Set-up optimization for tandem cold mills: A case study

C.T.A. Piresa,∗ H.C. Ferreirab, R.M. Salesb, M.A. Silvaa

a Companhia Siderúrgica Paulista (Cosipa), Estrada de Piacaguera, km. 6, CEP 11573-900 Cubatão, SP, Brazil
b University of São Paulo, Department of Telecommunication and Control Engineering, Av. Prof. Luciano Guadettno, trv. 3, n. 158, CEP 05508-900 São Paulo, SP, Brazil

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Abstract

This paper presents a set-up optimization system developed to calculate reduction for each stand of a four stand tandem cold mill installed at Cosipa plant, Brazil. This optimization system is composed of an initialization phase and an optimization phase. The initialization phase consists of a non-iterative calculation procedure, proposed as an alternative for the iterative algorithm presented by Guo [R.-M. Guo, Application of PC and LAN for a level 2 setup model of a single-stand reversing mill, Iron Steel Eng. (8) (1997) 41–46]. The optimization phase is based on Nelder and Mead simplex method and presents as the main contribution the definition of the objective function adopted, which takes into consideration quality and productivity aspects of the rolling mill. From the point of view of quality, the results after the implementation of this system are illustrated through characteristics of individual coils and of a set of produced coils; productivity aspects are illustrated through the comparison of rolling power and speed to nominal values.

Keywords: Tandem cold rolling; Set-up optimization; Nelder and Mead simplex method

1. Introduction

Set-up optimization for tandem cold mills has been frequently investigated in the last few years, motivated by the benefits they can provide in terms of quality and productivity improvements. Reductions, speeds, tensions and forces, which must be followed by the control loops, form the main part of the mill set-up. The importance of such optimization first appeared in Ref. [1] and it has been object of several recent works [2–5].

In the present work, recent developments will be discussed concerning to set-up optimization applied to a four stand tandem cold mill at Cosipa plant, Brazil, which, due to more high quality and productivity market demand, was totally revamped in 1998.

The plant modernization was implemented updating the main electrical and mechanical equipment and installing completely new hardware and software automation system. As part of the computational software, the automation and control system had been specified to have two set-up optimization phases. The first phase is now based on a new proposed non-iterative algorithm, which acts as a preliminary reduction set-up generation for each stand. During the second phase, these set-ups are optimized.

The proposed non-iterative algorithm is in fact a non-iterative version for the beta factor iterative algorithm presented in Ref. [6]. After Cosipa tandem cold mill revamping, this non-iterative algorithm replaced a proprietary iterative algorithm used to implement the set-up generation phase, which was the unique optimization phase adopted until 1998. For the optimization phase, Nelder and Mead simplex algorithm [7] has been employed. An objective function is defined such that variables related to quality and productivity, like force, power and tension, are taken into consideration. These process variables are calculated by a cold rolling classical model [8–10]. The main contributions with respect to the implementation of this phase are the definition of the objective function structure and the adjustment of its coefficients.

The software that implements the two new phases is based on static models of the process. On the other hand, dynamics control systems are responsible for keeping stands reductions as close as possible to the proposed reductions. As will be shown later, threading a coil and subsequently running the rolling mill as close as possible to optimal conditions will produce shorter heads and tails lengths, more accurate thickness control of the...
coil body, smaller strip out-of-tolerance standard deviations, higher rolling mill speeds and finally rolling mill operational state close to nominal conditions, which means full use of the available power.

This paper is organized as follows: in Section 2, the mechanical and electrical characteristics of the tandem cold mill are introduced and the automation and control system architecture is described; Section 3 details the main contributions in the set-up initialization phase; in Section 4 the optimization algorithm and the cost function are presented; experimental results are explained in Section 5; finally, Section 6 presents the main conclusions.

2. Cosipa four stand tandem cold mill

Cosipa cold mill is a coil to coil four high, four stand mill, in which each stand is composed by two backup rolls and two work rolls, the later coupled to dc motors controlled by digital speed regulators. Two hydraulics actuators, installed at the top of the stands, complete the set of reduction of each stand. Fig. 1 shows a schematic diagram of the tandem cold mill and presents its main electrical and mechanical characteristics.

The whole rolling mill is commanded by a control system, whose architecture is shown in Fig. 2. The automation architecture of Cosipa four stand tandem cold mill includes the following four levels, as described in Ref. [11]:

- **Level 3 (production planning level).** This level is responsible to decide which product will be produced and according to which specification.
- **Level 2 (process optimization level).** From entry and exit coil data specifications, this level is responsible for finding the best mill set-up in order to ensure high quality and productivity. Based on static models this level includes the set-up optimization procedure and an adaptive loop which improves the optimization for each new coil.
- **Level 1 (process dynamic control).** According to the reference signals from level 2 and measured process signals, suitable control signals are generated in this level for the actuators. This level includes the dynamic model and the mill master logic. In addition, it records the process variables necessary to the adaptive functions of level 2.
- **Level 0 (actuators and sensors).** This level includes sensors, motor drives and hydraulic actuators for gap control.

![Fig. 1. Schematic diagram and main characteristics of Cosipa four stand tandem cold mill.](image-url)
The main contribution of this paper refers to the set-up optimization procedure of level 2, which aims the following objectives:

- lowest strip thickness variation;
- unchanged strip profile;
- maximum strip rolling speed.

3. Set-up initialization

The beta factor theory proposed in Ref. [6] was developed to ensure that the reduction in each pass, in single stand reversible rolling mills, is inside the established upper and lower reduction limits. This concept is here applied for tandem cold mills.

Fig. 3 shows a typical calculated reductions sequence inside the proposed upper and lower limit curves. The last stand is here used as a finishing stand, which leads to a low reduction imposed on this stand [12]. Consequently, the major reduction is produced by the first three stands.

It should be pointed out that an arbitrary reduction curve may not be appropriated for the optimization algorithm since it may require a great number of steps to converge, or worst, it may not converge. In order to get a suitable reduction curve, a family of reduction curves is thus defined so that the reduction of each pass is given by

\[
r_i = \beta r_{u} + (1 - \beta) r_{l}, \quad i = 1, \ldots, N
\]

where \( N \) is the number of passes, \( r_{u} \) the specified upper percent reduction at \( i \)th pass, \( r_{l} \) the specified lower percent reduction at \( i \)th pass, \( 0 \leq \beta \leq 1 \) is the beta factor and the reductions are considered conventional reductions at each stand.

The beta factor is simply an interpolation factor between the upper and lower reductions limits. The total reduction, for any schedule of passes inside the family, can be calculated by

\[
r_t = 1 - \frac{h_N}{h_0} = 1 - \prod_{i=1}^{N} (1 - r_i)
\]

Guo [6] proposes the solution of Eqs. (1) and (2) through the Newton–Raphson iterative algorithm, and thus the following
expression for beta sequence is obtained:

\[ \beta^{n+1} = \prod_{i=1}^{N} \left( \frac{1 - r_i - \beta^n(r_u - r_l)}{1 - r_i} \right) \]

\[ \beta^n = \frac{h_N}{h_0} \frac{1}{\sum_{i=1}^{N} (r_u - r_l) \prod_{j=1, j \neq i}^{N} (1 - r_j - \beta^n(r_u - r_l))} \]

(3)

Therefore, knowing the entry and exit thickness of the coil, and fixing the values of maximum and minimum reduction per stand, the ideal reduction of these stands can be calculated by the beta factor so that the reduction curve will be within the established limits.

The proposed solution to find the beta factor using Newton-Raphson in Ref. [6] has the disadvantage of being an iterative solution, which requires an initial approach sufficiently close to the solution, besides additional computational effort.

In what follows, a formula is developed for simultaneous calculation of reductions for each stand in a tandem mill, in a non-iterative way.

The proposed beta factor theory in Ref. [6] seeks the determination of a family of curves whose reduction in each pass is described by Eq. (1). Using the same expression, but now establishing limits.

\[ \epsilon_l = \beta_{m} + (1 - \beta_{m})\epsilon_{u}, \quad i = 1, 2, 3, 4 \]

(4)

where \( \epsilon_l \) denotes the logarithm reduction at stand \( i \) and is given by

\[ \epsilon_l = \ln \left( \frac{1}{1 - r_i} \right) \]

(5)

\( \epsilon_m \) denotes the maximum logarithmic reduction at stand \( i \) and is given by

\[ \epsilon_m = \ln \left( \frac{1}{1 - \epsilon_{u}} \right) \]

(6)

\( \epsilon_{u} \), in the same manner, denotes the minimum logarithmic reduction at stand \( i \) and is given by

\[ \epsilon_u = \ln \left( \frac{1}{1 - r_u} \right) \]

(7)

Taking the sum of the logarithm reductions at all stands, it results:

\[ \epsilon_m = \sum_{i=1}^{N} \epsilon_i = \beta \sum_{i=1}^{N} \epsilon_{u} + (1 - \beta) \sum_{i=1}^{N} \epsilon_{l} \]

(8)

and thus

\[ \beta = \frac{\epsilon_m - \sum_{i=1}^{N} \epsilon_{u}}{\sum_{i=1}^{N} (\epsilon_u - \epsilon_l)} \]

(9)

Knowing the value of \( \beta \), it will be possible to determine the value of the percent reduction on each stand, from Eqs. (4) and (5), as

\[ r_i = 1 - \frac{1}{\exp(\epsilon_l)} \]

(10)

The thickness on the exit side of the stands will now be given by

\[ h_{i+1} = (1 - r_i)h_i \]

(11)

The beta factor theory allows the set-up calculation model of any tandem mill to be initialized, being necessary only to supply the maximum and minimum reductions of each stand. Taking advantage of the process analyst knowledge, it is possible to supply, in advance, the ideal conditions of reduction, in order to facilitate the process of the optimization algorithm used later.

Next, the proposed initial reductions for a four stand tandem cold mill will be shown using first the beta factor theory comprising iterative solution, and then the proposed initial reductions using the beta factor theory with non-iterative solution.

The results found, considering a 3.00 mm entry strip thickness to 0.91 mm exit strip thickness, for the non-iterative calculation and for the iterative algorithm, with two different initial conditions and a tolerance criteria equal to 0.0001 are shown in Table 1.

Table 1 shows an example of how the results may be affected by the initial conditions in the iterative case. In particular, in this case, for similar reductions it was necessary very different numbers of iterations. As the rolling mill runs a great variety of coils, initial conditions should then be adjusted for each coil, what would require another algorithm to avoid incorrect results.

It is worth to mention that this only set-up initialization phase was used for many years at Cosipa tandem mill and is also used as the unique phase in many rolling mill plants.

We have, thus, determined the reductions on each stand and, as a consequence, the thickness in the zones areas between the stands. This set of reductions should represent the initial vertices of the optimization Nelder and Mead simplex algorithm.
4. Set-up optimization

4.1. Optimization algorithm

Among the various existing function minimization methods, some recent applications related to cold mill set-up optimization include nonlinear programming [3], genetic algorithms [5], and more specifically the Nelder and Mead simplex method [7], which was employed in Ref. [2] and also by Cosipa cold mill automation system. A detailed description of the simplex method can be found in Ref. [13].

The simplex method, initially proposed by Nelder and Mead, considers the unconstrained minimization of a nonlinear cost function, \( J = f(x_1, x_2, \ldots, x_n) \), of \( n \) variables, without evaluating its derivatives. The minimization step is variable according to the cost function. Briefly speaking, disturbances are introduced in the initial values of \( x_i \) and new values of the cost function are calculated, corresponding to each disturbance. Three operations may be accomplished, according to the following steps: reflection, contraction and expansion, as illustrated in Fig. 4, for an example of two variables.

The iterative process is initiated sorting the points \( x_W, x_N \) and \( x_J \), for which the function has its maximum value \( J_B \), the second maximum value \( J_N \), and the minimum value \( J_J \), respectively. The average point or centroid \( x_C \) is determined finding the average of all points \( x_i \) except \( x_W \) (Fig. 4). From equation:

\[
    x = x_C + b(x_C - x_W)
\]

and assuming the minimization step \( b = 1 \), it results \( x = x_G \), known as reflection of \( x_W \) with respect to \( x_C \). The following four cases can then occur:

- If \( J_B < J_N < J_J \), then set \( b = 2 \) and get \( x = x_G \), known as expansion of \( x_W \) with respect to \( x_C \). If \( J_B < J_J \), \( x_W \) is replaced by \( x_G \) and a new process is started.
- If \( J_J < J_N < J_B \), then set \( b = 2 \) and get \( x = x_J \), a contraction with change in direction must be done, generating a vertex \( x = x_T \) for which \( b = -1/2 \). If \( J_T < J_B \), \( x_W \) is replaced by \( x_T \) and a new process is started.
- If \( J_T < J_B \), a contraction is made, generating a vertex \( x = x_E \) which result in new values of power, forces and tensions and subsequently in new value for the cost function. The algorithm described above is executed several times until a minimum value for the cost function is reached. The criterion for stopping this process is the number of iterations or a given incremental reduction of cost function between two consecutive iterations.

The Nelder and Mead simplex method will now be applied to the minimization of a cost function conceived to reflect the main targets of the rolling mill process, which are related to quality, productivity and operational aspects.

4.2. Objective function

In order to define a suitable objective function for the tandem mill, the following targets and constraints [14] were taken into account:

- Rolling mill speed is directly related to productivity. Thus, it is desirable that the stand maximum set-up speed be achieved using the total available power of that stand [15].
- The applied forces should be smoothly distributed through the first stands in order to avoid flatness problems. Furthermore, the last stand force is critical due to imposed quality purposes like roughness and flatness.
- The required per unit power of each stand should be the same, taken the total available power of the rolling mill as the base power. Thus, the total set-up power should not be greater than the nominal power of the rolling mill.
- The specific tension applied to the strip on each zone should not be greater than one third of the yield strength of the strip on that zone [1]. Furthermore, the distribution of specific tension through the zones should follow the same law as the distribution of reduction through the stands in order to avoid unbalancing of back and front tension on any stand.

From these considerations, power, force and tension were assumed to be the most important variables to form the objective function. The objective function was then conceived as

\[
    J = \sum_{j=1}^{j_1} \left( f_j^P + f_j^F \right) + \sum_{j=1}^{j_2} f_j^T
\]

Fig. 4. Simplex algorithm steps.
where \( J_i^p \) and \( J_i^f \) are the power and force cost functions of stands \( i = 1, 2, 3, 4 \), respectively. \( J_i^T \) is the tension cost function of zones \( j = 1, 2, 3 \) between two consecutive stands.

The cost function of power, force and tension are given by

\[
J_i^p = K_i^p \left( \frac{P_i - P_{i_{min}}}{P_{i_{max}} - P_{i_{min}}} \right)^{N_i^p}
\]

(14)

\[
J_i^f = K_i^f \left( \frac{F_i - F_{i_{min}}}{F_{i_{max}} - F_{i_{min}}} \right)^{N_i^f}
\]

(15)

\[
J_i^T = K_i^T \left( \frac{T_i - T_{i_{min}}}{T_{i_{max}} - T_{i_{min}}} \right)^{N_i^T}
\]

(16)

\( N_i^p, N_i^f, N_i^T \) and \( K_i^p, K_i^f, K_i^T \) are exponents and coefficients of cost functions of power, force and tension, respectively. The maximum and minimum limits for power (\( P_{i_{min}} \) and \( P_{i_{max}} \)), force (\( F_{i_{min}} \) and \( F_{i_{max}} \)) and tension (\( T_{i_{min}} \) and \( T_{i_{max}} \)) are normally defined based on the process analyst knowledge.

In fact, every component in Eqs. (14)–(16) can be seen as a variation for that one considered in Ref. [13], which has the basic structure of Eq. (17).

\[
J_i = \frac{y_i - y_{i_{min}}}{y_{i_{max}} - y_{i_{min}}}
\]

(17)

Eq. (17) reflects how distant \( y_i \) is located from the average point, considered as the nominal or ideal point between the specified maximum and minimum values.

The reasons for the specific structure of Eqs. (14)–(16) are explained in Fig. 5. Taking the values of coefficients and exponents given in Table 2, the objective function is strongly penalized if \( P < P_{i_{min}} \) or \( P > P_{i_{max}} \).

After many experiments, focused mainly on a regular distribution of reductions, power and forces throughout the rolling mill, the final values for the coefficients and exponents adjusted for each stand are presented in Table 2. It may be observed the higher stand 4 force \( K_4^f \) coefficient of the cost function due to the most demanding quality function of this stand.

The cost function, expressed by Eq. (13), is evaluated starting from three tensions and three thicknesses, each one calculated for the zone located between two adjacent stands. The three starting thicknesses are found using the reduction initialization algorithm presented in Section 2. The ranges of the three starting tensions are chosen using some analyst experience together with the recommendations of Section 4.2. The process variables, which form the cost function, are calculated from Bland, Ellis and Ford model [8–10]. Employing the simplex method, suitable thicknesses and tensions are achieved as the cost function gets near to a minimum value.

5. Experimental results

The beta factor algorithm allows the reduction calculation model of any tandem mill to be initialized, being necessary only to supply the maximum and minimum reductions of each stand. With the process analyst knowledge, it will be possible to supply the ideal conditions of reduction, decreasing the computational effort of the optimization algorithm which will be used later.

The implementation of the second phase produced, as shown in Table 3, a significant improvement for the global performance. The values summarized in Table 3 show the final result (after approximately 300 iterations) of a set-up calculation according to the two phases and including the optimized cost functions described in this paper, which sets the speed of the rolling mill last stand to a value above 1000 m/min. That speed is close to the top speed of the rolling mill, 1080 m/min. It is worthwhile to compare the reductions of this final phase with the reductions presented after the end of the first phase (Table 1) where a similar reductions profile was obtained, meaning that the reductions given by the initialization phase were not so distant of the ideal values. It can also be noticed the smooth distribution of power amongst the stands which allows the full use of the available power of the rolling mill, providing a high productivity.

The initial 50 m of the coil are shown in the lower left corner of Fig. 6. It can be observed that the maximum thickness deviation required by the customer is achieved within the first 12 m of the strip, which represents a very high material efficiency. The same is true at the lower right corner of Fig. 6, where a tail of 6 m is observed before the thickness tolerance gets out of the customer limit.

Fig. 7 shows the coil body standard deviation for one coil. It is not taken into consideration the initial 12 m and the final

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Exponents and coefficients of the cost functions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Stand 1</td>
</tr>
<tr>
<td>( K_i^p )</td>
<td>1</td>
</tr>
<tr>
<td>( N_i^p )</td>
<td>20</td>
</tr>
<tr>
<td>( K_i^f )</td>
<td>0.001</td>
</tr>
<tr>
<td>( N_i^f )</td>
<td>20</td>
</tr>
<tr>
<td>( K_i^T )</td>
<td>1</td>
</tr>
<tr>
<td>( N_i^T )</td>
<td>6</td>
</tr>
</tbody>
</table>
Table 3
Optimization results using the Nelder and Mead simplex method

<table>
<thead>
<tr>
<th>Zone</th>
<th>Thick (mm)</th>
<th>Reduction (%)</th>
<th>Speed (m/min)</th>
<th>Tension (N)</th>
<th>Tension, N (t)</th>
<th>Force (t)</th>
<th>Force, N (t)</th>
<th>Power (kW)</th>
<th>Power, N (kW)</th>
<th>Cost F</th>
<th>Cost P</th>
<th>Cost T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 0</td>
<td>2.56</td>
<td>35.7</td>
<td>283.4</td>
<td>8.40</td>
<td>972</td>
<td>1005</td>
<td>2721.1</td>
<td>2701.2</td>
<td>0.0</td>
<td>3.12</td>
<td>0.048</td>
<td></td>
</tr>
<tr>
<td>Zone 1</td>
<td>1.646</td>
<td>34.4</td>
<td>440.8</td>
<td>20.45</td>
<td>19.85</td>
<td>869.9</td>
<td>1005</td>
<td>4548.9</td>
<td>4502.1</td>
<td>0.0</td>
<td>4.95</td>
<td>0.040</td>
</tr>
<tr>
<td>Zone 2</td>
<td>1.079</td>
<td>30.9</td>
<td>672.3</td>
<td>17.86</td>
<td>17.35</td>
<td>864.8</td>
<td>1005</td>
<td>4551.9</td>
<td>4502.1</td>
<td>0.0</td>
<td>5.46</td>
<td>4.711</td>
</tr>
<tr>
<td>Zone 3</td>
<td>0.746</td>
<td>3.5</td>
<td>972.4</td>
<td>16.83</td>
<td>15.78</td>
<td>1050.6</td>
<td>954.8</td>
<td>3615.2</td>
<td>3731.7</td>
<td>1.03</td>
<td>0.05</td>
<td>0.00</td>
</tr>
</tbody>
</table>

6 m of the coil. It can be observed that the distribution of the thickness deviation for approximately all the coil body is within ±1% thickness deviation.

Fig. 8 shows the distribution of the standard deviation for 500 coils rolled with set-ups generated by the initialization and optimization phases. In this case a mean standard deviation of approximately 0.384% was obtained for a mean thickness of 1.139 mm, indicating high production repeatability.

Table 4 shows the mean values of length for the body, head and tail, after the rolling of 500 coils, considering thickness tolerances of 1%, 2%, 3% and 4%.

6. Conclusions

This work presents an optimization procedure for set-up generation for a recently revamped four stand tandem cold rolling mill, located at Cosipa plant, near São Paulo, Brazil. The used algorithm consists of two phases: the first phase is based on the beta factor algorithm [6], modified by the authors, and is used to generate initial reductions for each stand; for the second phase, called set-up optimization, a proposed objective function, which takes into consideration forces, tensions and power, is minimized using Nelder and Mead simplex algorithm [7]. Experimental results show that the obtained set-up lead to high quality and productivity in the tandem cold mill.

References