PRESENTATION 31.01.2022

Implementation of a Modelica library for modeling and simulation with neural networks in OpenModelica

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Structure of the presentation

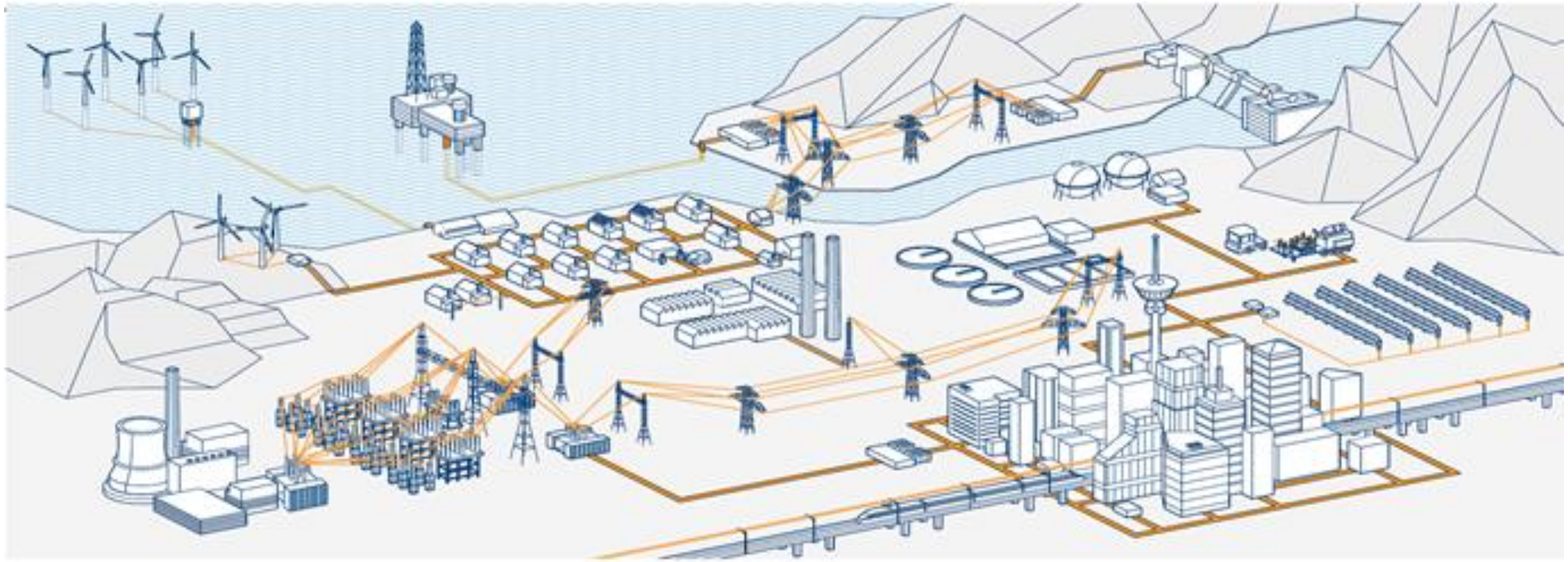
1. Introduction
2. State of the art
3. Neural Network Library
4. Results
5. Conclusions and further work

Introduction

Multi-energy systems

Challenges

- Energy supply facing massive changes and major challenges
- Decentralized energy systems
- Cross-sectoral coupling

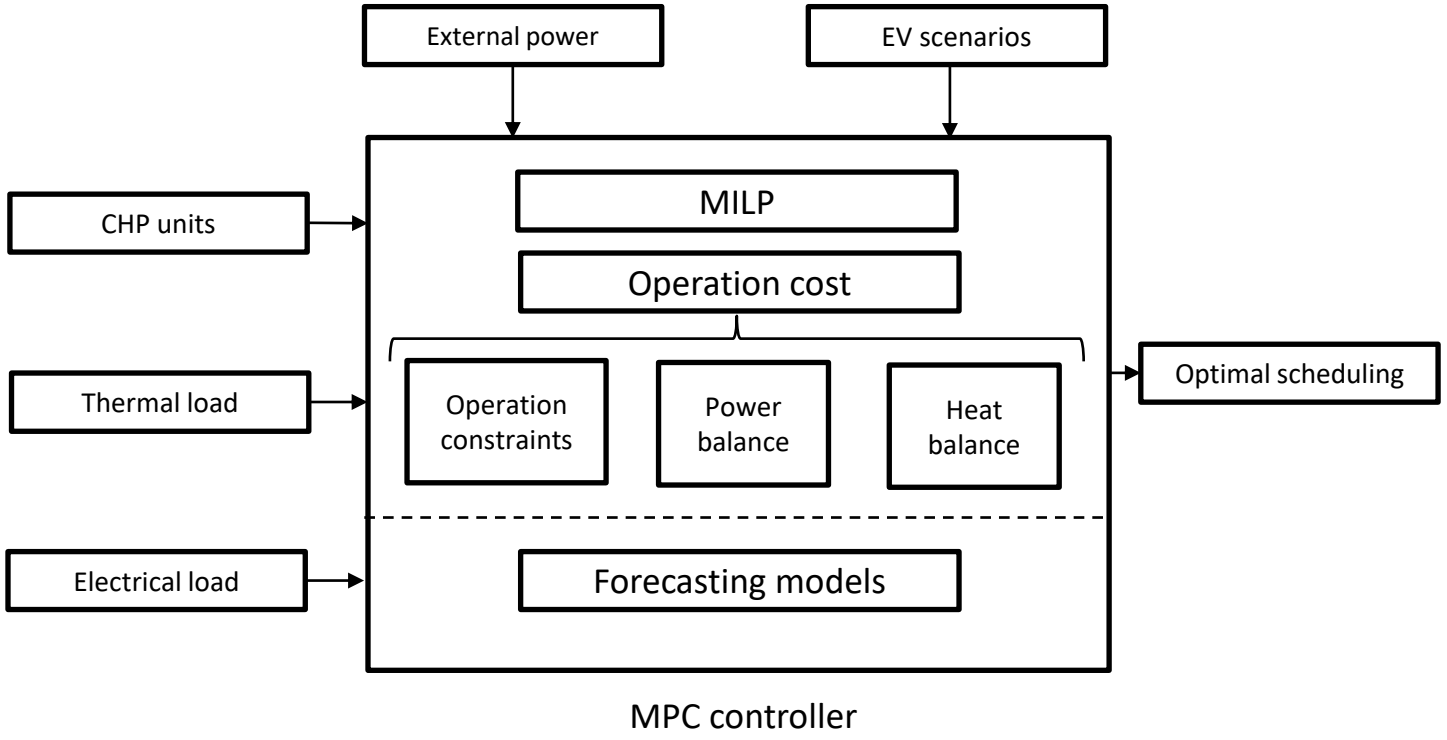


Introduction

Multi -energy systems

MPC for multi-energy system

- Finding optimal setpoints
- Essential task: Transform dynamic behavior into an accurate mathematical model
- White-box-models: precise theoretical analysis
- Black-box-models: no or little prior knowledge
- Use artifical neural networks to model complex systems



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State of the art

Data Transformation

Hypercube Standardisation

- Useful for neural networks
- Normalize inputs to [0,1] or [-1,1]

$$\hat{x}^{(i)} = \frac{x^{(i)} - x_{min}^{(i)} * (1,1,\dots)^T}{x_{max}^{(i)} - x_{min}^{(i)}}$$

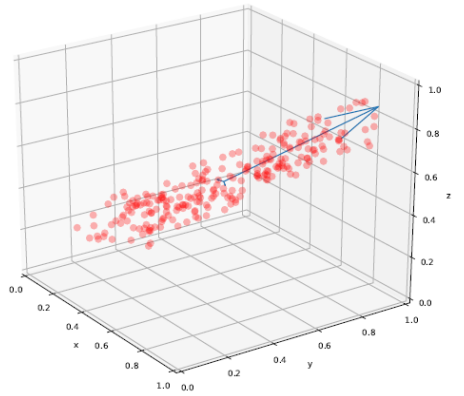
Mu-Sigma Standardisation

- Another approach for data preprocessing
- Arithmetic mean zero and empirical variance one

$$\tilde{x}^{(i)} = \frac{x^{(i)} - \bar{x}^{(i)} * (1,1,\dots)^T}{\sigma_{x^{(i)}}}$$

Principle component analysis (PCA)

- Transforming attributes of a dataset into a new set of uncorrelated attributes
- Reduce dimensionality of a dataset
- A linear combination of features is searched for, so that the variance is maximized



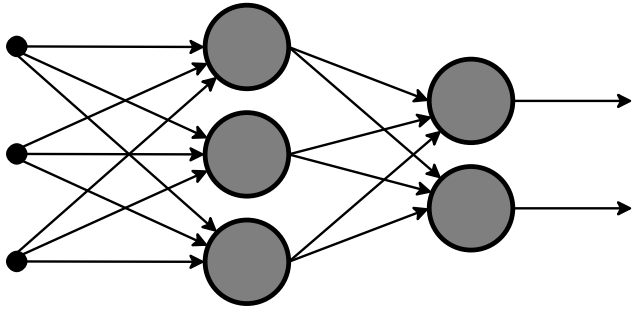
State of the art

Feed-forward neural networks

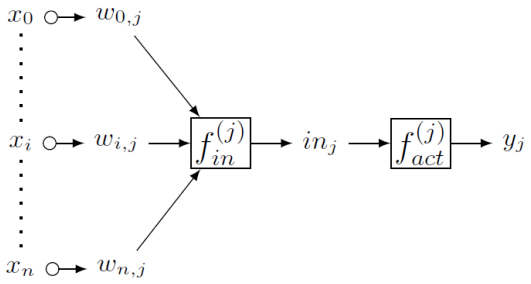
Characteristics

- Most commonly used neural networks
- Good results in many application areas
- Universal approximation theorem
- No internal state

Structure



Neuron



Actication functions

- $sig(a * x) = \frac{1}{1+\exp(-a*x)}$
- $\tanh(a * x) = \frac{\exp(2a*x)-1}{\exp(2a*x)+1}$
- $Identity(a * x) = a * x$
- $ReLU(x) = \begin{cases} x, x \geq 0 \\ 0, x < 0 \end{cases}$

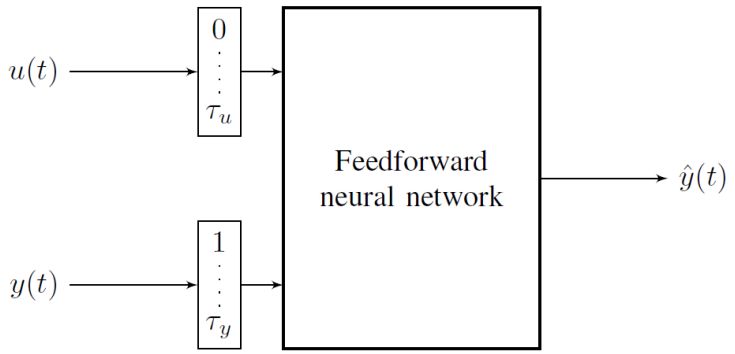
State of the art

Dynamic neural networks

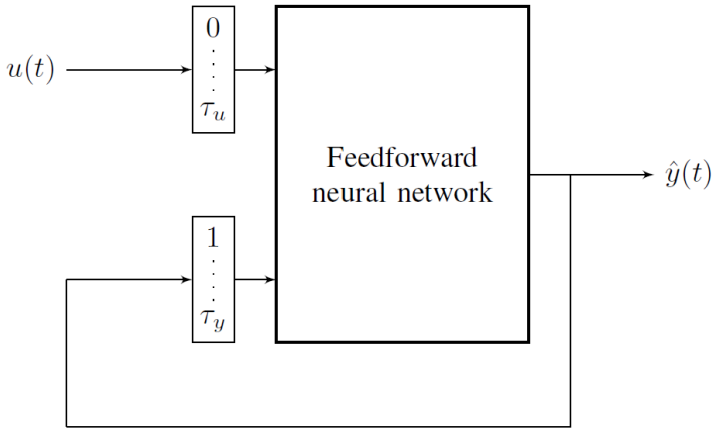
Nonlinear Autoregressive Networks with Exogenous Inputs (NARX)

- Model nonlinear dynamical systems
- Based on recurrent dynamic neural networks
- Storing past values
- Two different architectures
- Good convergence and generalization properties

Serial parallel architecture



Parallel architecture



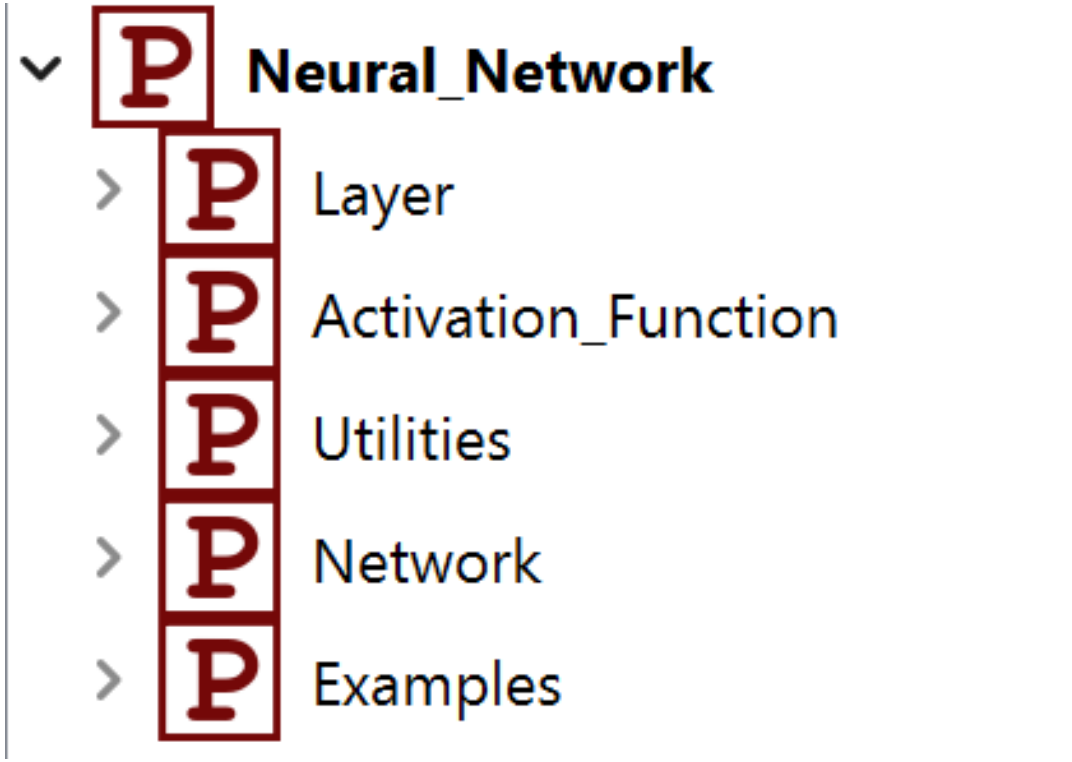
Neural Network Library

Structure

General

- Neural networks for black-box-modeling in OpenModelica
- Reactivation of *Neural Network Libaray* (Casella et. al)
- Included various data transformation elements
- Five sub-packages:
  1. Layer
  2. Activation_Function
  3. Utilities
  4. Network
  5. Examples

Overview

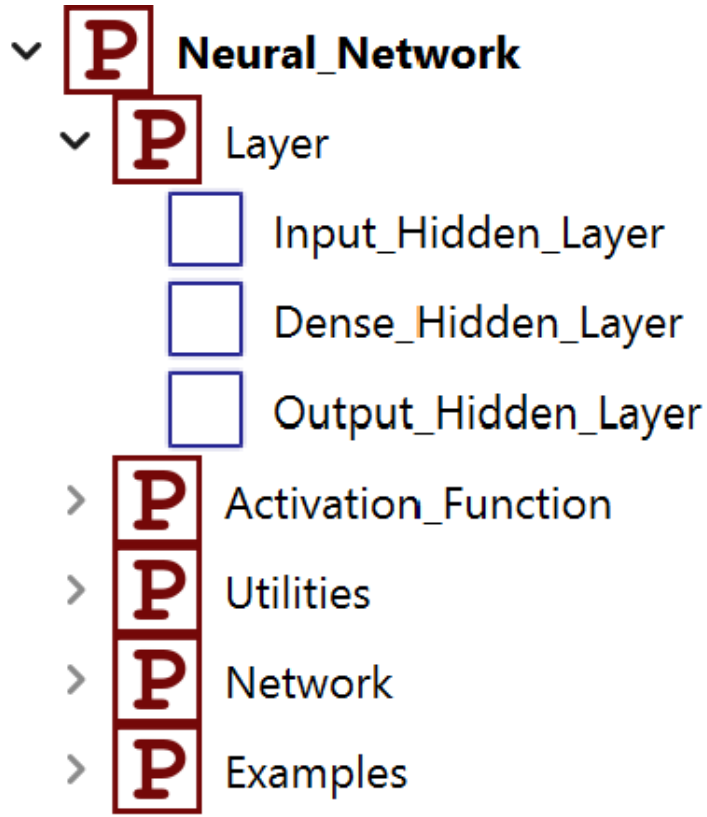


Neural Network Library

Layer

Description

- Set of neurons with weights and a given activation function
- Implemented as multiple-input-multiple-output interfaces
  - bias
  - weights
  - NeuronActivation_Function
  - numInputs
  - numNeurons
- Additional methods for data transformation of inputs and outputs
  - PCA in input layer
  - Apply hypercube and/or mu-sigma standardization
  - Rescaling of the targets

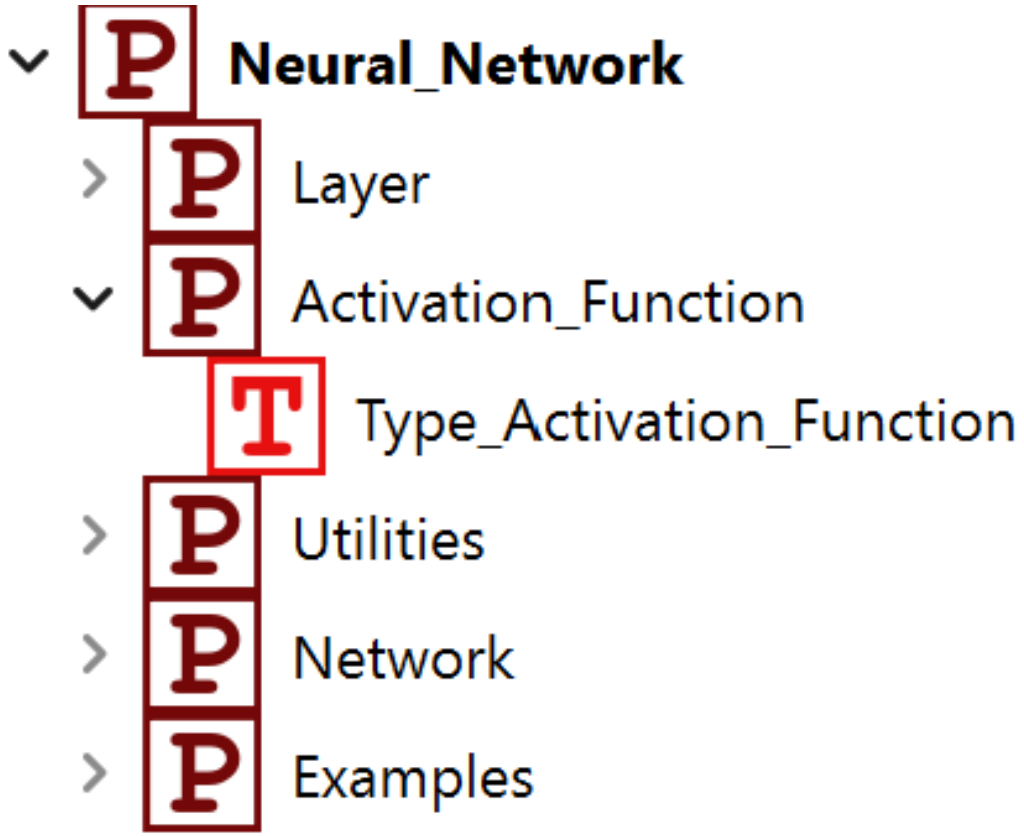


Neural Network Library

Activation_Function

Description

- Activation function describes behavior of neurons in the corresponding layer
- Selected activation function is set for whole layer
- Available activation functions:
  - ReLU
  - Sigmoid function
  - Tangent hyperbolic
  - Identity

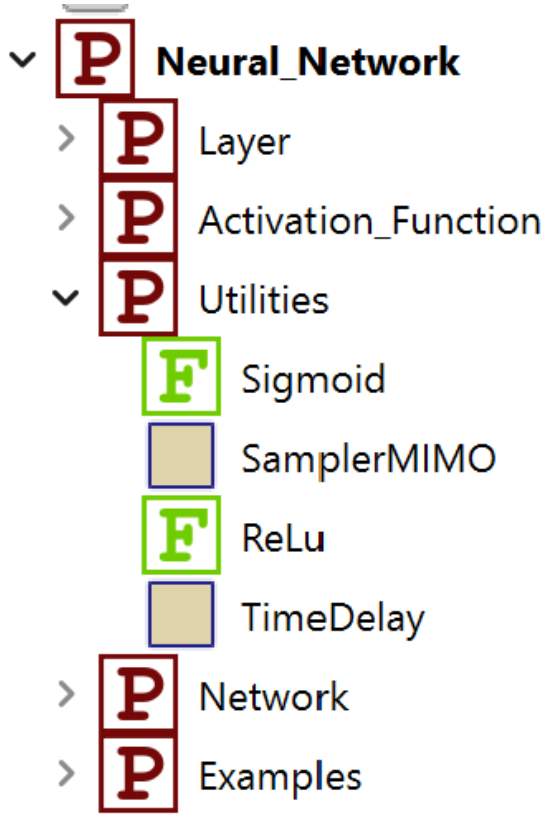


Neural Network Library

Utilities

Description

- Definition of the activation functions
- SamplerMIMO discretizes its input signals according to a selected sampling rate
- TimeDelay serves as an external shift register



Neural Network Library

Model generation

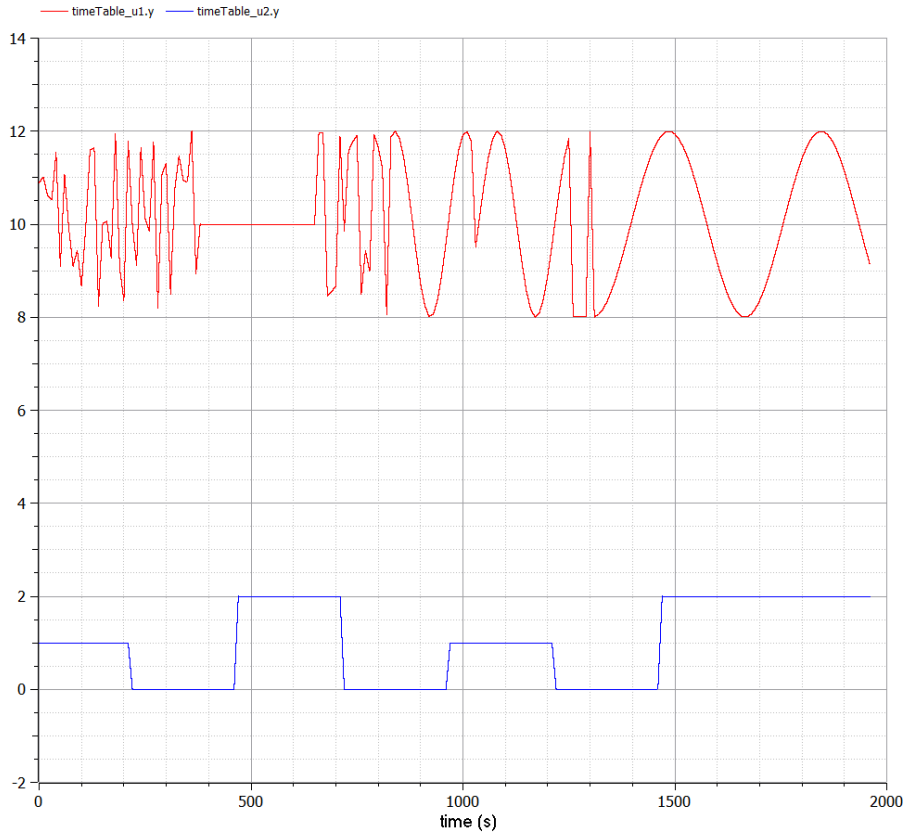
- Usefull to use already implemented frameworks for the training
- Offer a variety of learning methods and functionalities to efficiently train neural networks (early stopping, regularization, optimization methods,…)
- Use Keras for the implementation of the training
- Developed a Python module to generate a Modelica model of the neural network

Results

Case study pH neutralization process

Process

- Multivariable pH neutralization process
- Constant volume stirring tank (1100 liters)
- Two input flows
  - Acid solution (0.0032 mol/l)
  - Base solution (0.05 mol/l)



Results

Case study pH neutralization process

NARX Model

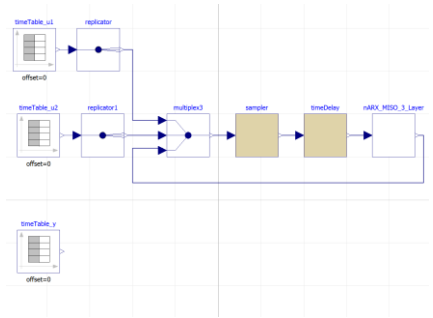
- Model the nonlinear, dynamic behavior of the system with a 2001 samples with a sampling rate of 10 seconds
  - First 201 as test set
  - Following 1800 for training
- Delay of $\tau = 4$
- No PCA

Layer	# Inputs	# Outputs	Activation
input	14	32	ReLU
hidden	32	32	ReLU
output	32	1	Identity

Pure Modelica Model

```
block NARX_MISO_3_Layer
  parameter Neural_Network.Activation_Function.Type_Activation_Function
        ActivationFunction=Neural_Network.Activation_Function.ReLu;
  Neural_Network.Layer.Input_Hidden_Layer Layer_1(bias={...},weights=[...],
        NeuronActivation_Function=ActivationFunction,numInputs=14,numNeurons
        =32,scale=true,max={...},min={...},standardization=false,mean={},std
        ={});
  Neural_Network.Layer.Dense_Hidden_Layer Layer_2(bias={...},weights=[...],
        NeuronActivation_Function=ActivationFunction,numInputs=32,numNeurons
        =32);
  Neural_Network.Layer.Output_Hidden_Layer Layer_3(bias={...},weights=[...],
        numInputs=32,numNeurons=1,rescale=false,max={},min={},destandardization
        =false,mean={},std={});
 extends Modelica.Blocks.Interfaces.MIMO(final nin=14,final nout=1);
equation
  connect(u,Layer_1.u);
  connect(Layer_1.y,Layer_2.u);
  connect(Layer_2.y,Layer_3.u);
  connect(Layer_3.y,y);
end NARX_MISO_3_Layer;
```

Graphic Modelica Model

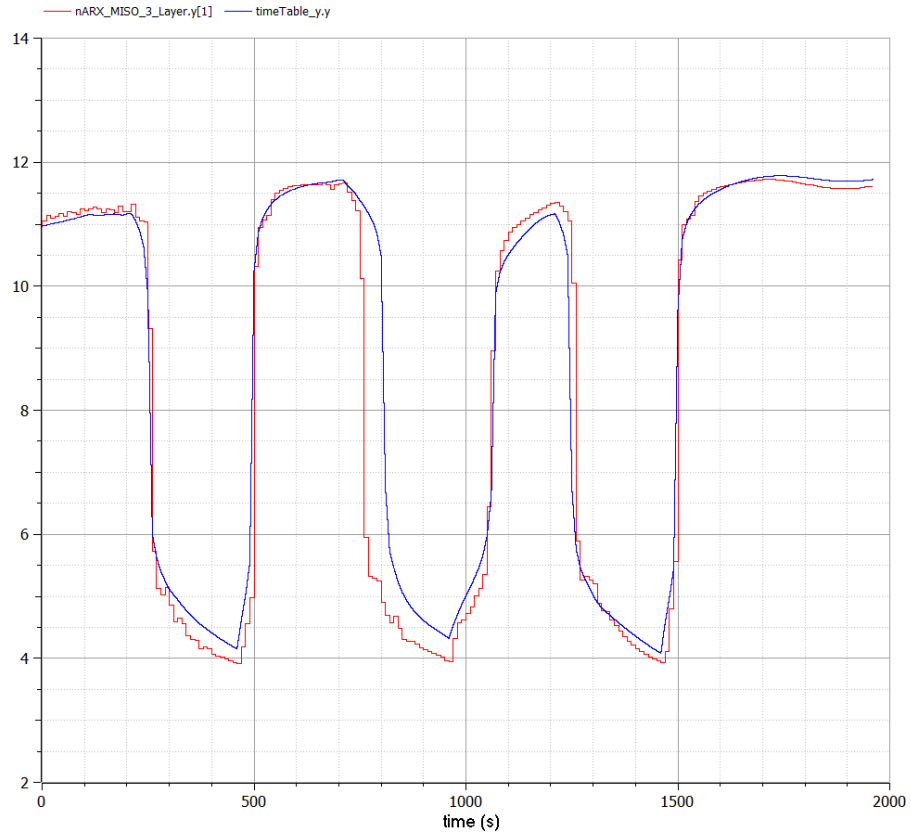


Results

Case study pH neutralization process

Results of the estimation

- NARX estimates the pH concentration of the tank
- Network can learn behavior of systems with multiple inputs
- Not always very well



Conclusion and further work

- Presented basic structure of the newly implemented *Neural Network Library*
- Explained the essential methods and procedures by which the library was extended
- Training takes place in Keras
- Interface between Keras and OpenModelica
- Presented a method to generate a Modelica model for a feedforward network
- Good foundation for making OpenModelica usable for black-box modeling
- Extend the library by further, more complex structures


ABB