

# Data-Driven Roll Pass Design of Wire Rod Mills

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**Abstract.** The classical approach for roll pass design of a wire rod mill employs an iterative technique incorporating spread calculation and rectangular equivalent pass methods. This method comes to its limits in terms of computational efficiency and numerical stability when a complete pass design for a wire rod mill with lots of different final dimensions and materials must be designed. To improve the pass design technique, a fast data-driven method for pass design based on synthetic data generated by the classical pass design model was created. The results are compared to the original training data, as well as newly generated test data. It is shown that the artificial neural network (ANN) is able to predict appropriate oval groove geometries with good precision.

## Introduction

Nowadays, hot rolling processes for long products like wire rod and bars are of great importance for industrial economies around the world. The core feature of a long product rolling mill is the pass design, which dictates the design data of rolling stands, rolls and the driving motors in the rolling mill. It must therefore be worked out with high precision, but also high speed because of the high numbers of different roll pass designs a single rolling mill must maintain for all final dimensions and material variations. Figure 1 shows the schematic structure of the pass design for a wire rod mill with 28 rolling stands. The starting billet, having a sidelength of 150 mm is reduced in the 6-stand roughing mill to a round section. After passing through a cropping shear, it is further reduced in the intermediate mills using an oval-round pass sequence. Up to stand 10V, a unified pass design is used for all final dimension, which splits up into multiple paths for the the smaller diameters. For all rolling modes, entry sections between 17.4 mm and 24.7 mm are produced for the finishing block, which can provide final rod diameters between 5.5 mm and 20 mm.

For the purpose of working out the pass design, a lot of work was put in the development of deterministic analytical and numerical models for simulation and design of rolling processes [1, 2]. These models serve their purpose, but sometimes their possibilities may be limited due to numerical instabilities or long computation times.

As of today, Machine Learning methods like artificial neural networks (ANN) are available which allow a precise prediction of process behaviour from measured data [3]. These techniques can also be applied to synthetic data to allow complicated mathematical models to be simplified in application and increased in computational speed based on previously calculated data [4].

ANNs have been already successfully applied to problems in rolling mills. Tamaraebi showed that an ANN can be used for fast interstand tension assessment in a tandem cold rolling mill [5]. Shen et al. presented an ANN for roll force predictions in a hot strip mill [6]. Roll design optimizations for round and square sections using ANNs were shown by Lambiase [7] based on training data gathered from Finite Element Simulations.

The idea covered in this paper is to construct a data-driven model for pass design based upon analytical pass design computations carried out by a deterministic pass design model which was developed at the Chair of Metallurgy and Metal Forming of the University of Duisburg-Essen [8, 9]. In order to allow the digitization of groove geometries, these were reduced to a set of few simple geometric parameters.

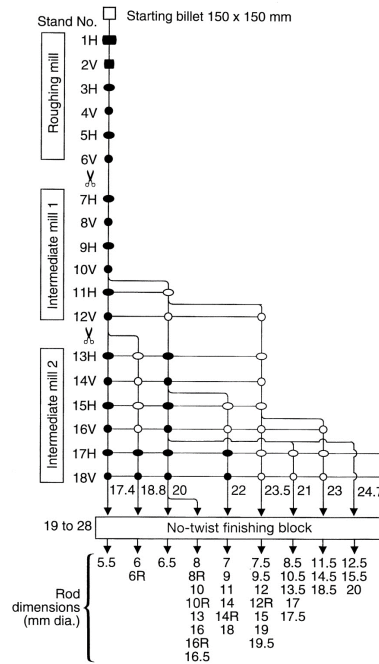


Fig. 1: Schematic pass design of a wire rod mill [10]

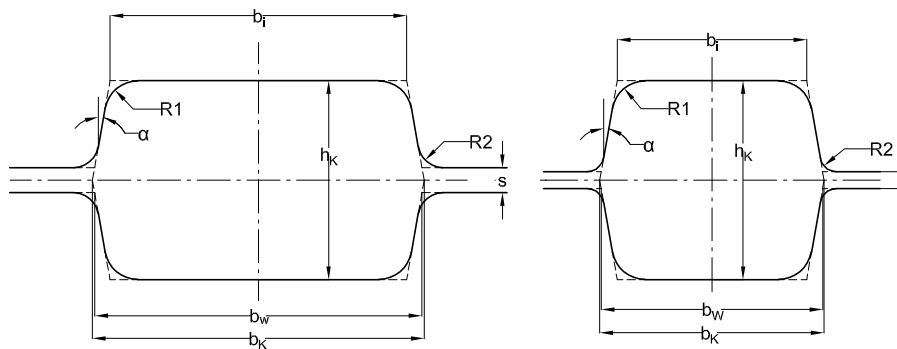


Fig. 2: Box grooves used in the roughing mill[1]

### Groove Sequences Used in Wire Rod Mills

In a typical continuous wire rod rolling mill, the initial section, often a continuous cast billet is reduced to a final section of diameters down to 5.0 mm. Most typically, the starting billet has a quadratic cross section with a sidelength of 130 mm to 140 mm. For the total cross sectional reduction needed to produce a thin wire rod, the stands in a continuous or semi-continuous arrangement are grouped into a roughing mill (4-6 stands), two intermediate mills (each 6-8 stands) and a ten-stand finishing mill. The finishing mill may be realized by a classical rolling block with a group drive and a fixed gear system, or for the most modern rod mills, by separated units with single mill drives. In the roughing mill, so-called box grooves are used to ensure a homogeneous deformation of the as-cast microstructure of the initial billet.

From Figure 2, we conclude that the construction of the box groove can be very much standardized and the box groove can be represented by a few simple geometrical parameters. These are:

- Width of the groove  $b_K$ ,
- Height of the groove  $h_K$ ,
- Side angle of the groove  $\alpha$ ,

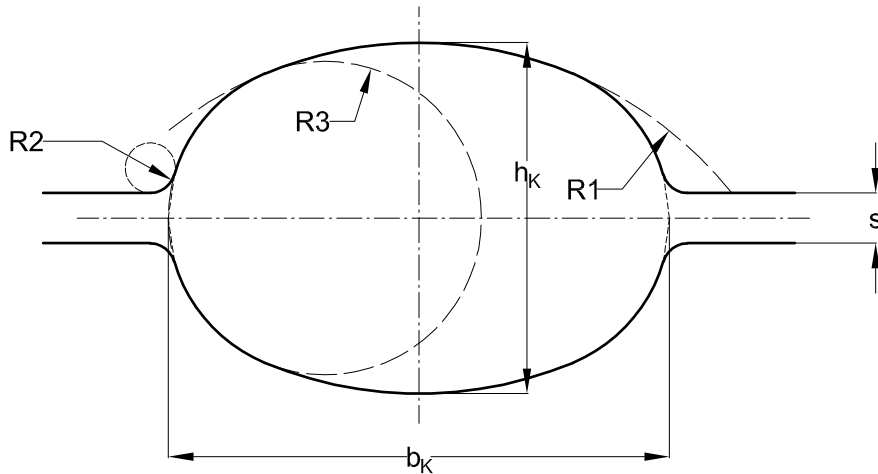


Fig. 3: Double radius oval groove for a roughing mill [1]

- Corner radius of the groove  $R_1$ ,
- Transition radius  $R_2$ ,
- Roll gap  $s$ .

When these parameters are known, the total geometry of the box groove can be defined uniquely. In Fig. 2, we can identify further parameters of the groove geometry which can be directly calculated from the geometry parameters given above. The inner width  $b_i$  and the width on face  $w$ , both of which are of great importance for the pass design procedure, follow according to [2]:

$$b_i = b_K - h_K \cdot \tan \alpha \quad (1)$$

$$b_w = b_K - s \cdot \tan \alpha \quad (2)$$

After two to four preliminary passes in box grooves, a first round section is formed as the exit section of the roughing mill. For this purpose, a double or triple radius oval groove is used.

As shown in Fig. 3, this groove shape can also be described by a set of few data:

- Width of the groove  $b_K$ ,
- Height of the groove  $h_K$ ,
- Main radius of the groove  $R_1$ ,
- Transition radius  $R_2$ ,
- Roll gap  $s$ .

Note that the minor radius  $R_3$  of the groove follows uniquely from the other parameters and is not included in this list.

When the rolled sections get smaller and smaller in the later mill stands, a simpler geometry of oval grooves is sufficient, reducing the effort of manufacturing and redressing the rolls, increasing the overall efficiency of the rolling mill. The simple single-radius oval groove is shown in Fig. 4.

This geometry can be uniquely parametrized by the following set of few parameters:

- Width of the groove  $b_K$ ,

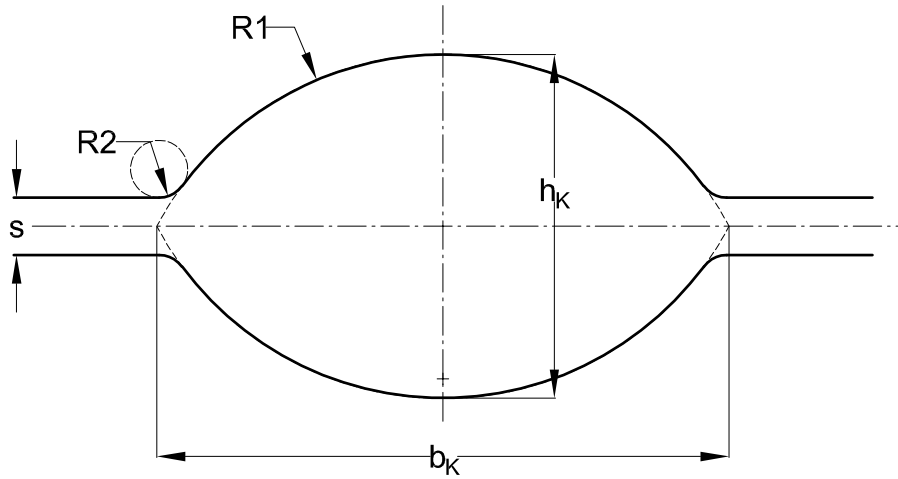


Fig. 4: Single radius oval groove [1]

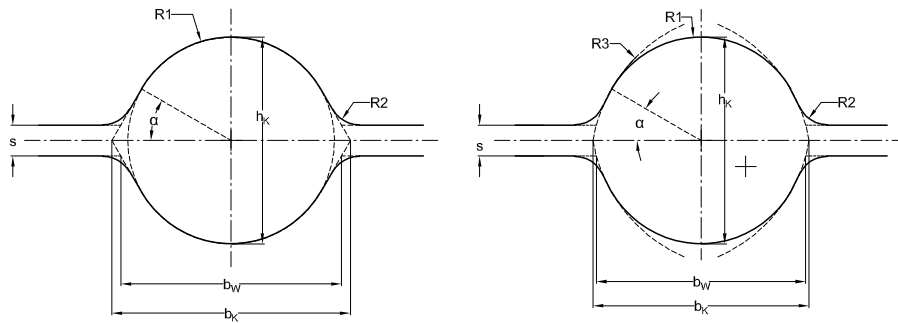


Fig. 5: Left: Opened preliminary round, Right: Opened final (double-radius) round, [1]

- Height of the groove  $h_K$ ,
- Transition radius  $R_2$ ,
- Roll gap  $s$ .

The main radius  $R_1$  follows directly from the width and height of the groove according to [2]:

$$R_1 = \frac{h_K^2 + b_K^2}{4h_K} \quad (3)$$

Later we will see that also for this groove, the width on face  $b_w$  is of great importance. It follows to [2]:

$$b_w = 2 \cdot \sqrt{R_1^2 - \left(R_1 - \frac{h_K - s}{2}\right)^2} \quad (4)$$

For the round grooves, tangentially opened grooves are used generally. Examples are shown in Fig. 5.

The first round groove is a preliminary groove, it means that the opening is realized by a tangential line. This opening of the groove serves the purpose to prevent rolling faults by overspreading, when the actual spread of the rolled round section changes due to temperature, tension or material variations. However, to improve the shape of the rolled round section, a so-called final or double-radius round groove as shown in the right part of Fig. 5 can be used. Here, the groove not opened by a line, but by a second radius  $R_3$ . This brings us to the following list of parameters for the parametrization of round grooves:

- Height of the groove  $h_K$ ,
- Main radius of the groove  $R_1$ ,
- Opening angle of the groove  $\alpha$ ,
- Transition radius  $R_2$ ,
- Opening Radius  $R_3$  (only for the double-radius round)
- Roll gap  $s$ .

### Classical Procedure of Pass Design

When we look at a typical pass design in the classical two-roll rolling process, we recognize a sequentialized structure, i.e. each two passes form a sequence between the so called main grooves. Main grooves are the square or round sections.

Fig. 6 shows a representation of an older pass design for a wire rod mill. A pre-rolled entry section with a sidelength of  $s_0 = 80mm$  would be reduced to a final rod of diameter  $d_f = 5.5mm$  in 24 passes. The first reductions (passes  $B$  to  $I$ ) are carried out in a square-diamond-square pass design. Here, the main grooves are square grooves and the minor grooves are diamond grooves. In the passes  $K$  to  $P$ , the minor grooves change to oval grooves for smaller sections, defining the square-oval-square pass design. The final passes are carried out in the typical round-oval-round design. We see from this example, that we can distinguish different standardized pass design methods (square-diamond, square-oval, round-oval) by their characteristic shapes of minor and major grooves. From these examples, we can deduce that the pass design is usually split into several pass sequences, each of which consists of two passes (minor groove and major groove). If we call the total number of passes  $n$ , this number is connected to the number of sequences  $N$  in the following way [1]:

$$N = \frac{n}{2} \quad (5)$$

The classical method of pass design is divided into two steps. In the first step, we design the sizes of the major sections, i.e. only considering each second pass.

If  $\lambda_{tot}$  denotes the total elongation from the initial section  $A_0$  to the final section  $A_n$ , we can write:

$$\lambda_{tot} = \frac{A_0}{A_n} \quad (6)$$

The elongation of sequence  $i$  will now be worked out in a degressive manner as follows:

$$\lambda_i = \lambda_m \cdot Z^{y_i} \quad (7)$$

In equation 7,  $\lambda_m$  is the mean elongation per sequence according to  $\lambda_m = \sqrt[N]{\lambda_{tot}}$ ,  $Z$  is a degression form factor with  $Z > 1$  and  $y_i$  is an exponent which is a function of the sequence index  $i$  according to:

$$y_i = \frac{N+1}{2} - i \quad (8)$$

Once the elongations  $\lambda_i$  have been designed for each sequence  $i$ , the cross section after the  $i$ th sequence follows from  $A_i = \frac{A_{i-1}}{\lambda_i}$ .

After the definition of the cross sections, the diameters or sidelengths of the corresponding main groove sections can be calculated, depending on the type of main groove (round or square). By this method, the main grooves can already be fixed for the pass design.

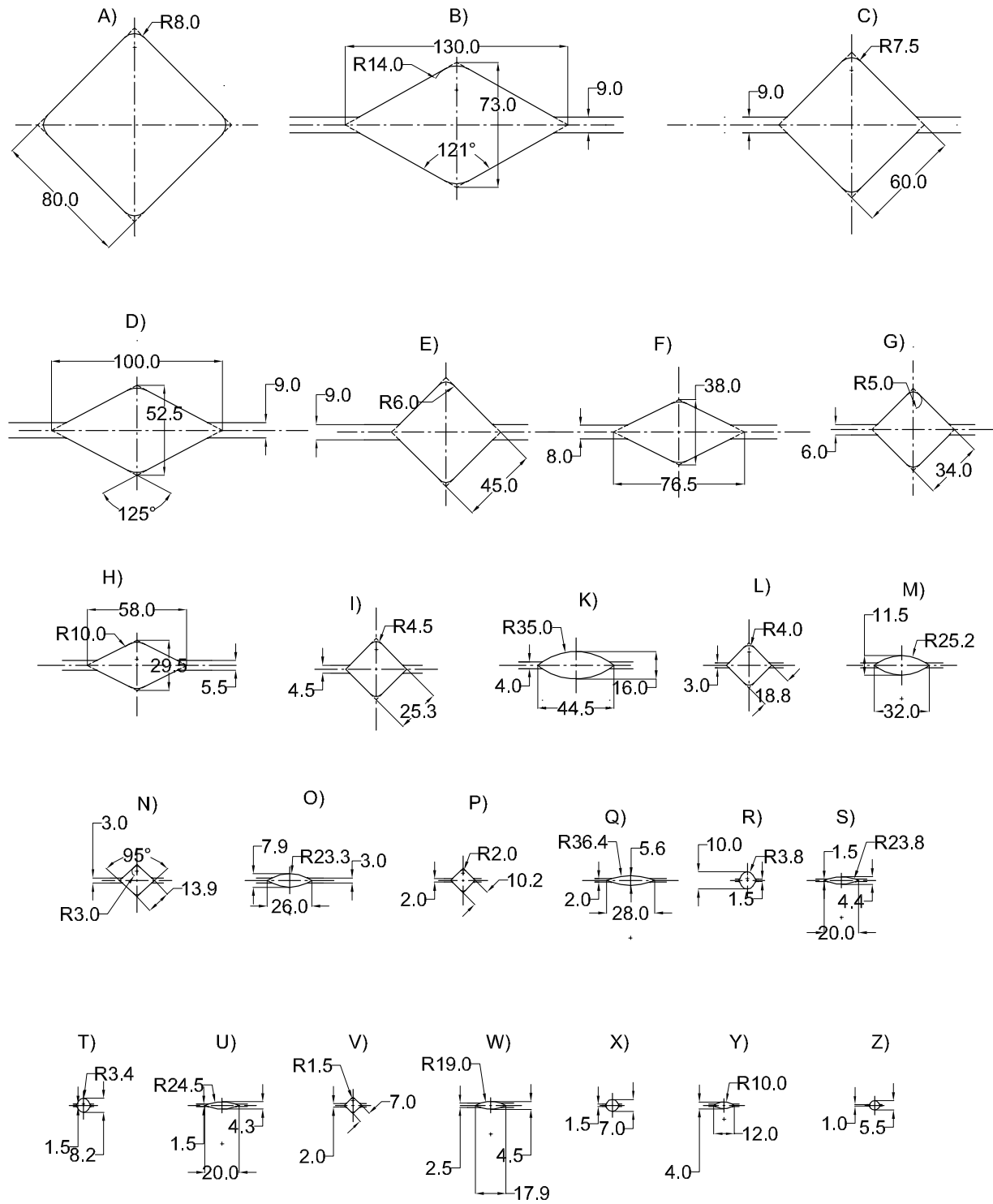


Fig. 6: Classical pass design for a wire rod mill from 80 mm square to 5.5 mm round, after [2]

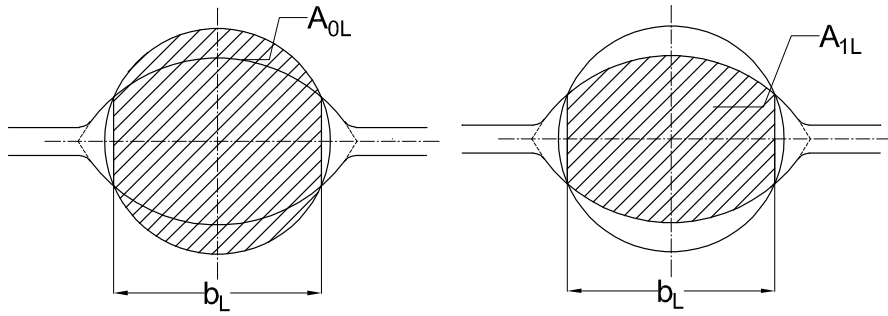


Fig. 7: Definition of equivalent areas  $A_{0L}$  and  $A_{1L}$  for Lendl's equivalent pass method [1]

The remaining problem and therefore the second step of the pass design procedure is to find the correct minor groove which ensures the deformations between the subsequent major grooves. This problem will be solved by an iterative procedure. First, a minor groove (oval or box) is guessed. With this groove, the spread calculation of the two passes of each sequence is carried out and the spreading errors of both passes are evaluated. After this, the minor groove is updated and the calculation is repeated. By this procedure, it takes a few iterations for each pass sequence to calculate the minor grooves in a way that they fulfill the desired filling conditions.

These formulation of filling conditions and the actual filling conditions are evaluated with help of so-called filling factors  $f$ , which are defined in the following way for the different groove types with the actual section width  $b_{act}$ , the width on face of the groove  $b_w$ , the groove height  $h_K$  and the inner width of the box groove  $b_i$ :

- For oval grooves:  $f = \frac{b_{act}}{b_w}$
- For round grooves:  $f = \frac{b_{act}}{h_K}$
- For box grooves:  $f = \frac{2 \cdot b_{act}}{b_w + b_i}$

The target values for the oval grooves are usually:

- $f_{tgt} \approx 0.80 \dots 0.85$  for single radius ovals,
- $f_{tgt} \approx 0.85 \dots 0.9$  for double radius ovals,
- $f_{tgt} \approx 0.95 \dots 1.0$  for round grooves,
- $f_{tgt} \approx 0.97 \dots 1.0$  for box grooves.

For the spread calculation of each single pass where the pass geometry deviates from that of a simple rectangular flat pass, we must use an appropriate equivalent pass method to define an equivalent flat pass for spread calculation. Here, we use Lendl's equivalent method [11]. The principal idea of this method is shown in Fig. 7.

The equivalent areas  $A_{0L}$  of the entry section and  $A_{1L}$  of the exit section only include the parts of the cross sections which are deformed under direct pressure of the rolls. The remaining parts are shifted outwards by lateral spread. This leads to the circumstance that these cross sections are not equal to the actual areas of the rolled cross sections, but are smaller:

$$A_{0L} < A_0 \quad (9)$$

$$A_{1L} < A_1 \quad (10)$$

We now calculate the mean heights as the entry and exit heights  $h_{0L}$  and  $h_{1L}$  of an equivalent flat pass by means of  $A_{0L}$ ,  $A_{1L}$  and the intersection distance  $b_L$ :

$$h_{0L} = \frac{A_{0L}}{b_L} \quad (11)$$

$$h_{1L} = \frac{A_{1L}}{b_L} \quad (12)$$

Additionally, a mean or so-called working roll diameter  $d_w$  is needed for the spread calculation by means of the equivalent flat pass, which follows from a comparison of the pass geometries of the section and the flat passes in terms of the nominal roll diameter  $d_N$  and the roll gap of the groove  $s$  to:

$$d_w = d_N + s - h_{1L} \quad (13)$$

With this concept in mind, we can calculate the spread of each section pass by transfer of the pass geometry to a simple flat pass, which allows any known spread model for flat passes to be applied. For example, the spread model according to Roux [12] has proven to be reliable and is used in the present analysis. The exit width is given by:

$$b_1 = b_0 + \Delta h \cdot \frac{1}{\left(1 - \frac{\Delta h}{h_0}\right) + \frac{3 \cdot A}{\left(2 \frac{R}{d_0}\right)^{\frac{3}{4}}}} \cdot \frac{\frac{b_0}{h_0}}{1 + 0.57 \cdot B} \quad (14)$$

with

$$A = \left[ 1 + 5 \cdot \left( 0.35 - \frac{\Delta h}{h_0} \right)^2 \right] \sqrt{\frac{h_0}{\Delta h} - 1} \quad (15)$$

$$B = \left( \frac{b_0}{h_0} - 1 \right) \cdot \left( \frac{b_0}{h_0} \right)^{\frac{2}{3}} \quad (16)$$

### An Artificial Neural Network for Pass Design

The pass design method described above works well for the most pass geometries and has proven its reliability in industrial practice in both the mill building and rolling mill industries. In contrast, many repeated calculations of multiple iterations may consume a lot of calculation time. It was shown that the groove geometries can be easily parametrized and therefore digitized. On this basis, we now want to construct a data-driven model by generating pass design data using the method described before and feed this data into an artificial neural network. In the present paper, the method is described and exemplified on a restricted data range, leaving space for further studies to extend the data range.

The discussed example is the reduction of an initial round section with a diameter of  $d_0 = 50\text{mm}$  to a final diameter of  $d_f = 15\text{mm}$ , made of carbon steel C55 in a total of 10 passes in a round-oval-round pass design, i.e. 5 two-pass sequences.

The pass design was worked out for six different roll diameters from 300 mm up to 800 mm in a 100 mm stepwidth. Therefore, the neural network to be constructed should be able to describe the influence of the roll diameter on the pass design for the given set of deformations.

Table 1 shows the pass design data which were generated using the analytical pass design model described in chapter for the roll diameter of 300 mm.

If the roll diameter is increased, the ovals will get flatter, i.e. height of the ovals decreases and the width of the ovals increases. This is due to the fact, that under a higher roll diameter, the rolling process will exhibit an increased spread. Exemplarily, table 2 shows the generated pass design data for a nominal roll diameter of 800 mm.



Table 1: Original Pass Design Data for a nominal roll diameter of 300 mm

Pass	Groove	Width in mm	Height in mm	Roll Diameter in mm
1	Oval(1R)	74.65	30.15	300
2	Round	-	38.5	300
3	Oval(1R)	57.92	23.54	300
4	Round	-	30.00	300
5	Oval(1R)	46.58	17.98	300
6	Round	-	23.6	300
7	Oval(1R)	38.12	13.76	300
8	Round	-	18.70	300
9	Oval(1R)	31.01	10.75	300
10	Round	-	15.00	300

Table 2: Original Pass Design Data for a nominal roll diameter of 800 mm

Pass	Groove	Width in mm	Height in mm	Roll Diameter in mm
1	Oval(1R)	90.11	25.45	800
2	Round	-	38.5	800
3	Oval(1R)	71.86	19.39	800
4	Round	-	30.00	800
5	Oval(1R)	58.43	14.65	800
6	Round	-	23.6	800
7	Oval(1R)	48.35	11.11	800
8	Round	-	18.70	800
9	Oval(1R)	39.43	8.65	800
10	Round	-	15.00	800

These two data tables should be compared in terms of the width-to-height relations of the oval grooves (note that the round sections remain unchanged). While the width-to-height relation of the oval in pass 9 in table 1 is 2.88, it is 4.56 in table 2, which significantly reduces the deformation efficiency for the higher roll diameter.

Together with the corresponding data for the remaining roll diameters (400 mm, 500 mm, 600 mm, 700 mm), these tables form the base data for the training of an ANN.

To understand the structure of the input data, it is important to comprehend that each oval only fulfills the task of bridging the gap between two completely known round grooves - the complete ten-pass design is there decoupled and reduced to 10 easier problems of finding the transition oval between two round sections. It is a common philosophy in pass design to keep the round sections unchanged to enable this problem break-up.

Accordingly, we chose the entry and exit section diameters of a two-pass sequence, as well as the roll diameter as input parameters and the resulting height and width of the oval necessary to accomplish this deformation as target parameters. The structure of the feed-forward neural network was chosen with 2 hidden layers with 5 hidden neurons in each layer. As there are 6 pass designs, each of which consists of 5 pass sequences, the base data for the training consists of 30 samples with 2 inputs and 2 targets.

For the training, 80 percent of the data was used (24 samples). 3 samples were used for validation and 3 samples for testing.

Training of the ANN was carried out using MATLAB Neural net fitting tool *nftool* with *R*-values of  $R = 0.99998$ , therefore a good approximation between the ANN model and the training data can be expected.

### Comparison Between Classical Approach and ANN

The ANN was first tested against the training data by choosing the third pass of the trained pass design, which is the oval pass between the round sections of  $d = 38.5\text{mm}$  and  $d = 30\text{mm}$ .

The oval groove for the same circumstances (400 mm nominal roll diameter, from 38.5 mm to 30 mm round) was predicted by the neural network and the pass was recalculated without groove iteration, using the oval geometry proposed by the neural network. The graphical results are shown in Fig. 8. We can see that the predicted groove is almost identical to the original one.

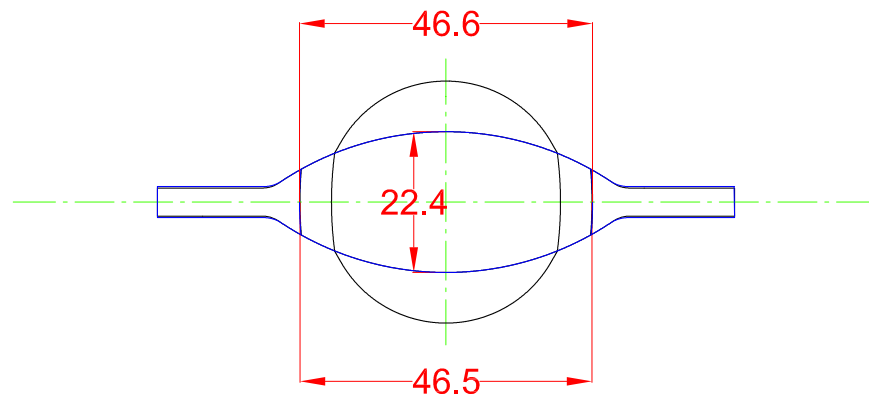


Fig. 8: Third pass for a nominal roll diameter of 400 mm - black: initial section and original groove, blue: predicted groove

A comparison of the numerical results for these two cases is shown in table 3.

Table 3: Comparison of the original and predicted oval sections of the third pass for a nominal roll diameter of 400 mm

Parameter	Original Groove	ANN Predicted Groove
Section Width	46.48 mm	46.62 mm
Section Height	22.39 mm	22.39 mm
Cross Sectional Reduction	25.16 %	25.18 %

The difference between the original and the predicted groove is very low, therefore the result is acceptable.

To give further proof that the ANN is capable of reliable groove prediction inside the range of the training data, it was tested with validation data which was generated by the classical pass design method just like the training data, but at a different set of roll diameters. Therefore, a validation check can be performed using data which the neural network did not see during training.

Fig. 9 shows the height of the oval sections as a function of the nominal roll diameter for the sequence from 23.6 mm to 18.7 mm. The black curve shows the original training data, which indicated clearly that the height of the oval must decrease when the roll diameter increases. The blue curve shows the grooves which were predicted at the very same roll diameters from the training data. Now, the green curve shows the grooves which are output by the ANN for roll diameters between 300 mm and 700 mm at an 80 mm stepwidth. Apart from the last and first roll diameter, the ANN has not seen these values during training. Another example is the yellow curve, which represents the grooves for roll diameters between 400 mm and 650 mm and a 50 mm stepwidth.

In total, a good agreement between the original curve and the predicted curves is found.

Fig. 10 shows the same cases as Fig. 9, but for the widths of the oval sections. Here, it should be noted that the red curve in Fig. 10 represents the grooves predicted at the very roll diameters used for training (corresponding to the blue curve in Fig. 9. For the widths of the oval passes, an even better agreement with the original curve was achieved.

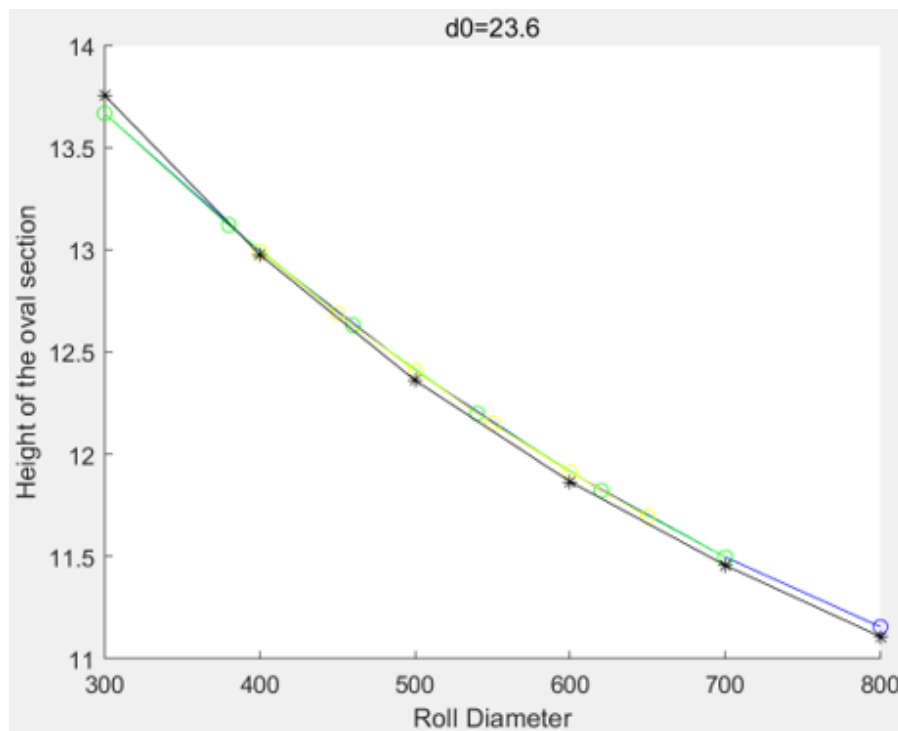


Fig. 9: Height of the oval section as a function of the nominal roll diameter

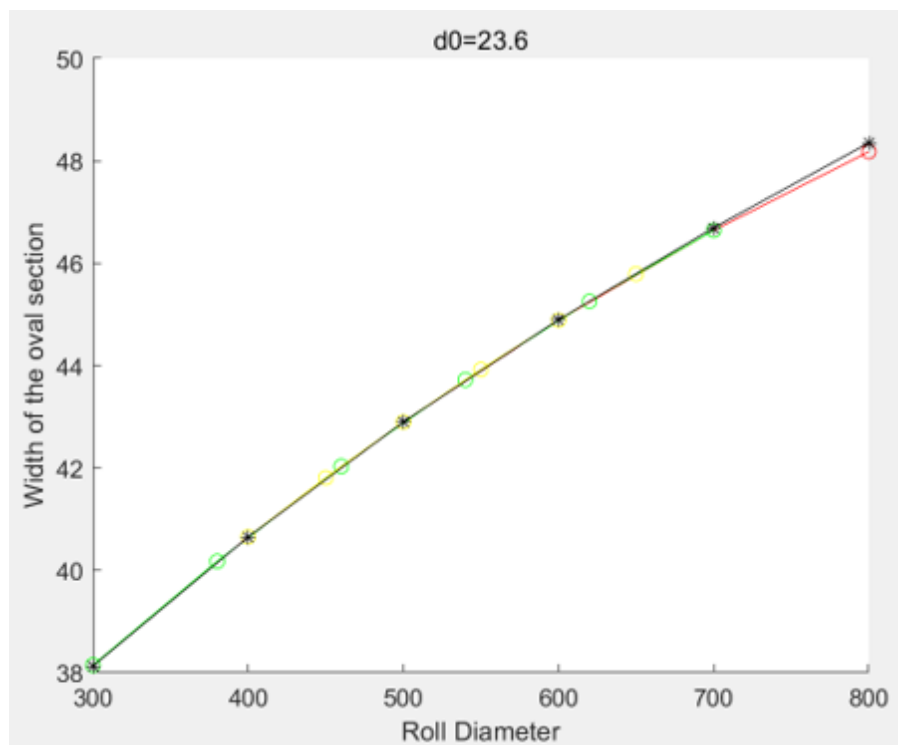


Fig. 10: Width of the oval section as a function of the nominal roll diameter

## Discussion

An artificial feed-forward neural network was trained with pass design data for an oval-round-pass sequence which have been calculated by an analytical pass design solution. The neural network was tested against the training data and against test data generated by the same procedure as the training data, but at different roll diameters. It was found that the neural network is well capable of predicting geometries of oval grooves as a function of the nominal roll diameter. However, a data-driven approach is always limited to the data ranges of the provided training data. Extrapolation can be difficult and should be avoided. The study carried out suggests that machine-learning methods with synthetic data can play an important role in transferring analytical and numerical direct simulation methods into fast data-driven methods to further increase the efficiency and robustness of roll pass design methods in the mill building and rolling mill industries. For the design of rolling schedules with multiple final dimensions and materials, the time saving by using a data-driven technique can be huge, since the classical iterative approach needs up to 5 to 10 iterations, each lasting a few seconds per pass schedule. The data driven approach does not need any iterations, is thus more stable and provides immediate results.

In further studies, the data range of the model will be extended to a broader range of sections, reductions and roll diameters. Also, the inclusion of further process parameters like temperature variations and interstand tensions will be addressed using data-driven approaches in conjunction with analytical rolling models to form a hybrid approach of roll pass design. The ANN model was not yet tested against experimental results due to the inavailability of such data. However, validation checks were performed against foreign test data generated by the same analytical pass design model, which has proven to be reliable for industrial pass design and simulation applications [9]. In the continued work on this topic, the authors plan to perform direct experimental validation in the near future.

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