.py

```
%%bash
git clone https://github.com/janpeter19/BPL_TEST2_Batch_calibration
```

```
Cloning into 'BPL_TEST2_Batch_calibration'...
```

```
%cd BPL_TEST2_Batch_calibration

/content/BPL_TEST2_Batch_calibration
```

▼ BPL_TEST2_Batch_calibration - demo

Author: Jan Peter Axelsson

This notebook shows the possibilities for calibration of the model BPL_TEST2_Batch using `scipy.optimize.minimize()` routine. There are several different methods to choose between. In this notebook we work with simulated data.

The text-book model of batch cultivation we simulate is the following where S is substrate, X is cell concentration, and V is volume of the broth

$$\frac{d(VS)}{dt} = -q_S(S) \cdot VX$$

$$\frac{d(VX)}{dt} = \mu(S) \cdot VX$$

and where specific cell growth rate μ and substrate uptake rate q_S are

$$\mu(S) = Y \cdot q_S(S)$$

$$q_S(S) = q_S^{max} \frac{S}{K_s + S}$$

where Y is the yield, q_S^{max} is the maximal specific substrate uptake rate and K_s is the corresponding saturation constant.

The parameter estimation is done with optimization methods that only require evaluation of the mismatch between simulation with given parameters and data. At start the allowed range for each parameter is given. The method used for optimization is SLSQP but can easily be changed [1].

In the near future the FMU may provide first derivative gradient information, that will make it possible to choose corresponding method of minimize() for improved performance. This possibility is related to the upgrade to the FMI-standard ver 3.0 for the Modelica compiler.

The Python package PyFMI [2] that is the base for FMU-explore has a simplified built-in functionality for parameter estimation that also use scipy.optimize.minimize(). However, there is estimation functionality but the purpose seems to only address smaller examples. There is for instance no support to handle models that takes sub-models from libraries and necessary changes of default parameters not to be estimated. Therefore we here define a Python function evaluate() that facilitate the formulation of the parameter estimation and also bring flexibility to choice of optimization method, default Nelder-Mead.

```
run -i BPL_TEST2_Batch_fmпы_explore.py
```

```
Linux - run FMU pre-compiled OpenModelica 1.21.0
```

```
Model for bioreactor has been setup. Key commands:
```

```
- par()           - change of parameters and initial values
- init()          - change initial values only
- simu()          - simulate and plot
- newplot()       - make a new plot
- show()          - show plot from previous simulation
- disp()          - display parameters and initial values from the last simulation
- describe()      - describe culture, broth, parameters, variables with values/units
```

```
Note that both disp() and describe() takes values from the last simulation
```

```
Brief information about a command by help(), eg help(simu)
```

```
Key system information is listed with the command system_info()
```

```
# Adjust the size of diagrams
```

```
plt.rcParams['figure.figsize'] = [15/2.54, 12/2.54]
```

▼ 1 Generate data later used for parameter estimation

```
import pandas as pd
```

```
# Data generated
```

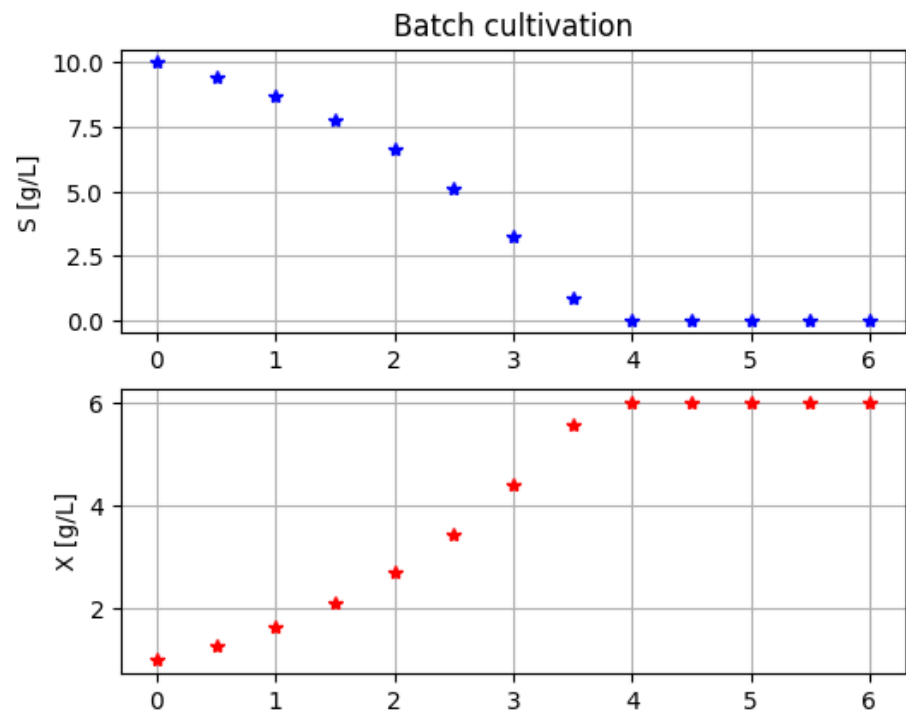
```
simulationTime = 6.0
```

```
par(Y=0.50, qSmax=1.00, Ks=0.1)
```

```
init(V_0=1.0, VS_0=10, VX_0=1.0)
```

```
newplot(plotType='Demo_2')
```

```
simu(simulationTime, options=opts_data)
```



```
# Store data in a DataFrame for later use
data = pd.DataFrame(data={'time':sim_res['time'], 'X':sim_res['bioreactor.c[1]'], 'S':sim_res['bioreactor.c[2]']})
```

	time	x	s
0	0.0	1.000000	1.000000e+01
1	0.5	1.280777	9.438447e+00
2	1.0	1.640089	8.719823e+00
3	1.5	2.099634	7.800732e+00
4	2.0	2.686794	6.626412e+00
5	2.5	3.435509	5.128981e+00
6	3.0	4.385357	3.229286e+00
7	3.5	5.559274	8.814516e-01
8	4.0	6.000000	4.618858e-07
9	4.5	6.000000	-7.022022e-11
10	5.0	6.000000	-2.610415e-12
11	5.5	6.000000	1.020722e-14
12	6.0	6.000000	-1.037244e-17

2 Simulation with initial guess of parameters compared with data

Here we define the parameters that should be estimated and specify allowed ranges. Nominal parameters are chosen as the mid-point of the allowed parameter range.

Simulation with these nominal parameter set and compare with data give an idea of how well the model fit data.

```
# Parameters to be estimated using parDict names and their bounds
parEstim = ['Y', 'qSmax', 'Ks']
```



```

parBounds = [(0.4, 0.8), (0.7, 1.3), (0.05, 0.20)]
parEstim_0 = [np.mean(parBounds[k]) for k in range(len(parBounds))]

```

```

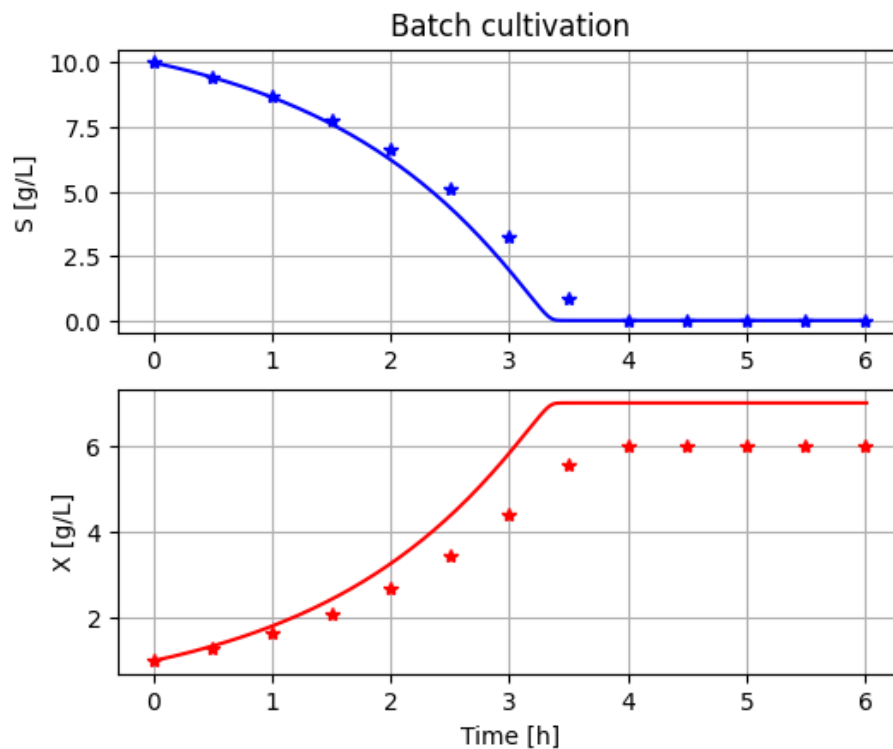
# Simulation with nominal parameters
newplot(plotType='Demo_1')
par(Y=parEstim_0[0], qSmax=parEstim_0[1], Ks=parEstim_0[2])
simu(simulationTime)

```

```

# Show data
ax1.plot(data['time'], data['S'],'b*')
ax2.plot(data['time'], data['X'],'r*')
plt.show()

```



```

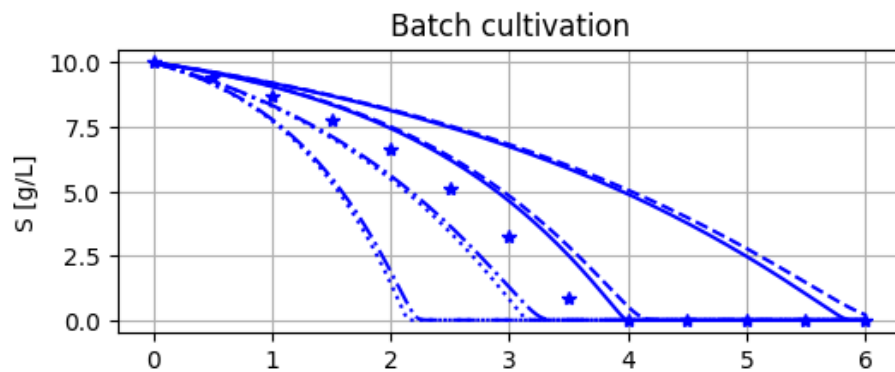
# Simulation over the parameter ranges given
newplot(plotType='Demo_1')
for Y_value in parBounds [0]:
    for qSmax_value in parBounds[1]:
        for Ks_value in parBounds[2]:
            par(Y=Y_value, qSmax=qSmax_value, Ks=Ks_value)
            simu(simulationTime)

```

```

# Show data
ax1.plot(data['time'], data['S'],'b*')
ax2.plot(data['time'], data['X'],'r*')
plt.show()

```



Simulation over the different parameter combinations of the parameter bounds shows that data is "covered" and we have good hope to find a parameter combination that fits data well.



3 Parameter estimation

Here we use the `scipy.optimize.minimize()` procedure which contains a family of different methods [1]. The default method is Nelder-Mead and is robust for fitting a model to data. Further we have chosen to work with bounds for the parameters to be estimated and the initial guess is chosen as the middle point in parameter space.

```
# Optimization routine import
import scipy.optimize

# Parameters to be estimated using parDict names and their bounds
extra_args = (parEstim, data, fmu_model, simulationTime, parDict, parLocation)

# Modified evaluation function tailored for Python optimization algorithms
def objective(x, parEstim, data=data, fmu_model=fmu_model, simulationTime=simulationTime,
             parDict=parDict, parLocation=parLocation):
    """The parameter list is tailored for scipy optimization algorithms interface,
    where the first parameter x is an array with parameters that are tuned
    and evaluated and parEstim is a list of the names of these parameters.
    The code can be made 20-30% faster, but loner, using pyfmi-commands directly."""

    # Update parameters and simulate
    for i, p in enumerate(parEstim): par(**{p:x[i]})
    simu(simulationTime, options=opts_data)

    # Calculate loss function V
    V={}
    V['X'] = np.linalg.norm(data['X'] - np.interp(data['time'], sim_res['time'], sim_res['bioreact']))
    V['S'] = np.linalg.norm(data['S'] - np.interp(data['time'], sim_res['time'], sim_res['bioreact']))

    return V['X'] + V['S']

import time

# Run minimize()
start_time = time.time()
result = scipy.optimize.minimize(objective, x0=parEstim_0, args=extra_args,
                                method='Nelder-Mead', bounds=parBounds, options={"disp":True})
print('CPU-time =', time.time()-start_time)

Optimization terminated successfully.
Current function value: 0.045511
Iterations: 39
```

Function evaluations: 75
CPU-time = 1.456897258758545

result

```

message: Optimization terminated successfully.
success: True
status: 0
  fun: 0.045510651189744136
   x: [ 5.001e-01  1.007e+00  1.405e-01]
  nit: 39
 nfev: 75
final_simplex: (array([[ 5.001e-01,  1.007e+00,  1.405e-01],
                        [ 5.001e-01,  1.007e+00,  1.405e-01],
                        [ 5.001e-01,  1.007e+00,  1.405e-01],
                        [ 5.001e-01,  1.007e+00,  1.405e-01]]), array([ 4.551e-02,  4.552e-
02,  4.556e-02,  4.559e-02]))

```

The estimated parameters result.x are very close to the original values and no surprise.

▼ 4 Simulation with estimated parameters compared with data

```

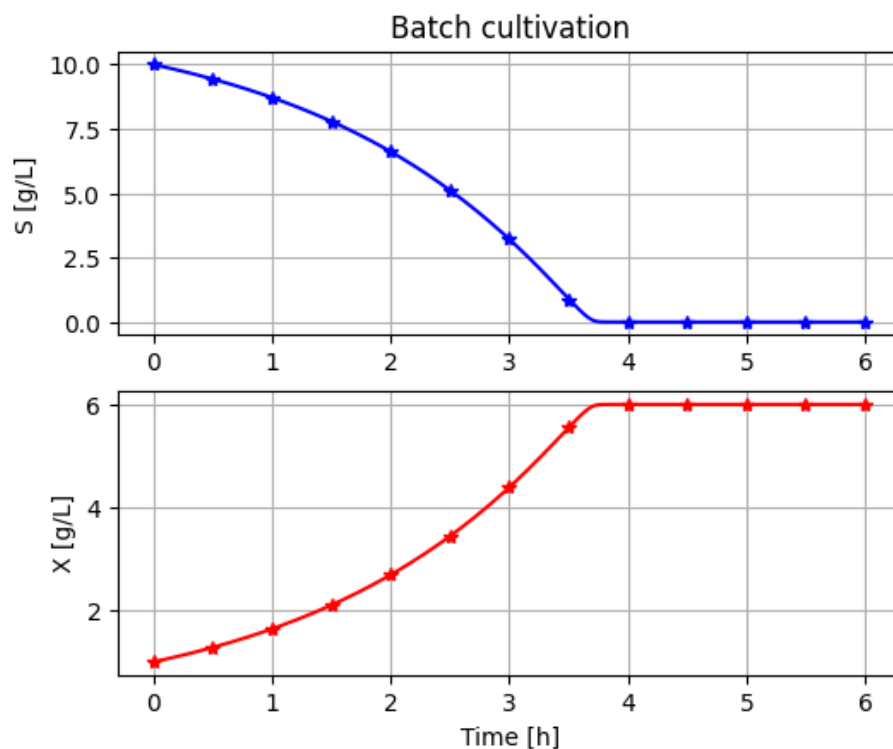
newplot(plotType='Demo_1')
par(Y=result.x[0], qSmax=result.x[1], Ks=result.x[2])
simu(simulationTime)

```

```

# Show data
ax1.plot(data['time'], data['S'],'b*')
ax2.plot(data['time'], data['X'],'r*')
plt.show()

```



```

# The estimated parameters are
for i in range(len(parEstim)): print(parEstim[i],':', result.x[i])

Y : 0.5000549816703198
qSmax : 1.0066481313036082

```

Ks : 0.14048278753421406

▼ 5 Analysis of the loss function

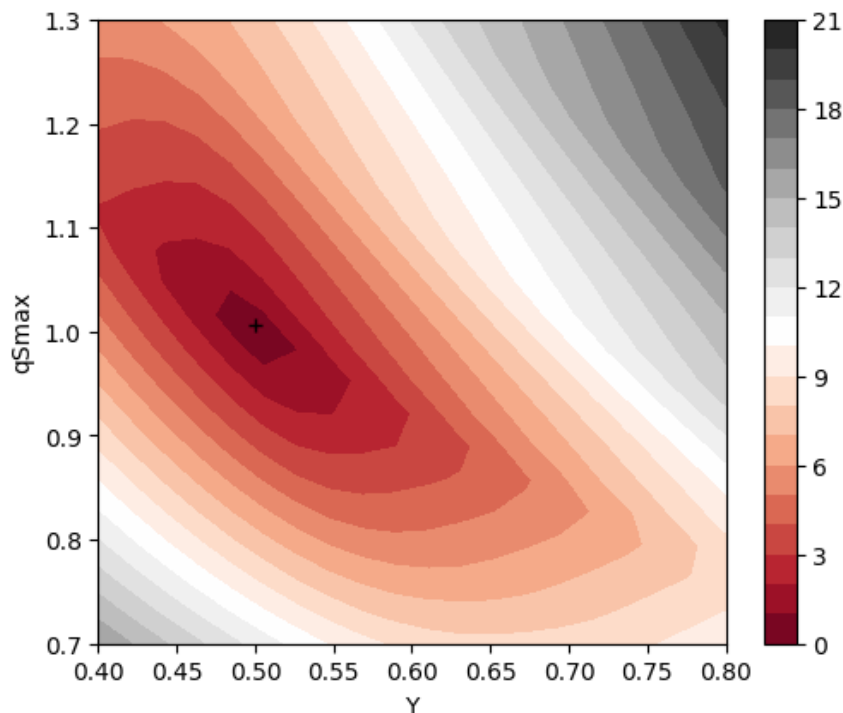
The problem is small and analysis of the loss function brings some insight. From the diagram above showing parameter sweep over combinations min- and max-parameters we see that the parameter K_s has little influence. Let us set that a fixed value and then plot the loss function in the parameters Y and $qSmax$. We do this by going through all the parameter combinations and evaluate each of them.

```
# Sweep through Y and qSmax variation and store the value of the loss-function for each
nY = 20
nqSmax = 20
V = np.zeros((nY, nqSmax))

Y = np.linspace(parBounds[0][0], parBounds[0][1], nY)
qSmax = np.linspace(parBounds[1][0], parBounds[1][1], nqSmax)

for j in range(nY):
    for k in range(nqSmax):
        V[k, j] = objective([Y[j], qSmax[k], 0.1], parEstim)

# Contour plot
plt.figure()
plt.clf
plt.subplot(1,1,1)
plt.contourf(Y, qSmax, V, 20, cmap='RdGy')
plt.plot(result.x[0], result.x[1], 'k+')
plt.colorbar()
plt.ylabel('qSmax')
plt.xlabel('Y')
plt.show()
```



We see the following in the contour diagram of the loss function simplified:

- The minima is unique in the range of parameters we study. This is good news.

- The contour plot is ellipsoid and rather narrow. The more narrow the ellipsoid the more difficult and more time it takes to converge to the minima.
- The direction of the ellipsoid axis indicate the correlation you may get between the two parameters during the minimization process.

Note that the form of the contour plot change with the parameters (and initial values) of the actual proces. You can see the impact by changing the parameters in "cell # 4" where data is generated and then just choose to run that cell and the cells below. No need to restart the notebook.

6 Summary

A choice was made to work with allowed ranges of parameters to be estimated and a start value was defined as the center point in this parameter space. There are only three methods available in `optimize.minimize()` that can handle bounds on parameters.

An `evaluate()` function was created that define how the difference between simulation and data is measured. The function is rather transparent and easy to modify and you may want to change weight on the loss in S and X, for instance. Here they have so far equal weight.

The FMU-explore workspace dictionaries `partDict[]` and `parLocation[]` are useful also here and simplify the code for the `evaluation()` function. But we also use the detailed PyFMI-functions to administrate and set parameters of the actual simulation.

The call `optimize.minimize()` has several parameters and can easily be modified, for instance change of method. For fitting a model to data Nelder-Mead is ao a robust and good choice, but can be somewhat slow.

The estimated parameters were close to perfect!

The contour plot of the simplified loss function shows that the minima is unique and should not be difficult too difficult to obtain. More narrow elliptical contour plots would indicate difficulties. Multiple local minima would also be a problem.

7 References

[1] Scipy Reference guide on `optimize.minimize()` [here](#)

[2] Andersson, C., Åkesson, J., Fuhrer C. : "PyFMI: A Python package for simulation of coupled dynamic models with the functional mock-up interface", Centre for Mathematical Sciences, Lund University, Report LUTFNA-5008-2016, 2016.

▼ Appendix

```
describe('parts')

['bioreactor', 'bioreactor.culture']

describe('MSL')

MSL: 3.2.3 - used components: none

system_info()
```

System information

```
-OS: Linux
-Python: 3.9.16
-Scipy: 1.10.1
-FMPy: 0.3.15
-FMU by: OpenModelica Compiler OpenModelica 1.21.0
-FMI: 2.0
-Type: ME
-Name: BPL_TEST2.Batch
-Generated: 2023-04-19T18:37:26Z
-MSL: 3.2.3
-Description: Bioprocess Library version 2.1.1
-Interaction: FMU-explore for FMPy version 0.9.7
```

✓ 0s completed at 09:15

