Thermo Mechanical Modeling of Continuous Casting with Artificial Neural Network

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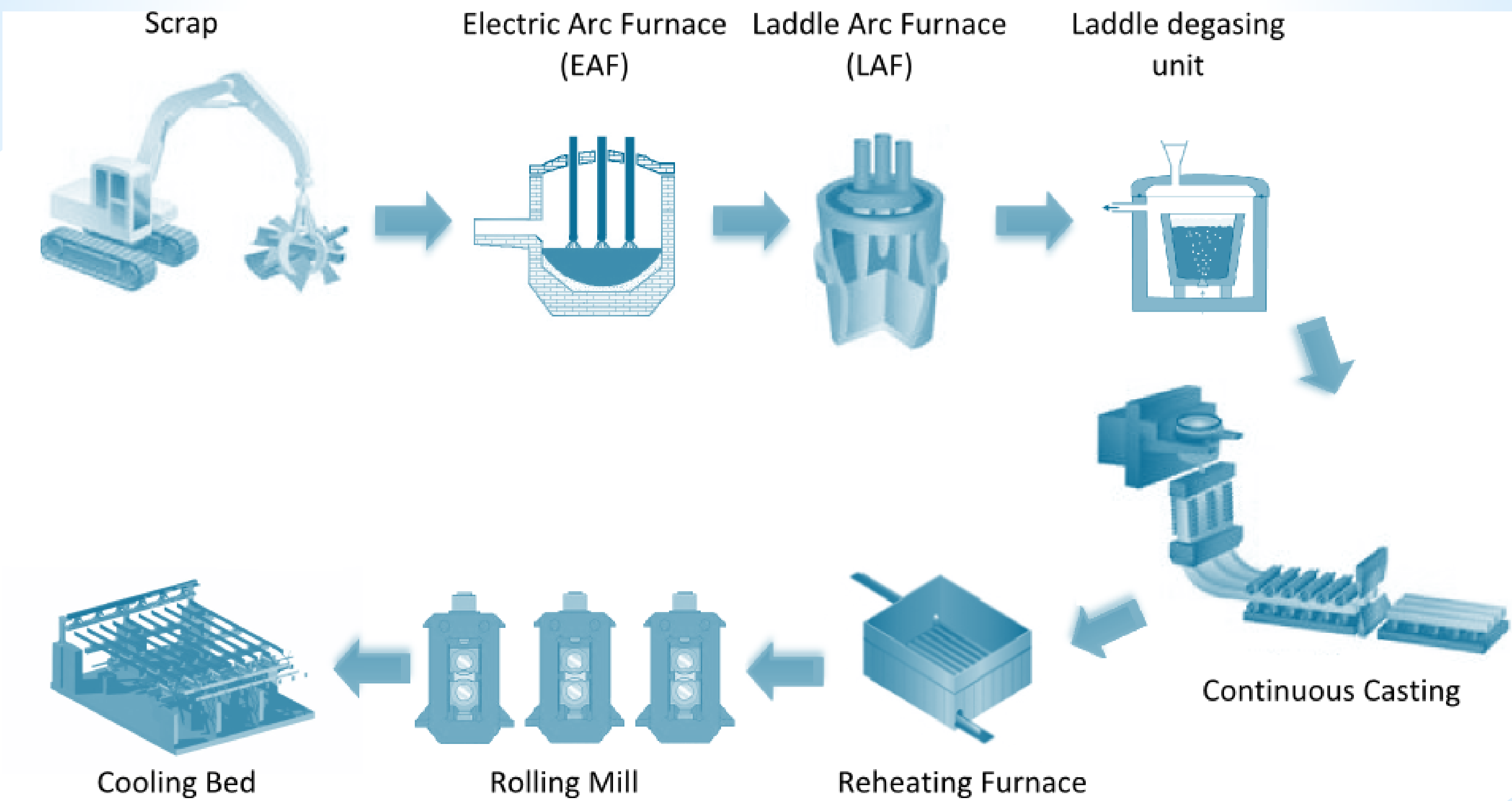
Scope

- Continuous casting of steel and its physics
- Approximative numerical models based on artificial neural network (ANN)
- Modelling of continuous casting of steel by ANN
- Conclusions and future work

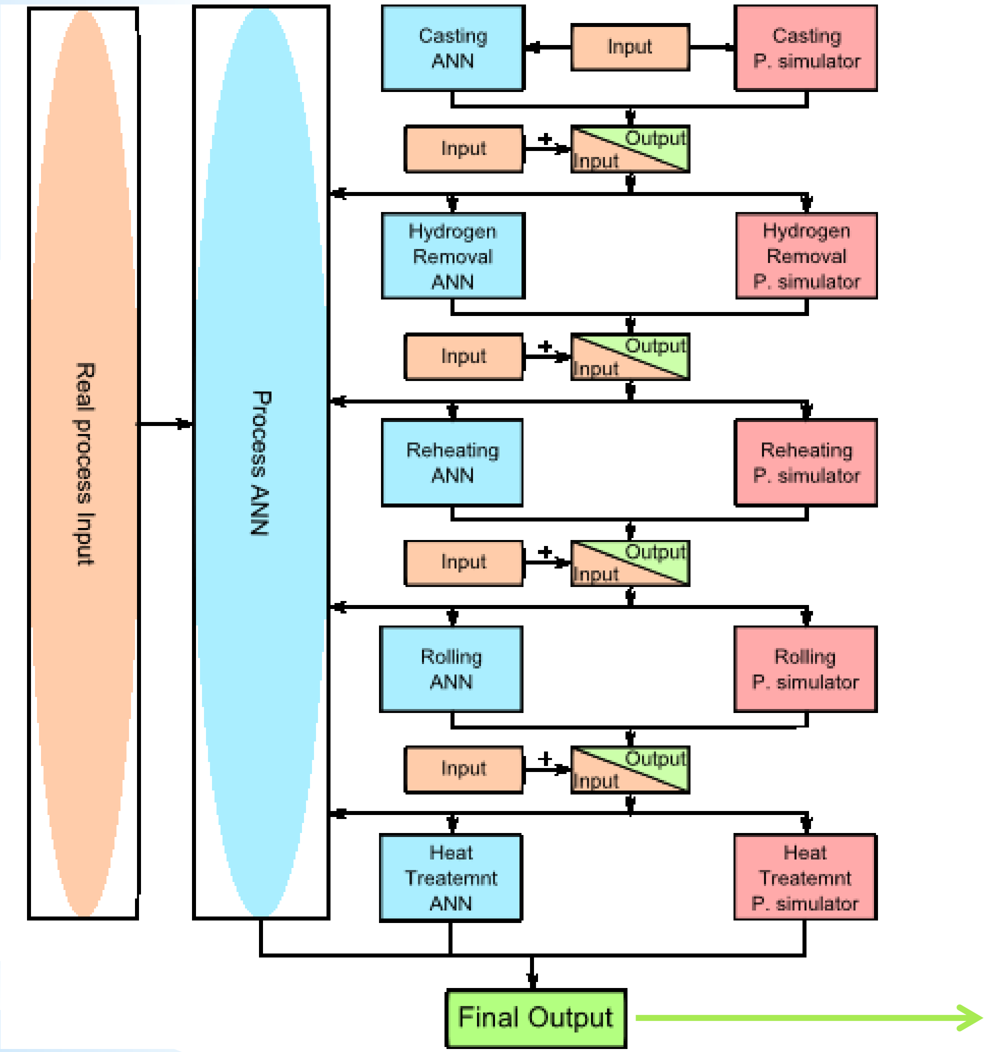
Goals

- Introduction to steel process modelling
- Introduction and motivation for ANN modelling
- Assessment of physical and ANN modelling of continuous casting of steel

Steel Production Process Path



Steel Production Simulation Scheme



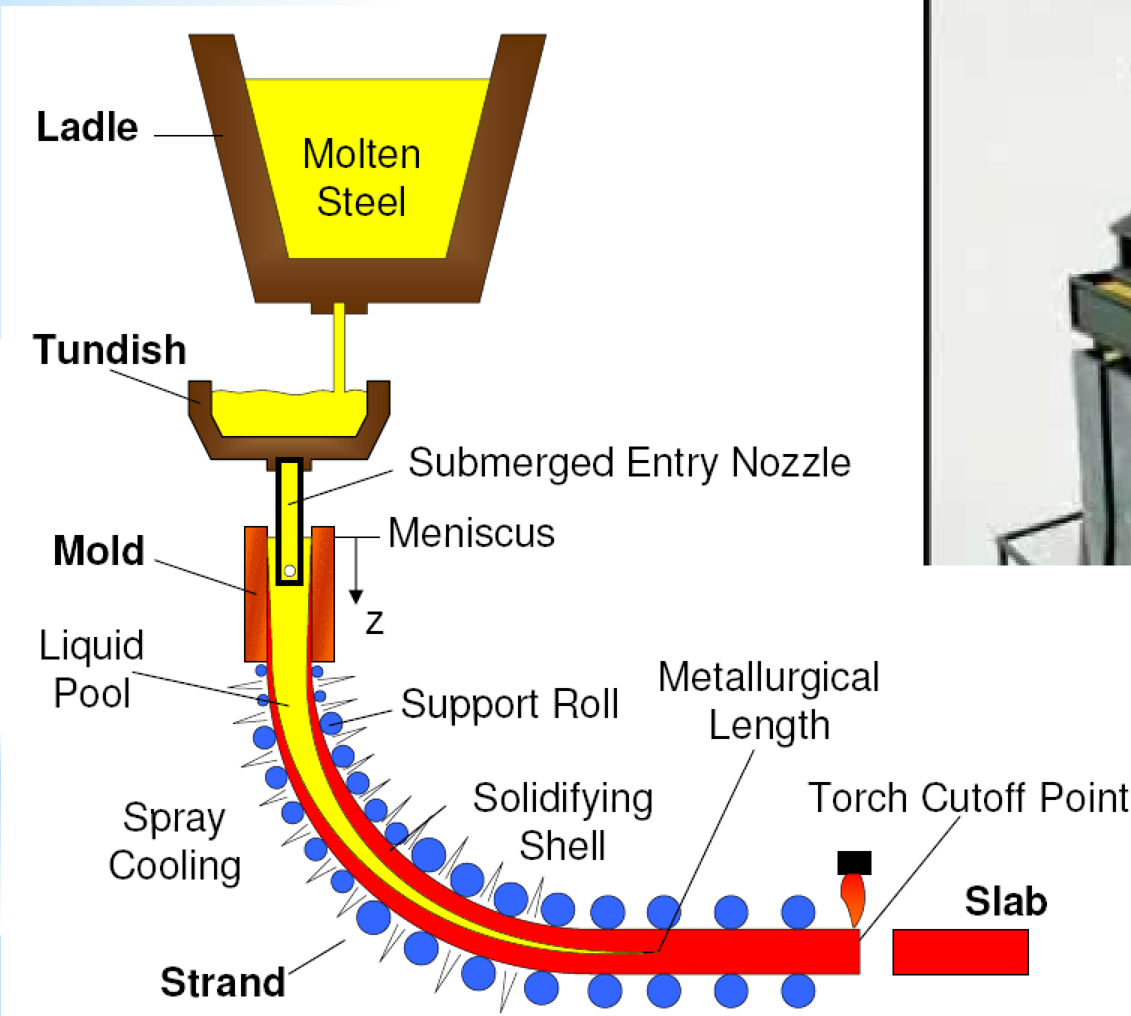
Final Measured Material Properties

Elongation (A)
Tensile strength (Rm)
Yield stress (Rp)
Hardness after rolling (HB)
Necking (Z)

Continuous Casting of Steel

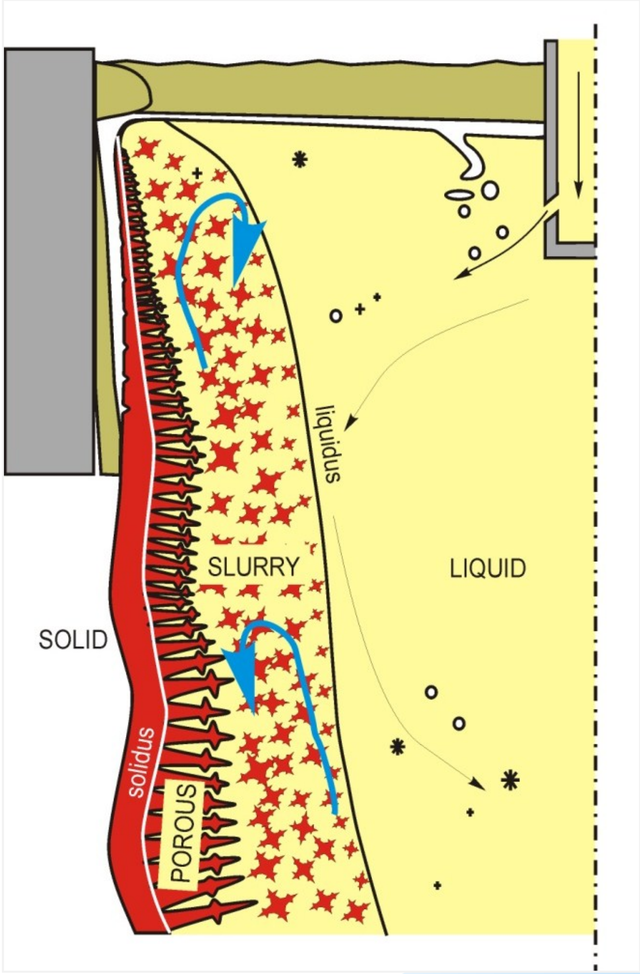
- Process was developed in the 1950s
- The most common process for production of steel
- 90% of all steel grades are produced by this technique
- Types
  - Vertical, horizontal, curved, strip casting
- Typical products
  - Billets, blooms, slab, strip

Continuous Casting of Steel



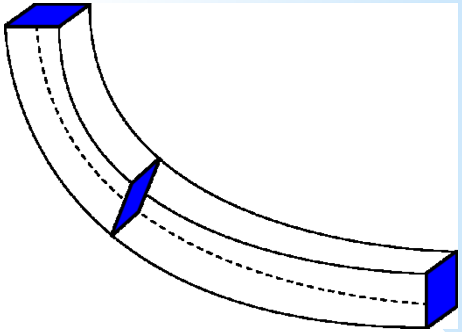
Characteristic Regimes in a Solidifying Continuous Casting

- Regimes
  - LIQUID (liquid, particles, inclusions,…)
  - SLURRY (equiaxed dendrites + liquid)
  - POROUS (columnar dendrites + liquid)
  - SOLID (dendrites)

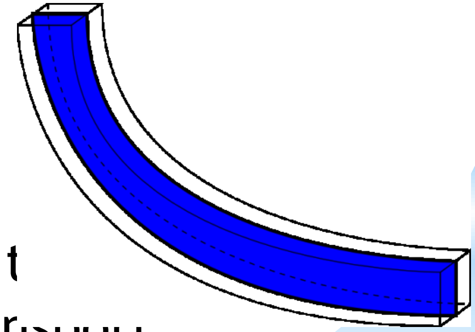


Numerical models of the Continuous Casting

- Thermal models
  - Describes heat transfer with solidification
  - Casting velocity is constant for all phases
  - Using slice model



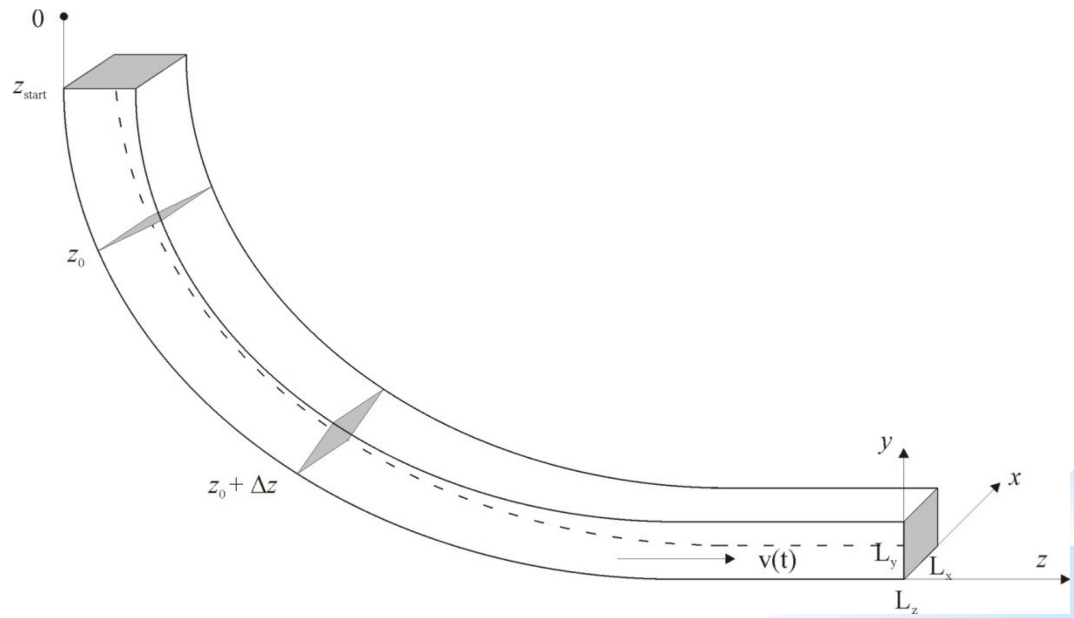
- Fluid models
  - Turbulent fluid flow on a fixed geometry
  - Modeling of the turbulent flow involves solving additional two transport equations



- Thermo-fluid models
  - Involves the solution of the fluid flow with t heat transfer, solidification and species transport
  - Much more complex to numerically implement

Slice Model

- Slice traveling schematics in the billet
  - Fast calculation time
  - x-y cross sectional slide is moving from top horizontal to bottom vertical position
  - Temperature and boundary condition are assumed as time dependent



Macroscopic Transport Model

- Governing equations
  - Enthalpy transport

$$\frac{\partial}{\partial t}(\rho h) = \nabla \cdot (k \nabla T)$$

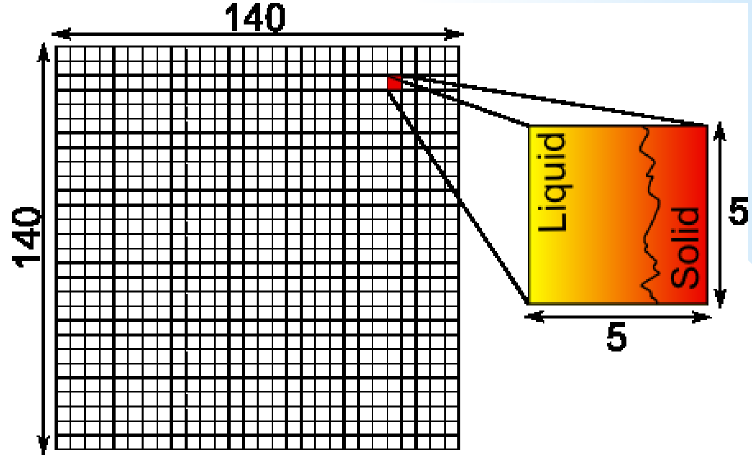
  - Mixture and phase enthalpies

$$h = f_L h_L + f_S h_S$$

$$h_L = c_L T + (c_S - c_L) T_{sol} + h_f$$

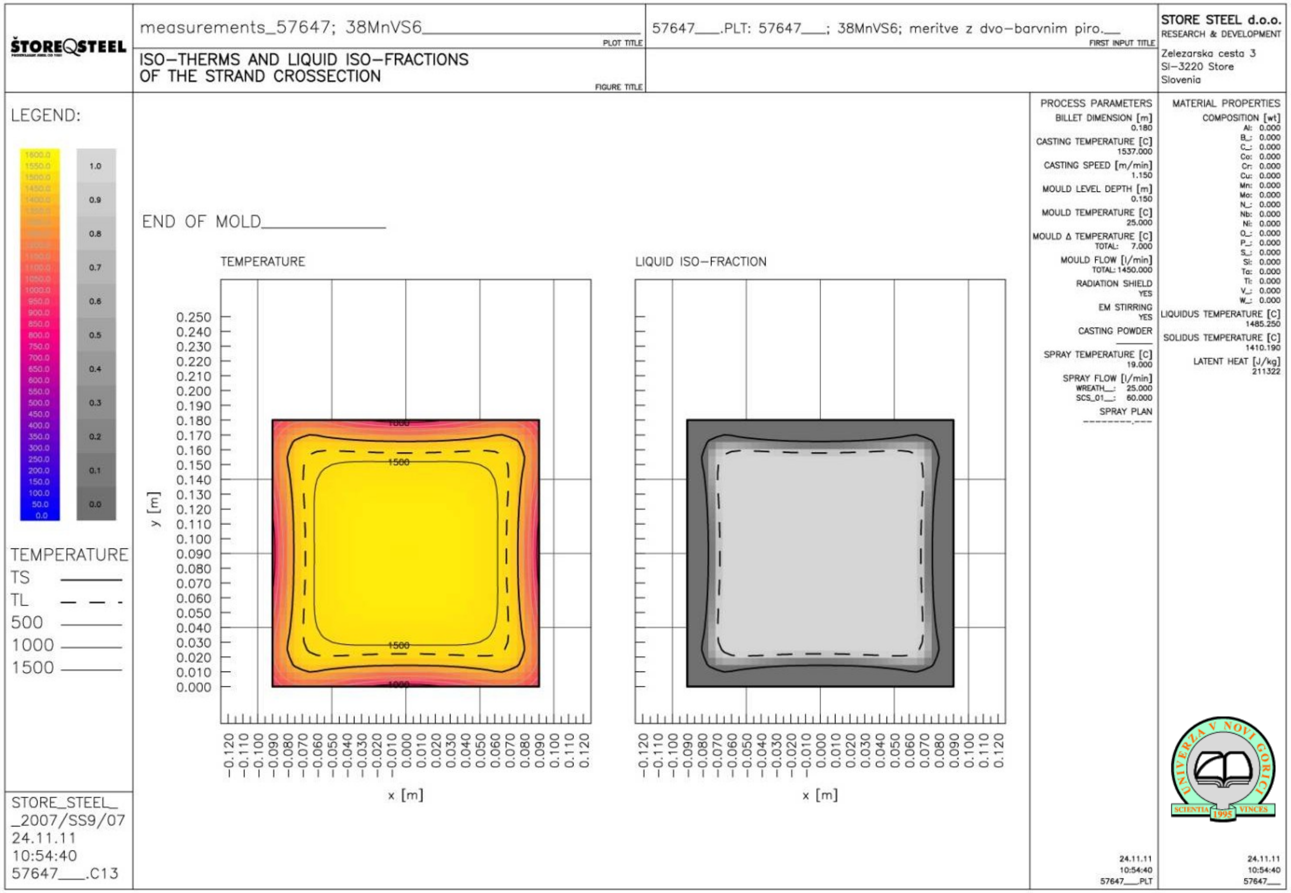
$$h_S = c_S T$$

  - Solved based on initial and boundary conditions that relate the enthalpy transport with the process parameters



28 x 28 points

Example of CC Simulation



Artificial Neural Network

Artificial Neural Network - ANN

- An information-processing system that has certain performance characteristic similar to biological neural networks
- Have been developed as generalizations of mathematical models of human cognition
  - Information processing occurs at many simple elements called neurons
  - Signals are passed between neurons over connection links
  - Each link has an associated weight
  - Each neuron applies an activation function

ANN - Types

- Feedforward NN
- Feedforward backporpagation NN
- Self organizing map (SOM)
- Hopfield NN
- Recurrent NN
- Modular NN
- …

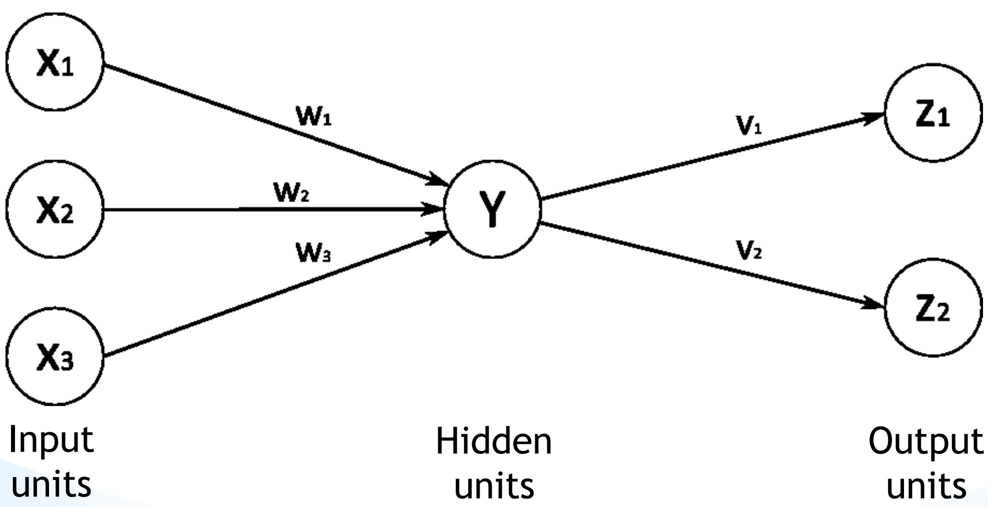
ANN – Examples of Applications

Is an extremely interdisciplinary field

- Signal processing
  - Suppressing noise on a telephone line
- Control
  - Provide steering direction to a trailer truck attempting to back up to a loading dock
- Pattern recognition
  - Recognition of handwritten characters
- Medicine
  - Diagnosis and treatment
- Speech production / recognition, business…

ANN - Characterization

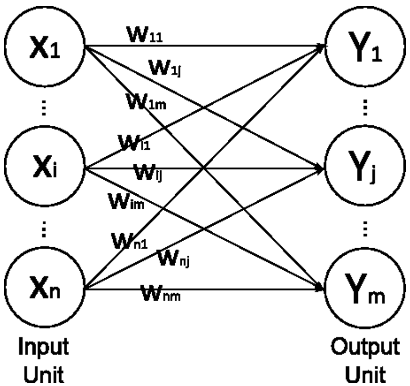
- Architecture - pattern of connections between the neurons
- Training or learning – method of determining the weights on the connections
- Activation function

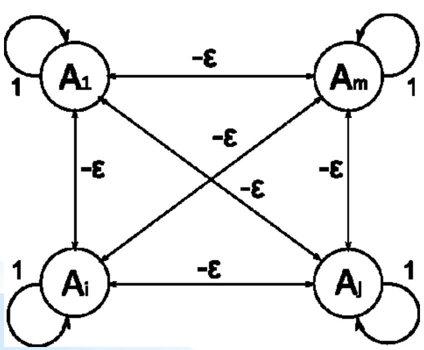


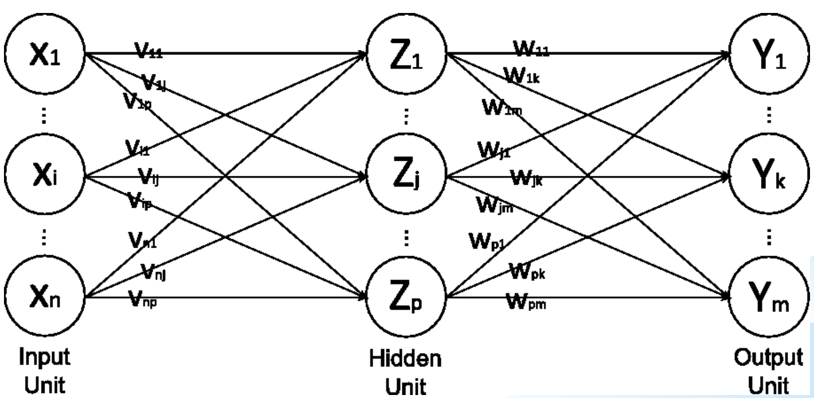
ANN - Architecture

The arrangement of neurons into layers and the connection patterns between layers

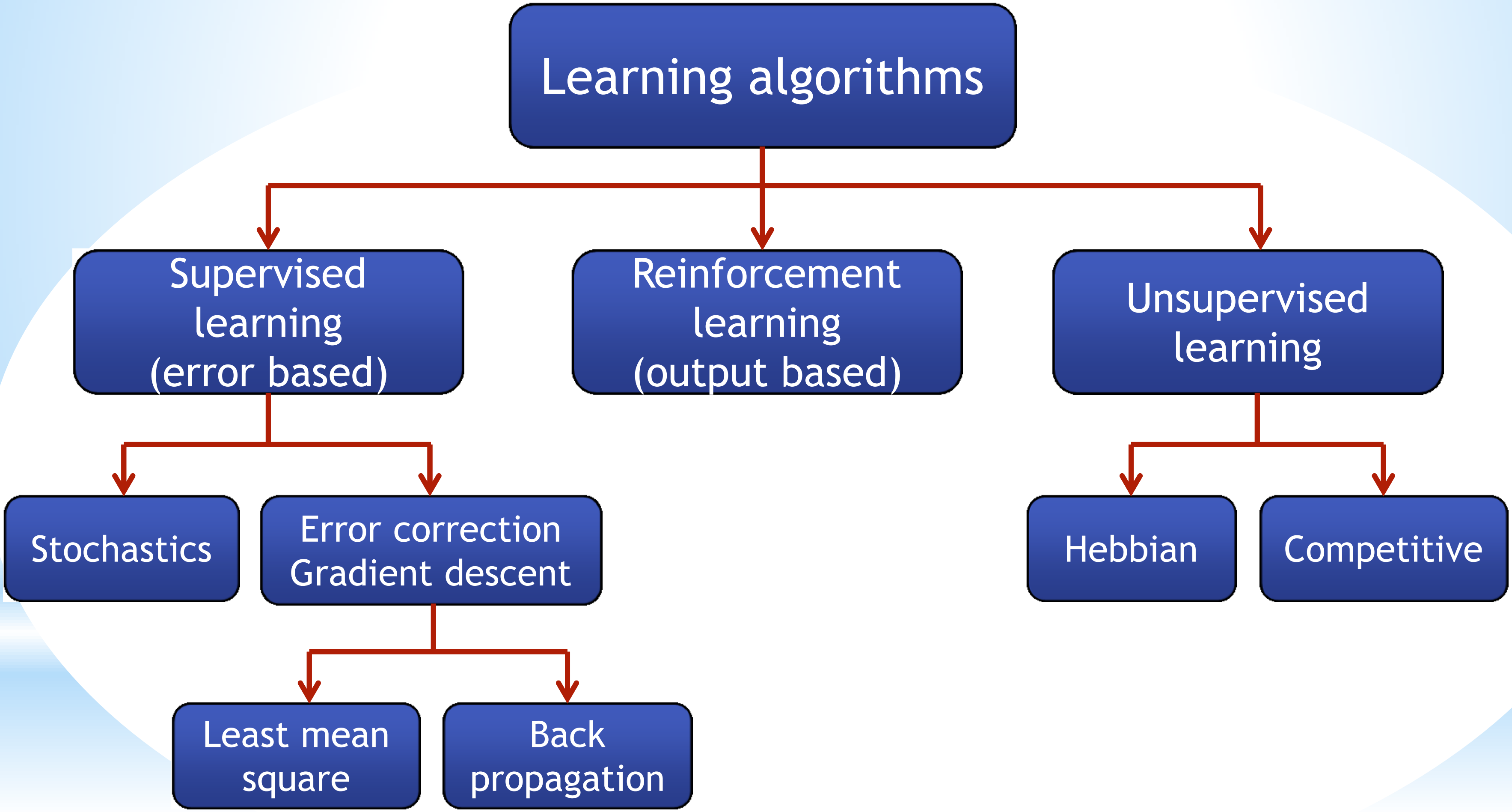
- Single-layer net
  - Input and output units
- Multi-layer net
  - Input, output and hidden units
- Competitive layer





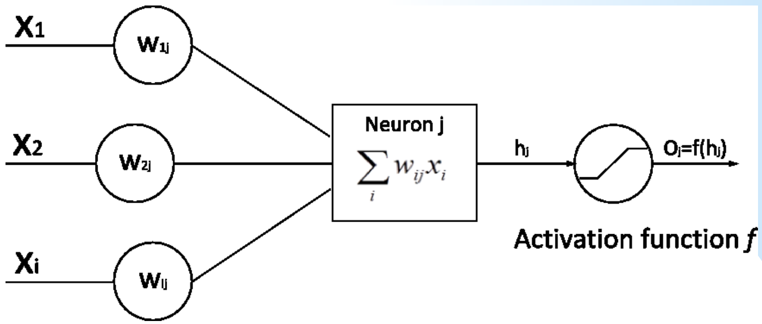


ANN - Training or Learning



ANN – Activation Functions

- Typically, the same activation function is used for all neurons in any particular level

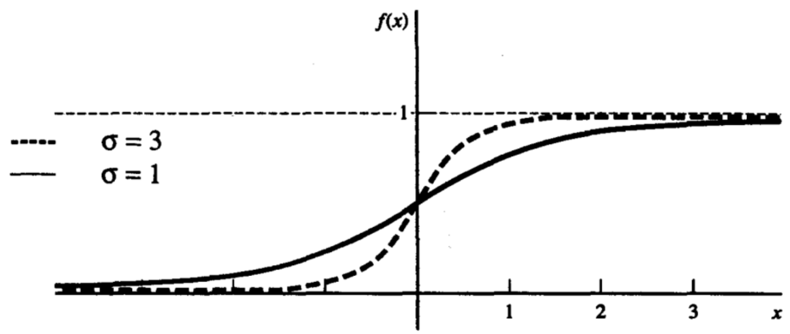


- Identity function

$$f(x) = x$$

- Binary step function
- Binary sigmoid

$$f(x) = \frac{1}{1 + \exp(-\sigma x)}$$

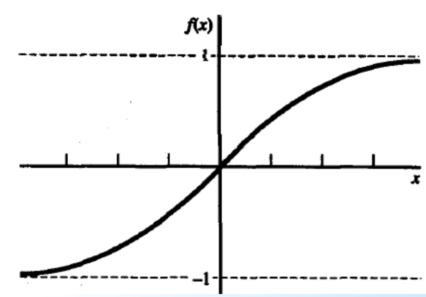


- Bipolar sigmoid

$$f(x) = \frac{1 - \exp(-\sigma x)}{1 + \exp(-\sigma x)}$$

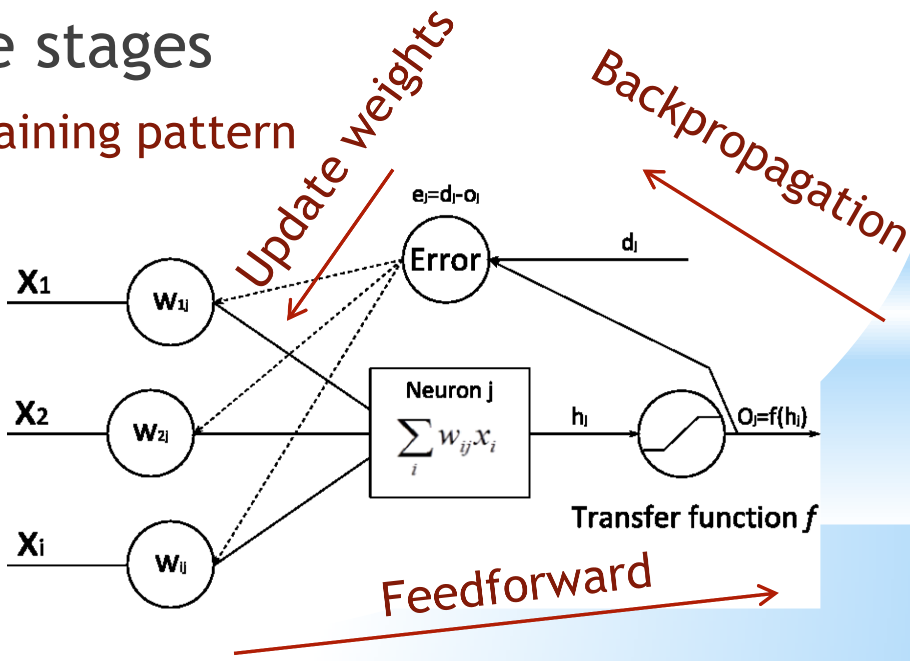
- Hyperbolic tangent

$$f(x) = \frac{1 - \exp(-2x)}{1 + \exp(-2x)}$$

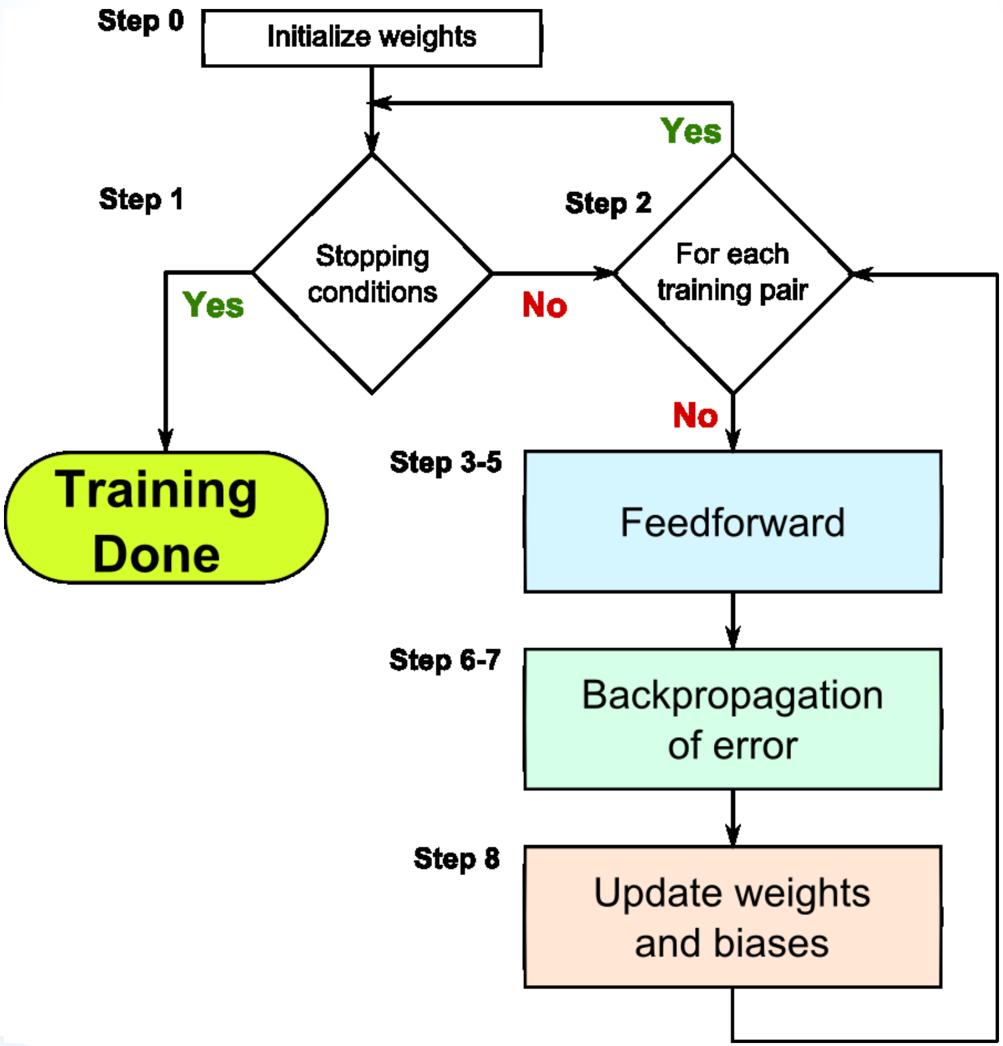


ANN – Feedforward Backpropagation

- A gradient descent method to minimize the total squared error of the output
- A backpropagation (multilayer, feedforward, trained by backpropagation) can be used to solve problems in many areas
- The training involves three stages
  - The feedforward of the input training pattern
  - The calculation and backpropagation of the associated error
  - The adjustment of the weights



ANN -Backpropagation Algorithm



ANN -Backpropagation Algorithm

Feedforward

- **Step 3**

Each input unit $\left(X_i, i = 1,\ldots,n\right)$ receives input signal and broadcasts the signal to all units in the layer above (hidden layer) x_i

- **Step 4**

Each hidden unit $\left(Z_j, j = 1,\ldots,p\right)$

sums its weighted input signals $z\_in_j = v_{0j} + \sum_{i=1}^{n} x_i v_{ij}$

applies its activation function $z_j = f\left(z\_in_j\right)$

and sends this signals to all units in the layer above (output unit)

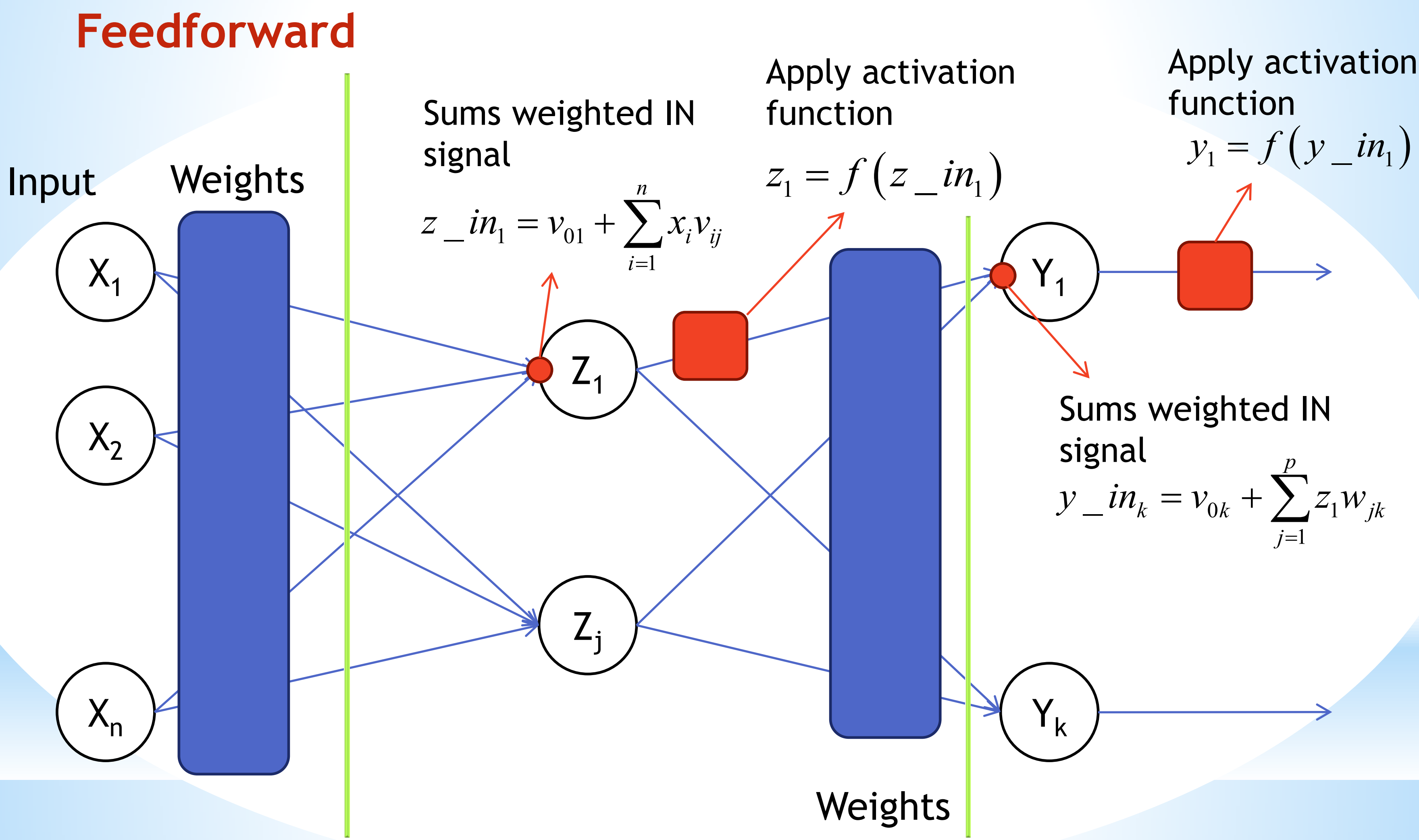
- **Step 5**

Each output unit $\left(Y_k, k = 1,\ldots,m\right)$

sums its weighted input signals $y\_in_k = w_{0k} + \sum_{j=1}^{p} z_j w_{jk}$

and applies its activation function $y_k = f\left(y\_in_k\right)$

ANN -Backpropagation Algorithm



ANN –Backpropagation Algorithm

Backpropagation of errors

- **Step 6**

Each output unit $(Y_k, k = 1,...,m)$ receives a target pattern

computes its error information term $\delta_k = (t_k - y_k) f'(y\_in_k)$

calculates its weight correction term $\Delta w_{jk} = \alpha \delta_k z_j$

calculates its bias correction term $\Delta w_{ok} = \alpha \delta_k$

and sends δ_k to units in the layer below

- **Step 7**

Each hidden unit $(Z_j, j = 1,..., p)$ sums its delta inputs $\delta\_in_j = \sum_{k=1}^{m} \delta_k w_{jk}$

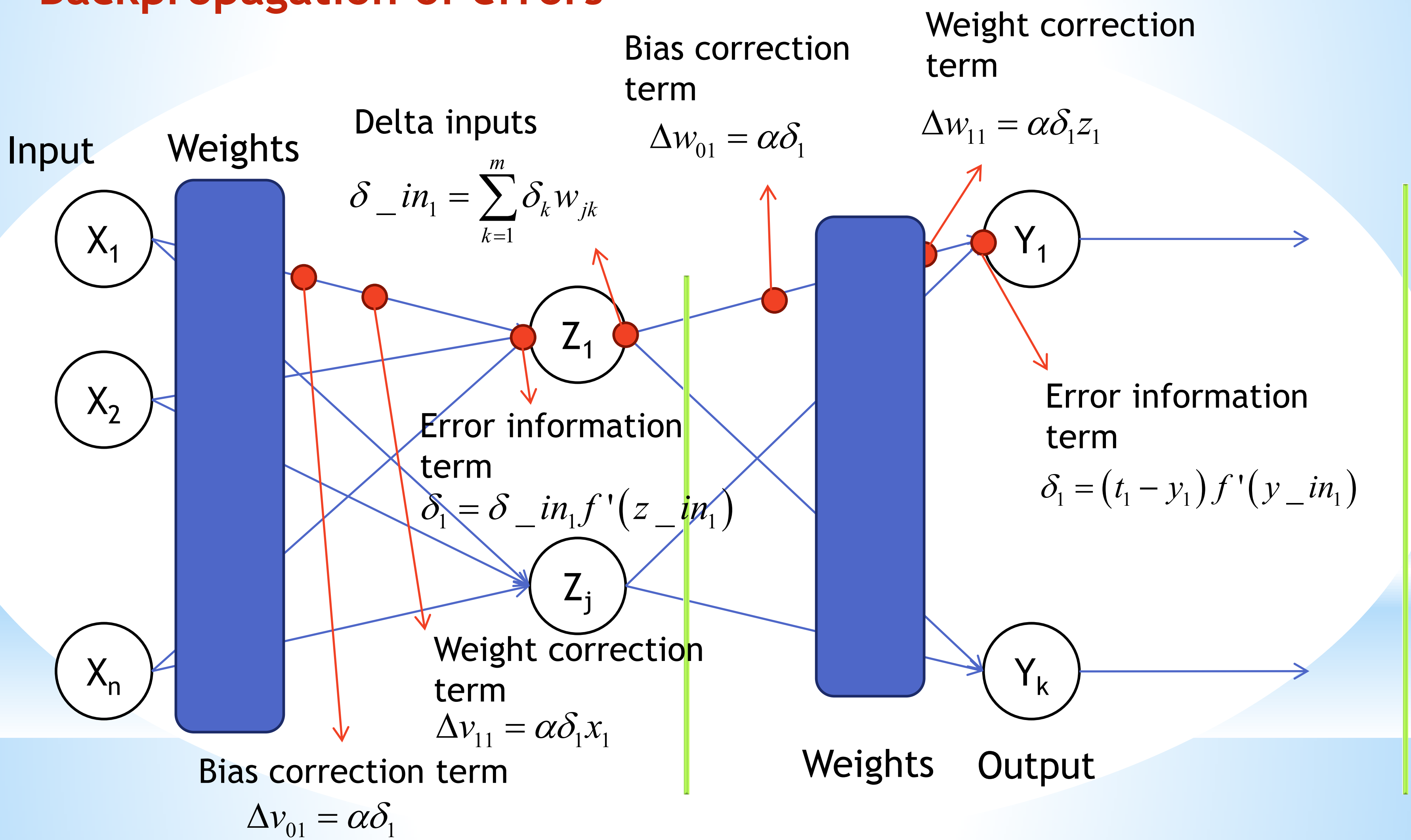
calculates its error correction term $\delta_j = \delta\_in_j f'(z\_in_j)$

calculates its weight correction term $\Delta v_{ij} = \alpha \delta_j x_i$

and calculates its bias correction term $\Delta v_{0j} = \alpha \delta_j$

ANN –Backpropagation Algorithm

Backpropagation of errors



ANN -Backpropagation Algorithm

Update weights and biases

- **Step 8**

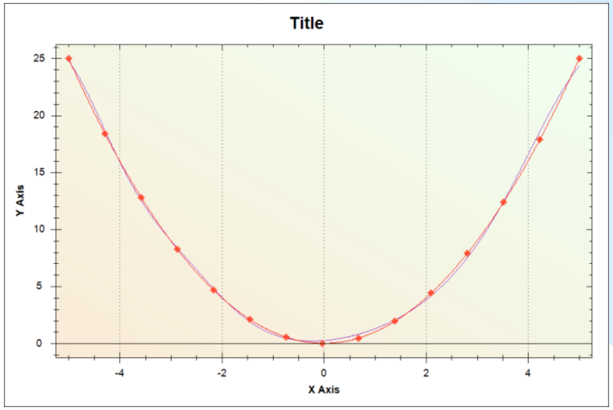
Each output unit $\left(Y_k, k=1,\ldots,m\right)$ updates its bias and weights $\left(j=0,\ldots,p\right)$

$$w_{jk}\left(new\right)=w_{jk}\left(old\right)+\Delta w_{jk}$$

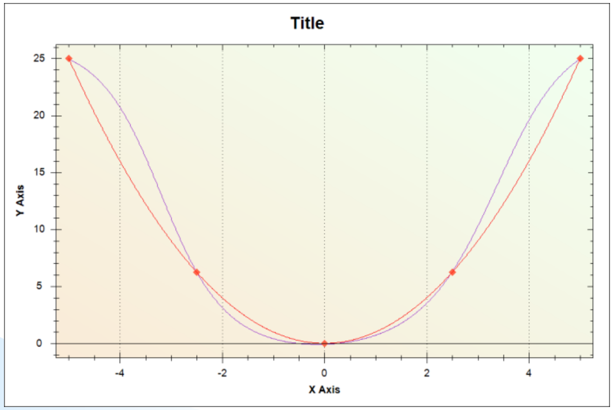
Each hidden unit $\left(Z_j, j=1,\ldots,p\right)$ updates its bias and weights $\left(i=0,\ldots,n\right)$

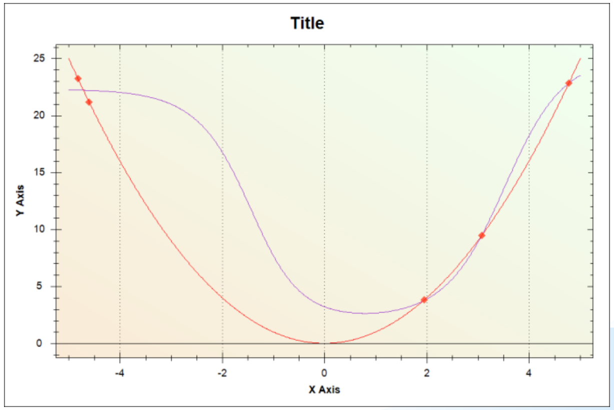
$$v_{ij}\left(new\right)=v_{ij}\left(old\right)+\Delta v_{ij}$$

ANN – Training-Data



- Training-data quality
- Sufficient number of training data pairs
- Training data points distribution
- Verification points selection





ANN – Calculation of response

After training, a backpropagation NN is using only the feedforward phase of the training algorithm

- Step1

  Initialize weights

- Step2

  For $i = 1, \ldots, n$ set activation of input unit x_i

- Step3

  For $j = 1, \ldots, p$ $\quad z\_in_j = v_{0j} + \sum_{i=1}^{n} x_i v_{ij}$ $\quad z_j = f\left(z\_in_j\right)$

- Step4

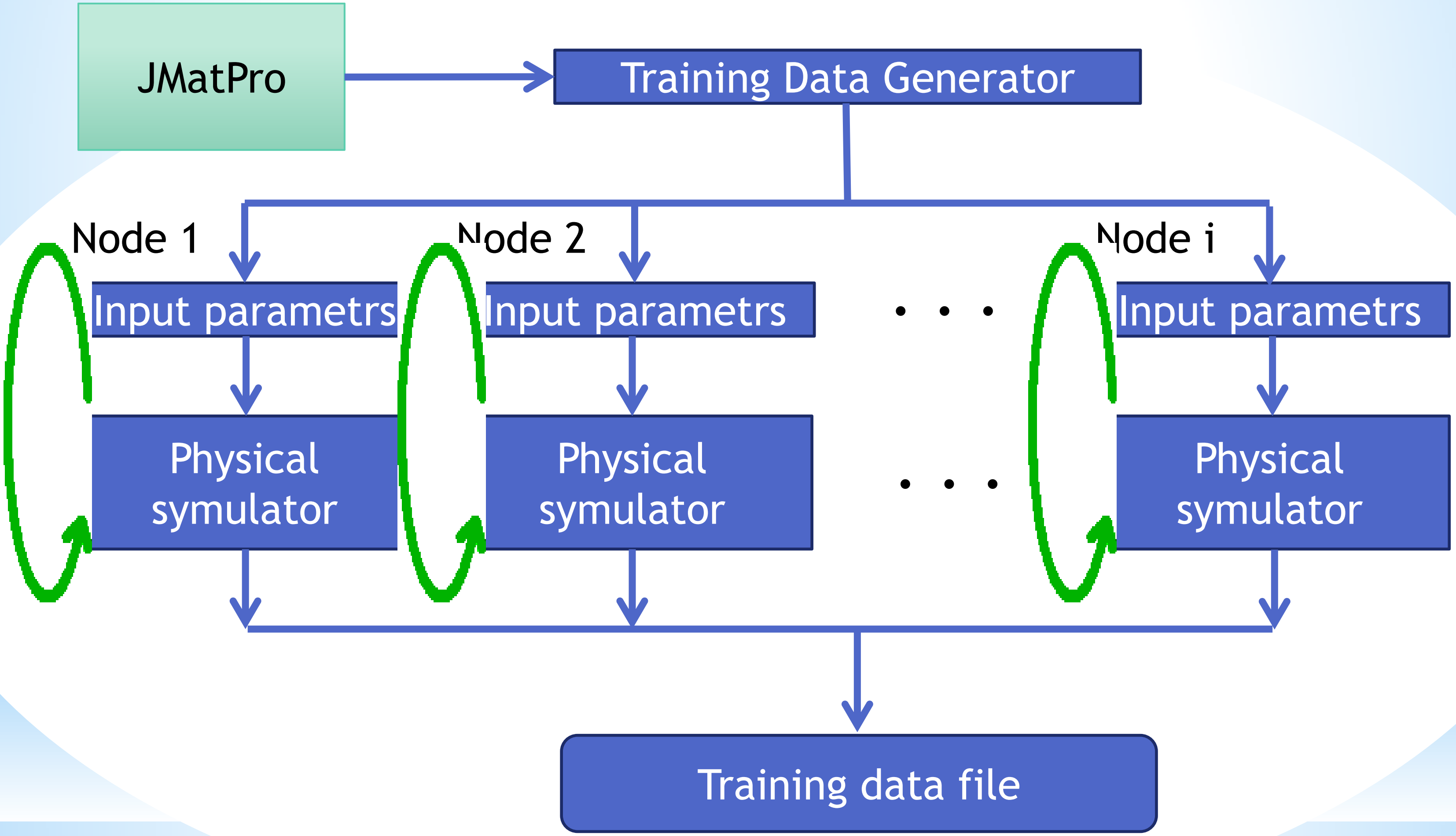
  For $k = 1, \ldots, m$ $\quad y\_in_k = w_{0k} + \sum_{j=1}^{p} z_j w_{jk}$ $\quad y_k = f\left(y\_in_k\right)$

Modeling of continuous casting of steel by ANN

Physical Simulator Parameters

- 21 Input parameters
  - Charge number
  - Steel type
  - Concentration: Cr, Cu, Mn, Mo, Ni, Si, V, C, P, S
  - Billet dimension
  - Casting temperature
  - Casting speed
  - Delta temperature
  - Cooling flow rate in the mold
  - Cooling water temperature in sprays
  - Cooling flow rate in wreath spray system
  - Cooling flow rate in 1st spray system
- 21 Output parameters
  - ML
  - DS
  - T

Generating Parameters & Outputs

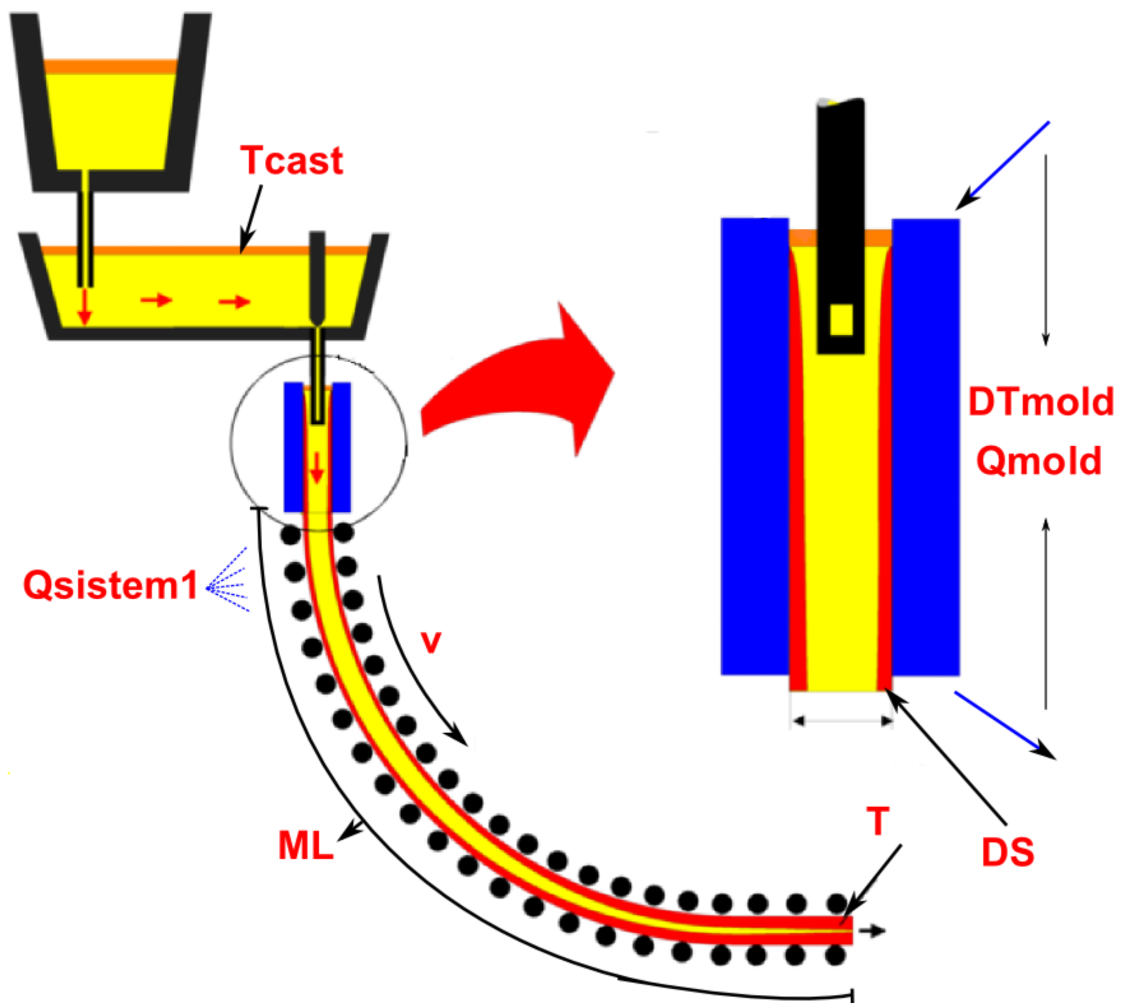


Casting Parameters & Outputs

ID	Name & units	Description	Range in the training set
1	Tcast [°C]	Casting temperature	1515 - 1562
2	v [m/min]	Casting speed	1.03 - 1.86
3	DTmold [°C]	Temperature difference of cooling water in the mold	5 - 10
4	Qmold [l/min]	Cooling flow rate in the mold	1050 - 1446
5	Qwreath [l/min]	Cooling flow rate in wreath spray system	10 - 39
6	Qsistem1 [l/min]	Cooling flow rate in 1st spray system	28 - 75

ID	Name & units	Description & units	Range in the training set
1	ML [m]	Metallurgical length	8.6399 - 12.54
2	DS [m]	Shell thickness at the end of the mold	0.0058875 - 0.0210225
3	T [°C]	Billet surface temperature at straightening start position	1064.5 - 1163.5

Casting Parameters & Outputs

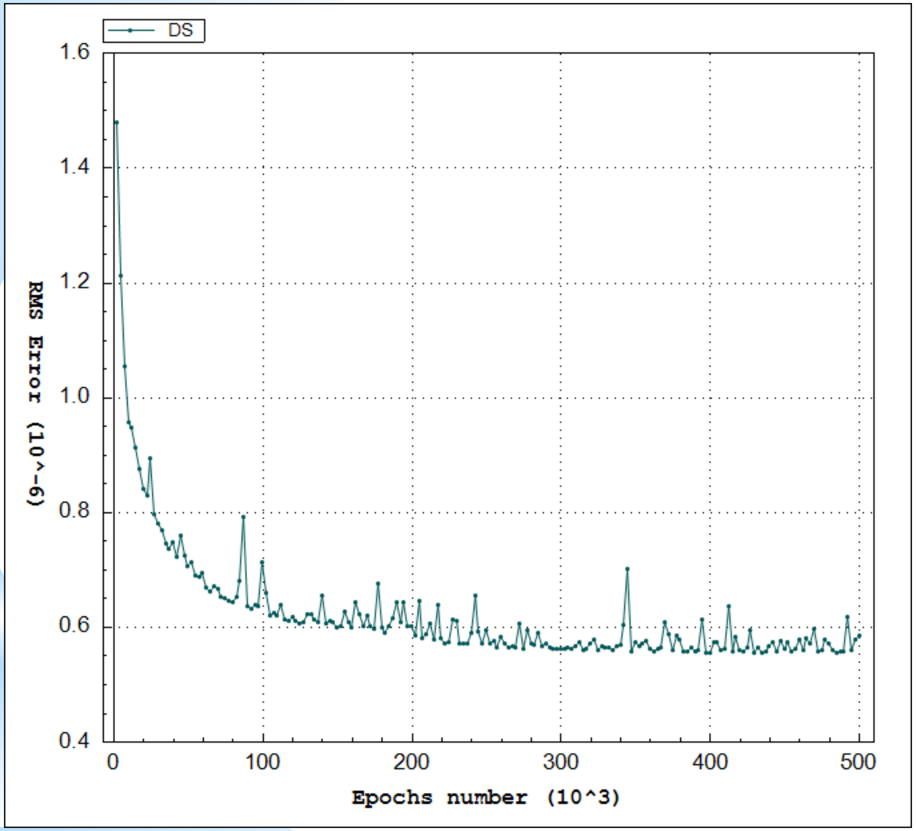


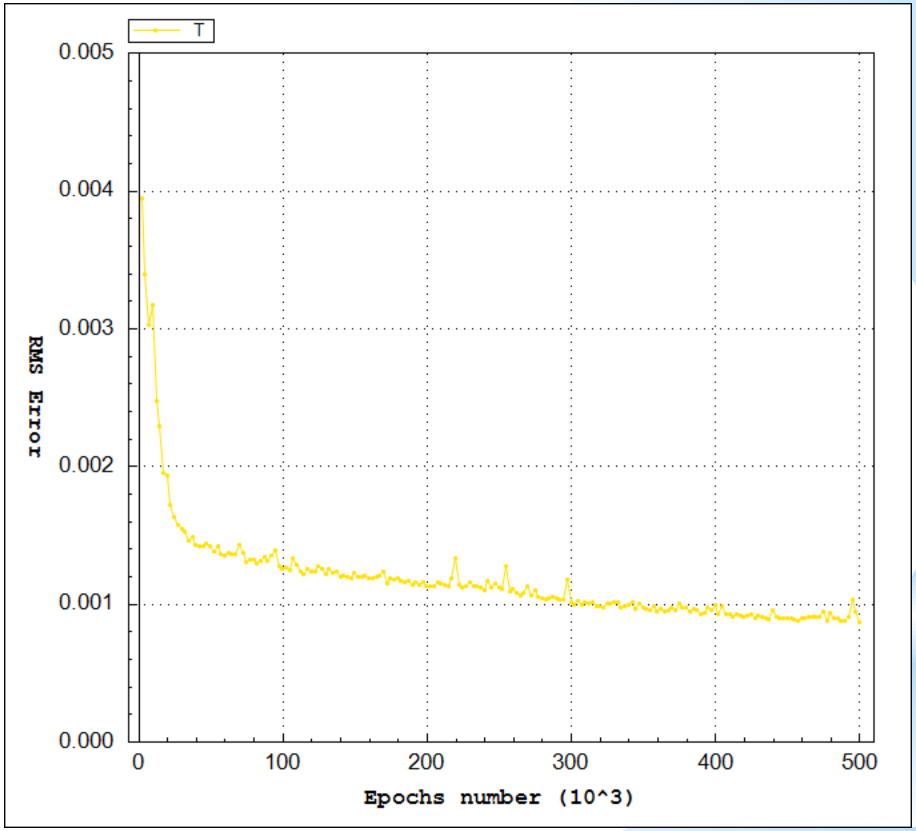
Training the ANN

- NeuronDotNet open source library
- 200000 total IO pairs
  - 100000 training IO pairs
  - 100000 verification IO pairs
- Settings for ANN
  - Epochs 50000
  - Hidden layers 1
  - Neurons in hidden layer 25
  - Learning rate = 0.3
  - Momentum = 0.6

Training the ANN

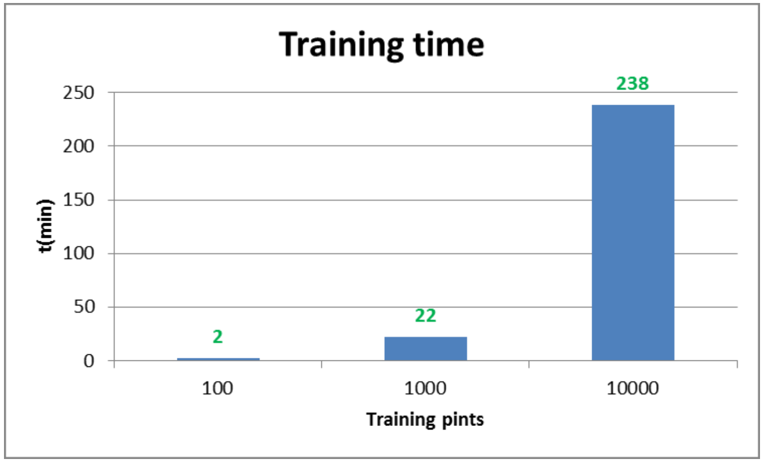
- RMS errors during training

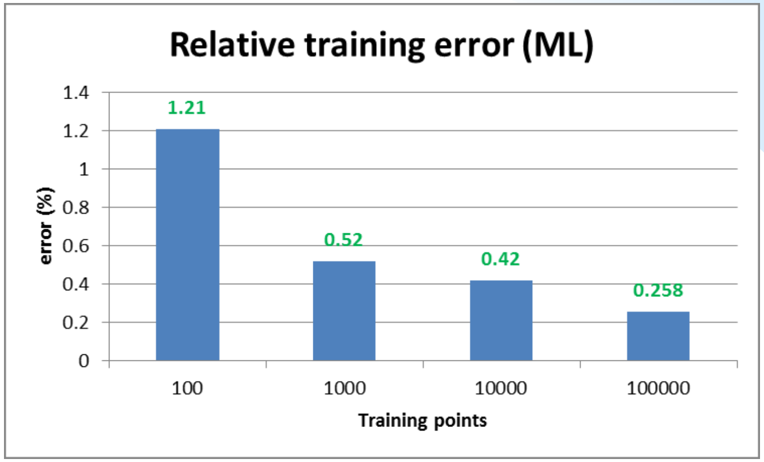


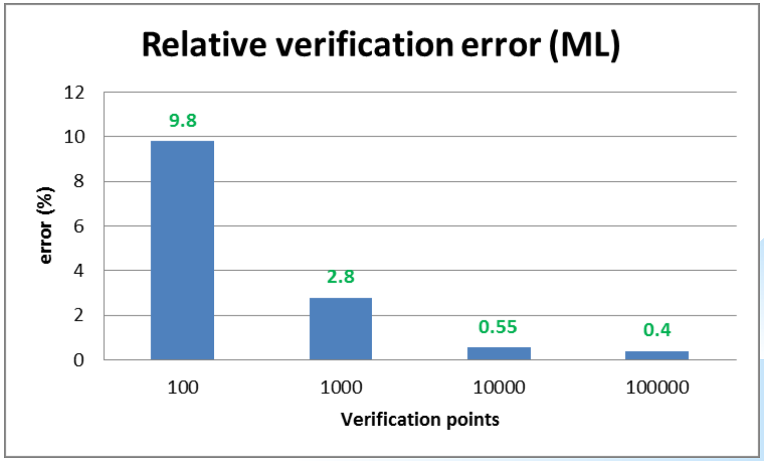


Studies

- Relations between training time, training data and errors

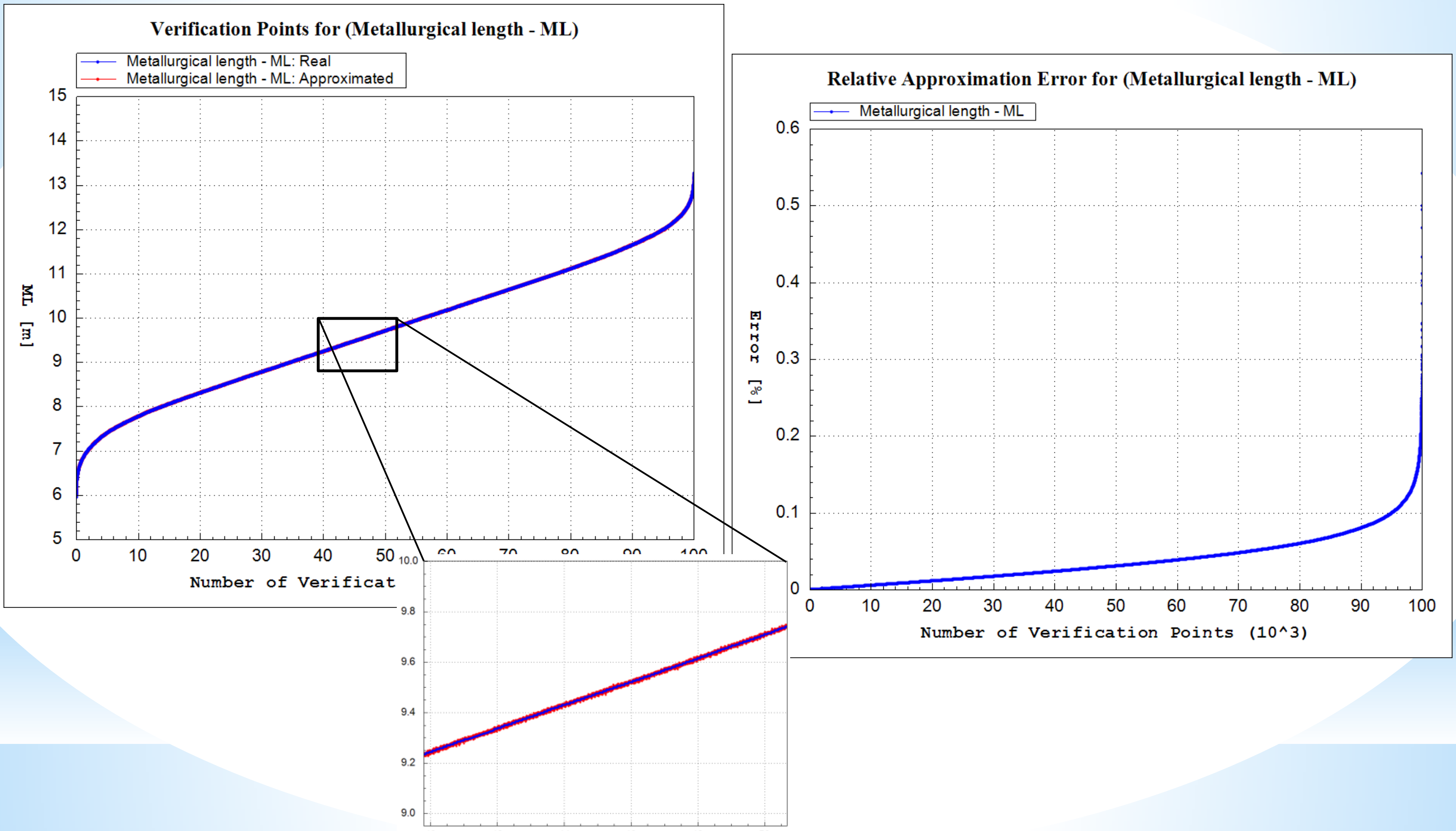






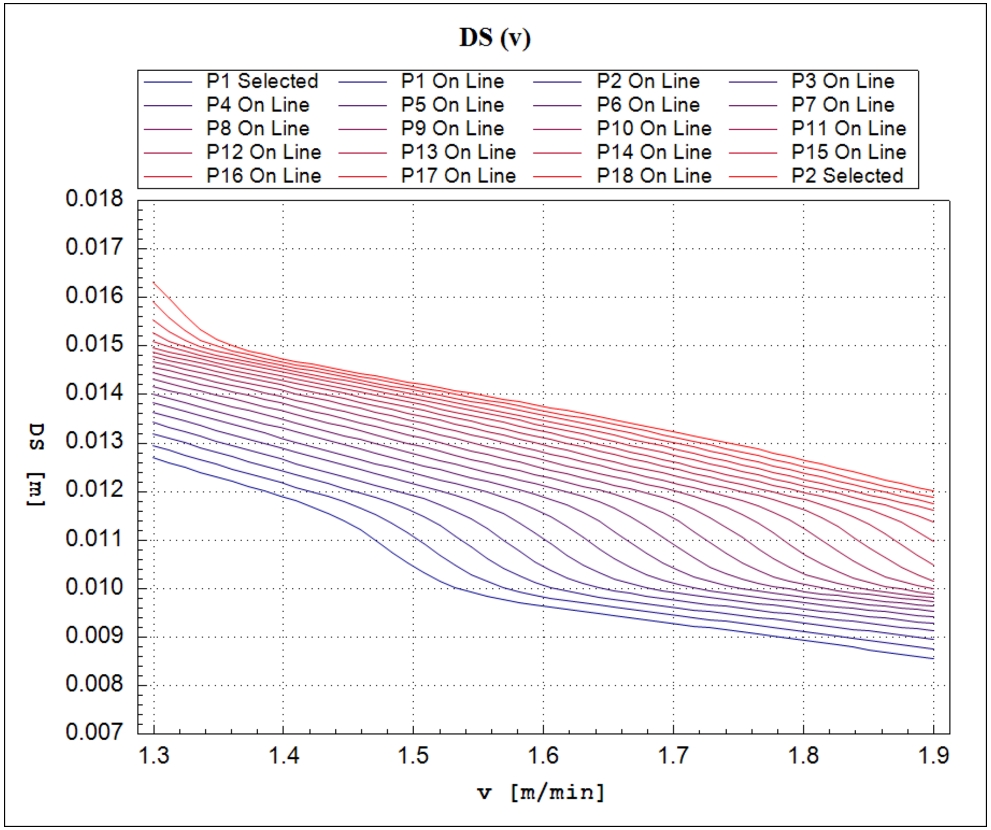
Study of Errors

- Relative errors in verification points



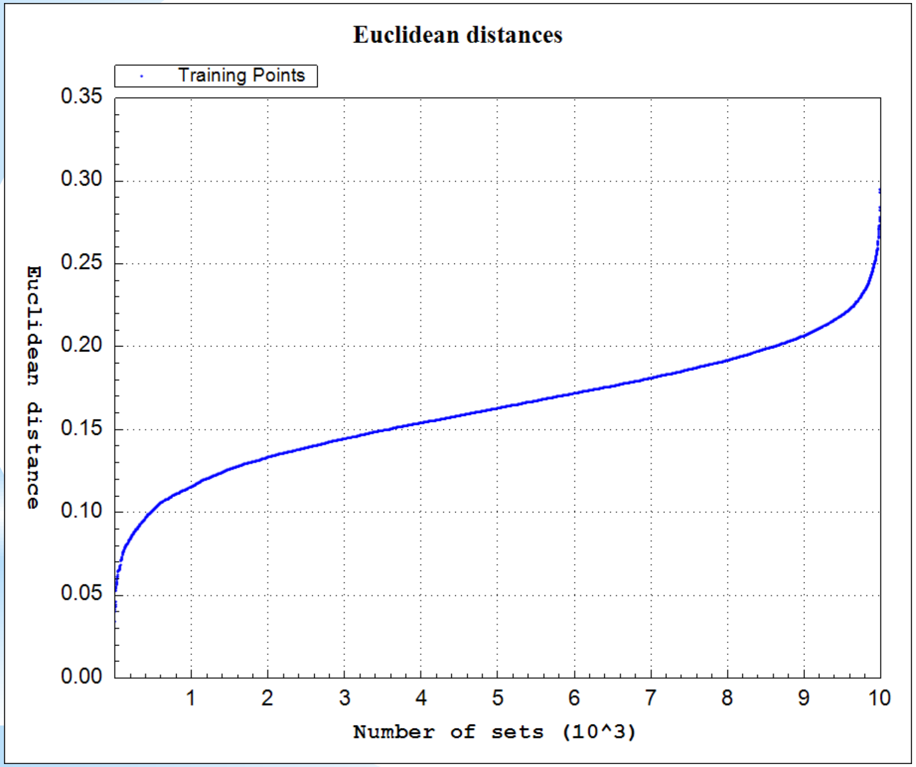
Parametric Studies

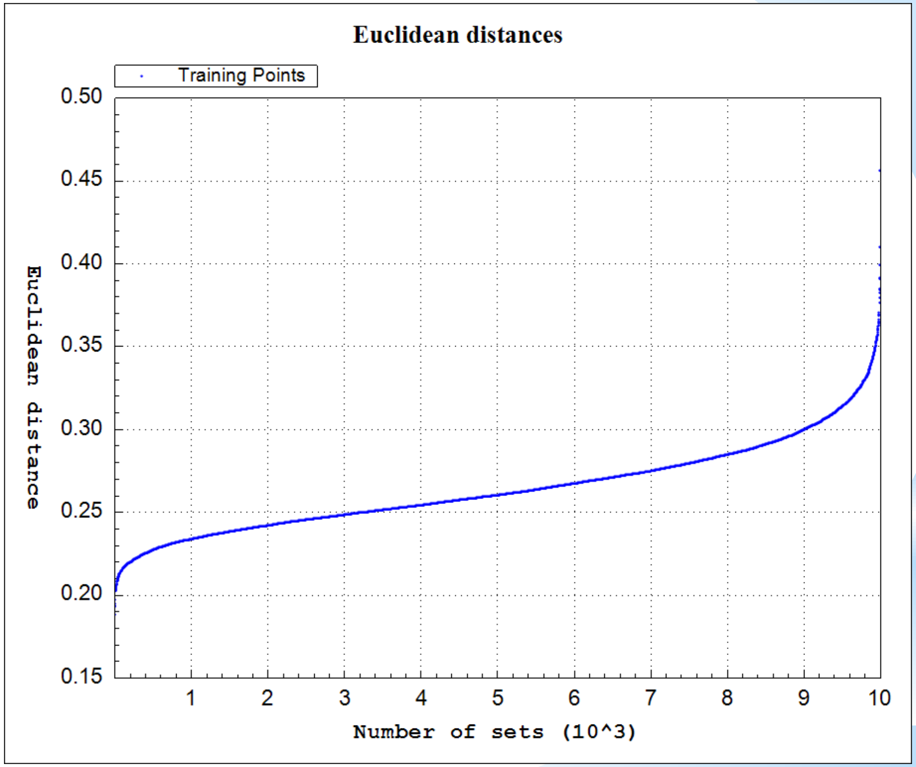
- Response around Points on a Line Between Two Points



Studiy: Uniformity of Training Points Distribution

- Euclidean distances to the N-th point
  - Closest point
  - 9-th closest point





Conclusions and future work

- Dedicated SW framework was developed
- Studies to examine the accuracy of ANN based on physical model
- ANN approximation is much faster than physical simulation

- Complementing physical models with ANNs
- Replacing physical models with ANNs
- Upgrading of the ANN model for continuous casting with the model of the whole production chain
- Development of new methods for checking the quality of training-data

References

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Acknowledements

Prof.dr.Božidar Šarler, dr. Igor Grešovnik, dr. Robert Vertnik

Thank you!