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Adequacy of Cold Rolling Models to Upgrade Set-up Generation Systems

Henrique Cezar FERREIRA,[1)] Carlos Thadeu DE ÁVILA PIRES[2)] and Roberto Moura SALES[1)]

1) Department of Telecommunication and Control Engineering, University of São Paulo, Av. Prof. Luciano Gualberto, trv. 3, n. 158, CEP 05508-900, São Paulo (SP), Brazil. E-mail: henrique@lac.usp.br, roberto@lac.usp.br
2) Companhia Siderúrgica Paulista (Cosipa), Estrada de Piaçagüera, km. 6, CEP 11573-900, Cubatão (SP), Brazil.
E-mail: carlospires@cosipa.com.br

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This paper presents two strategies for the upgrade of set-up generation systems for tandem cold mills. Even though these mills have been modernized mainly due to quality requests, their upgrades may be made intending to replace pre-calculated reference tables. In this case, Bryant and Osborn mill model without adaptive technique is proposed. As a more demanding modernization, Bland and Ford model including adaptation is recommended, although it requires a more complex computational hardware. Advantages and disadvantages of these two systems are compared and discussed and experimental results obtained from an industrial cold mill are shown.

KEY WORDS: automatic process control; automation; metals; models; process models; static models; optimization problems.

1. Introduction

Set-up generation is an important aspect for the operation of tandem cold mills. It defines speeds and powers for the drives and stand reductions, roll forces and interstand tensions for the control system. Set-up optimization should result in thickness accuracy, surface quality and good shape for the maximum length of the strip. The importance of such optimization first appeared in Ref. 1) and it has been object of several works.[2–6)]

Usually, set-up generation task is performed by a system including powerful hardware and robust software based on a detailed process model. In this paper, two systems, both based on a cost function which evaluates the mill quality and productivity, are proposed. In both cases, this function is minimized using the Nelder and Mead simplex method.[7)] The main difference between them relies on the process model on which each one is based: the first system, hereafter named the B&O system, is based on Bryant and Osborn model[8,9)] while the second system, the B&F system, is based on Bland and Ford model.[10,11)]

Production results, obtained from Cosipa tandem cold mill—a Brazilian steel industry—, are presented. Nowadays, set-up generation system in use at this mill is based on the B&F model implemented with adaptation technique. Nevertheless, this mill was first put into operation using a set of off-line calculated tables, which had the disadvantage of not to cover all coil characteristics, namely strip dimensions and strip chemical composition. After some years of operation using these tables, the mill received the B&O model without adaptation, and, following a complete modernization of the electrical e mechanical equipment, since then, it has been operated using the B&F model.

The organization of this paper is as follows. In Sec. 2, the mechanical and electrical characteristics of the tandem cold mill are presented and the automation architecture is described. The cold rolling model B&O used to estimate process variables is presented in Sec. 3 and the B&F model in Sec. 4. In Sec. 5, the cost function and the optimization algorithm for the minimization of this function are presented. In Sec. 6, set-up calculated by both systems as well as measured values of process variables are presented and compared. Finally, in Sec. 7, the main conclusions are presented.

2. Plant Description

Cosipa tandem cold mill is a coil to coil, four high, four stand mill, in which a pair of work rolls, supported by two back-up rolls, are driven by twin independent DC motors. Two hydraulics actuators, installed at the top of the back-up rolls, complete the set of reductions of each stand. **Table 1** presents its main electrical and mechanical characteristics.

Prior to rolling, set-up of the mill is calculated based on expected steady-state rolling behavior. The threading process, in which the strip is successively introduced into the mill stands, occurs at low speed. As soon as this threading process has been finished, the mill is accelerated to the desired rolling speed and the coil is processed at steady-state speed. Just before the end of the coil, the mill is decelerated to a low speed for the tailing-out of the strip and simultaneously the tandem cold mill must be set-up for the

Table 1. Electrical and mechanical characteristics.

Annual production (ton)		1248000			
Maximum speed (m/min)		1080			
Work rolls diameter (mm)		490 to 575			
Back up rolls diameter (mm)		1270 to 1422			
Motors	Stand	1	2	3	4
	Power (kW)	2× 1800	2× 1800	2× 1800	2× 1482
	Speed (rpm)	433 to 1046	433 to 1046	433 to 1046	200 to 485
	Voltage (V)	900	900	900	700
Material		Carbon Steel			
Entry thickness (mm)		2.00 to 4.75			
Exit thickness (mm)		0.38 to 3.00			
Coil width (mm)		650 to 1575			
Coil internal diameter (mm)		610			
Coil external diameter (mm)		1930			

next coil.

The whole mill process is commanded by an automation system, whose architecture is composed of 4 levels, according to the basic structure[12]:

- Production optimization level—Level 3: This level is responsible to decide which product should be processed and according to which specifications.
- Process optimization level—Level 2: Based on the product entry and exit characteristics, this level is responsible to determine the best set-up of the mill in order to ensure high product quality and productivity.
- Process control level—Level 1: This level is responsible to generate signals for the actuators according to the set-up received from the level 2. It includes the dynamic model and the mill master logic.
- Actuators and sensors level—Level 0: This level is responsible to implement the actions requested by the level 1 and to measure the necessary signals for this level. It includes equipments such as drives of the main motors, hydraulic actuators for gap control and gap sensors.

As pointed-out previously, set-up generation takes into consideration the dimensional and chemical characteristics of the material and the operational restrictions of equipments in order to select one set of reductions and tensions between stands, among an infinite number of combinations of these process variables, which provide the desired strip characteristics and mill productivity.

The main set-up generation system includes a cost function which evaluates how far roll forces, motor powers and interstand tensions are from the ideal values specified by process engineers. This cost function is minimized by the Nelder and Mead simplex method[7] and the process variables involved are estimated by the cold rolling model of each system.

3. B&O Cold Rolling Model

Cold rolling process models have been developed for more than half a century. Bryant and Osborn,[8,9] through model simplifications, developed a cold rolling model composed mainly by algebraic equations. This model demands lower computational effort and, despite to be simpler, it can produce satisfactory results, as can be shown in the last sections of this paper. **Figure 1** shows the main roll-gap variables used in the model.

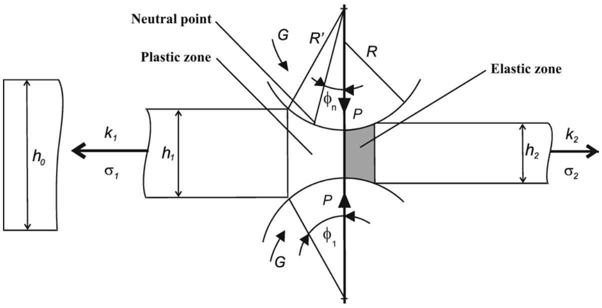


Fig. 1. Roll-gap variables.

3.1. The Force Model

Roll force per unit width is given by[8]

$$P=\frac{P_0}{1-0.4aB_0-bP_0} \quad (1)$$

where

$$P_0=(\bar{k}-\bar{\sigma})\sqrt{R\delta}\,(1+0.4\alpha_0)+P_{\mathrm{E0}} \quad (2)$$

$$\delta=h_1-h_2 \quad (3)$$

$$\alpha_0=\sqrt{\frac{h_2}{h_1}}\exp\left(\frac{\mu\sqrt{R\delta}}{\bar{h}}\right)-1 \quad (4)$$

$$\bar{h}=0.28h_1+0.72h_2 \quad (5)$$

$$P_{\mathrm{E0}}=\frac{2}{3}(k_2-\sigma_2)^{1.5}\sqrt{\frac{Rh_2(1-\nu_{\mathrm{S}}^2)}{E_{\mathrm{S}}}} \quad (6)$$

$$a=1.4\sqrt{\frac{h_2}{h_1}}\left(\frac{\mu}{\bar{h}}\right)^2 Rc \quad (7)$$

$$b=\frac{c}{2\delta}-\frac{P_0}{2}\left(\frac{c}{2\delta}\right)^2 \quad (8)$$

$$B_0=(\bar{k}-\bar{\sigma})\sqrt{R\delta} \quad (9)$$

$$c=\frac{4(1-\nu_{\mathrm{R}}^2)}{\pi E_{\mathrm{R}}} \quad (10)$$

$$\bar{\sigma}=\frac{2}{3}\sigma_1+\frac{1}{3}\sigma_2 \quad (11)$$

$$\bar{k}=\frac{1}{3}k_1+\frac{2}{3}k_2 \quad (12)$$

The yield stress at entry and exit from each stand can be evaluated by

$$k_p=k_0(\lambda_1+\lambda_2\varepsilon_p)[1-\lambda_3\exp(-\lambda_4\varepsilon_p)] \quad (13)$$

$$\varepsilon_p=\ln\frac{h_0}{h_p} \quad (14)$$

where k_0 and λ_1, λ_2, λ_3, λ_4 are constants and $p=1$ and $p=2$ are indexes associated to the entry and to the exit of each stand, respectively.

3.2. Torque and Power Model

According to Bryant and Osborn,[9] the roll torque per unit width is given by the following equation

$$G = RPC + \frac{R}{2}(h_1\sigma_1 - h_2\sigma_2) \quad\text{.................(15)}$$

where

$$C = \sqrt{\frac{\delta}{R'}}\,\frac{(2/3)(k_1-\sigma_1)+(1/3)(k_2-\sigma_2)}{(k_1-\sigma_1)+(k_2-\sigma_2)} \quad\text{......(16)}$$

$$R' = R\left(1+\frac{cP}{\delta}\right) \quad\text{...........................(17)}$$

Motor power is given by

$$M = \frac{GW_\mathrm{S}V_\mathrm{R}}{\eta_\mathrm{M}\eta_\mathrm{G}R} \quad\text{.............................(18)}$$

where

$$V_\mathrm{R} = \frac{V_1h_1}{(1+f)h_2} \quad\text{............................(19)}$$

$$V_1 = \frac{V_2h_2}{h_1} \quad\text{................................(20)}$$

$$f = \frac{R'\phi_\mathrm{n}^2}{h_2} \quad\text{................................(21)}$$

$$\phi_\mathrm{n} = \frac{1}{2}\frac{h_2}{\bar{h}}\sqrt{\frac{\delta}{R'}} - \frac{1}{4}\frac{h_2\delta}{\bar{h}\mu R'} + \frac{1}{4}\frac{h_2}{\mu R'}\left(\frac{\sigma_2}{k_2}-\frac{\sigma_1}{k_1}\right) \quad\text{...(22)}$$

4. B&F Cold Rolling Model

The most classic cold rolling process model was proposed by Bland and Ford[10,11] being composed by algebraic and integral equations for force and torque calculation. According to Bland and Ford theory, the strip is subjected to three different zones in the arc of contact between the strip and the work rolls. In the first zone, located at the entry of this region, the strip is elastically compressed until the yield stress condition is achieved. In the second zone, the strip is plastically deformed until a minimum thickness while in the third and last zone, it suffers elastic recover.

Specific rolling force P is given by

$$P = P_\mathrm{P} + P_\mathrm{E1} + P_\mathrm{E2} \quad\text{.........................(23)}$$

The specific rolling force in the plastic deformation zone P is obtained by integration of specific roll pressure s along the whole arc of contact between strip and work rolls. Specific roll pressure at entry and exit of stand are given by

$$s^- = \frac{kh}{h_1}\left(1-\frac{\sigma_1}{k_1}\right)\exp[\mu(H_1-H)] \quad\text{...........(24)}$$

$$s^+ = \frac{kh}{h_2}\left(1-\frac{\sigma_2}{k_2}\right)\exp(\mu H) \quad\text{................(25)}$$

respectively. Expression H depends on a roll bite geometry. Its value in any place of contact arc equals

$$H = 2\sqrt{\frac{R'}{h_2}}\tan^{-1}\left(\sqrt{\frac{R}{h_2}}\,\phi\right) \quad\text{..................(26)}$$

H_1 is obtained by substitution of value ϕ_1 in Eq. (26).

Angle ϕ_n follows from equality of s in Eqs. (24) and (25)

$$\phi_\mathrm{n} = \sqrt{\frac{h_2}{R'}}\tan\left(\frac{H_\mathrm{n}}{2}\sqrt{\frac{h_2}{R'}}\right) \quad\text{.................(27)}$$

where

$$H_\mathrm{n} = \frac{H_1}{2} - \frac{1}{2\mu}\ln\left\{\frac{h_1}{h_2}\left[\frac{1-(\sigma_2/k_2)}{1-(\sigma_1/k_1)}\right]\right\} \quad\text{........(28)}$$

Specific force P_P for plastic deformation is then given by equation

$$P_\mathrm{P} = R'\left(\int_0^{\phi_\mathrm{n}} s^+ d\phi + \int_{\phi_\mathrm{n}}^{\phi_1} s^- d\phi\right) \quad\text{................(29)}$$

Total specific rolling force also includes forces for elastic deformation at entry P_E1 and exit P_E2 of stand

$$P_\mathrm{E1} = \frac{1-\nu_\mathrm{R}^2}{4E_\mathrm{R}}h_1\sqrt{\frac{R'}{h_1-h_2}}(k_1-\sigma_1)^2 \quad\text{............(30)}$$

$$P_\mathrm{E2} = \frac{2}{3}\sqrt{\frac{1-\nu_\mathrm{R}^2}{E_\mathrm{R}}R'h_2(k_2-\sigma_2)} \quad\text{.............(31)}$$

The radius of the flattened arc of contact between the roll and the strip depends on the contributions of the plastic and elastic forces and must be calculated by Hitchcok formula

$$R' = R\left[1+\frac{16(1-\nu_\mathrm{R}^2)P}{(\sqrt{\delta+\delta_2+\delta_\mathrm{t}}+\sqrt{\delta_2})^2}\right] \quad\text{..........(32)}$$

where

$$\delta = h_1 - h_2 \quad\text{...............................(33)}$$

$$\delta_2 = \frac{1-\nu_\mathrm{R}^2}{E_\mathrm{R}}h_2(k_2-\sigma_2) \quad\text{....................(34)}$$

$$\delta_\mathrm{t} = \frac{\nu_\mathrm{R}(1+\nu_\mathrm{R})}{E_\mathrm{R}}(h_2\sigma_2 - h_1\sigma_1) \quad\text{................(35)}$$

Roll torque per unit width is given by the following equation

$$G = RR'\left(\int_0^{\phi_1} s\phi d\phi + \frac{\sigma_1h_1-\sigma_2h_2}{2R'}\right) \quad\text{............(36)}$$

5. Set-up Optimization

The adopted cost function for the present set-up generation system is given by

$$J(x) = \sum_{i=1}^{4}[J_\mathrm{M}^{(i)}(x)+J_\mathrm{F}^{(i)}(x)] + \sum_{j=2}^{4}J_\mathrm{T}^{(j)}(x) \quad\text{......(37)}$$

where

$$x = [h^{(2)}\ h^{(3)}\ h^{(4)}\ \sigma^{(2)}\ \sigma^{(3)}\ \sigma^{(4)}] \quad\text{............(38)}$$

Coefficients and exponents of the cost function terms are chosen so as to balance the weight of every process variable involved on the total cost function and also to adjust their rate of change. A detailed description of this function and its parametrization is presented in Ref. 6).

The optimization algorithm used to minimize the cost function for both set-up generation system is the Nelder Mead simplex method.7) In Ref. 13) it is presented an extensive explanation of this method. In brief form, the same algorithm is explained in Ref. 6).

6. Results

The proposed set-up generation systems were implemented in Matlab—for simulation—and in C language—to be implemented in the level 2 automation system—and includes the process models, the optimization algorithm and an adaptation procedure discussed in Ref. 14). In order to evaluate the accuracy of the two proposed process models, 20 coils were chosen and the prediction of the set-up model for these coils was quantified. In the next section, detailed set-up results for one of these 20 coils and average results for the set of 20 coils are presented.

6.1. Set-up Results for One Coil

Entry thickness and width of the strip in this section are 3.01 mm and 1 004 mm, respectively. The required exit thickness is 0.91 mm. **Table 2** presents the initial and final cost function values and the number of iteration obtained by the B&O model, and by the B&F model.

In both cases the stop criterion was fixed to $\Delta=0.001$. **Figures 2**(a) and 2(b) illustrate the fast convergence rate of the cost function value for the B&O and B&F models, respectively, which reveals a good efficiency of the Nelder and Mead simplex optimization algorithm for both models.

The cost function values and the number of iteration shown in Table 2 are very similar for both systems. The significant greater processing time of the system using B&F model is due to its more complex calculations, as noticed in Sec. 4. Its accuracy is verified in **Fig. 3**, comparing values of measured and preseted forces for 300 coils. It can be seen that the precision of this model is in the range of ±10%. With this in mind, it is possible to take B&F as reference and compare B&O model to it. Note the good agreement of results of power and thickness—the main set-up parameter that defines quality and productivity—between the two systems, as shown by the Table 3.

Table 2. B&O and B&F system performance data.

	B&O Model	B&F Model
Computer	PC Pentium IV	DEC Alpha
Language	Matlab	C
Initial cost function value	$1.83 \cdot 10^4$	$3.27 \cdot 10^5$
Final cost function value	20.23	33.18
Iteration number	198	213
Processing time (s)	0.77	11.15

6.2. Average Set-up Results for 20 Coils

In this section, set-up parameters thickness, tension, speed, power and force were firstly calculated for 20 coils, using the B&F set-up generation system. Then, the same parameters were calculated using the B&O system. **Table 4** presents the average deviation, in percent, between these two systems, taking B&F as the base system as we already compared it with the measured values in Fig. 3.

Thicknesses and tensions between payoff reel and the first stand—zone 1—and between the last stand and the tension reel—zone 5—are fixed, and thus they are not included in the simplex algorithm.

As can be observed in Table 4, thickness, tension and force rely on acceptable ranges of deviations. Taking these accuracies into consideration, it may be said that strip quality and mill productivity are guaranteed for both systems.

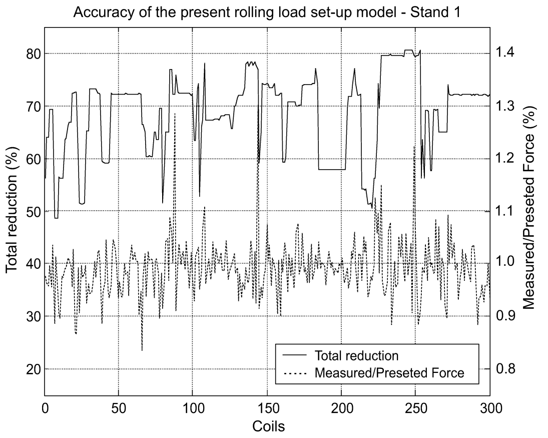
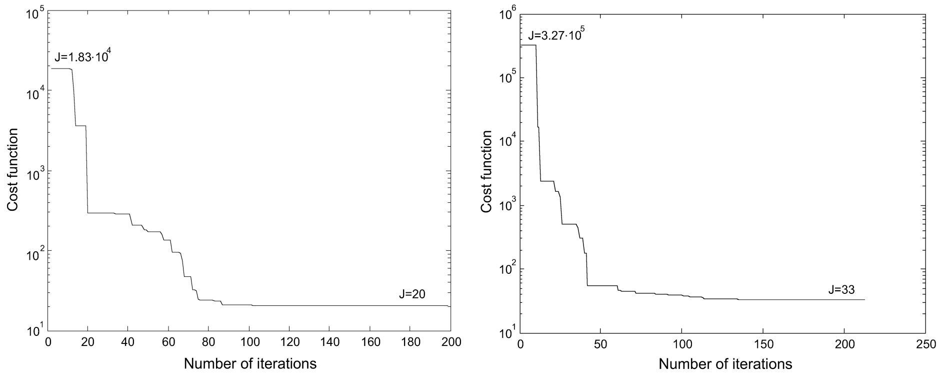


Fig. 3. Accuracy of the B&F cold rolling model.



(a) B&O model

(b) B&F model

Fig. 2. Cost function minimization.

Table 3. Set-up calculated for an arbitrary chosen coil.

	Thickness (mm)		Tension (ton)		Force (ton)		Speed (m/min)		Power (kW)	
	B&O	B&F	B&O	B&F	B&O	B&F	B&O	B&F	B&O	B&F
Zone 1	3.010	3.010	2.7	2.7			263.5	255.6		
Stand 1					983	1002			2227.1	2190.2
Zone 2	2.031	2.047	22.8	23.9			390.5	375.9		
Stand 2					979	940			4475.7	4302.0
Zone 3	1.382	1.382	20.7	20.1			573.8	556.7		
Stand 3					906	854			4389.6	4287.2
Zone 4	0.989	0.974	17.8	17.6			801.8	789.6		
Stand 4					991	991			3602.9	3557.5
Zone 5	0.910	0.910	3.2	3.2			871.6	845.5		

Table 4. Average deviation in percent between set-up calculated by B&O and B&F systems.

	Thickness	Tension	Force	Speed	Power
Zone 1	Fixed	Fixed		8.54 ± 6.99	
Stand 1			-5.52 ± 4.78		3.45 ± 2.61
Zone 2	-0.27 ± 1.15	-0.85 ± 6.76		8.83 ± 6.61	
Stand 2			1.21 ± 5.74		4.09 ± 2.48
Zone 3	2.31 ± 2.54	5.00 ± 7.04		6.13 ± 6.58	
Stand 3			1.15 ± 7.15		3.76 ± 3.29
Zone 4	2.38 ± 1.12	4.45 ± 9.04		6.01 ± 6.40	
Stand 4			3.23 ± 7.50		9.06 ± 12.58
Zone 5	Fixed	Fixed		8.54 ± 6.99	

7. Conclusion

In this paper, set-up generation systems were developed and implemented at Cosipa tandem cold mill using two different models following recent modernization phases of the mill. Although the B&O system is simpler and less accurate than the B&F, measured results show that both systems proved to be adequate alternatives to be used as set-up generation, because they provide accurate references representing a strong step to obtain high strip quality. It is also possible to obtain the best productivity using these systems taking into consideration that they work reasonably well with the chosen optimization algorithm, allowing the full use of the available power.

Nomenclature

E_R : Young's modulus of the work roll
E_S : Young's modulus of the strip
f : Forward slip
G : Specific roll torque
h : Strip thickness
J : Cost function
J_F : Roll force term of the cost function
J_M : Motor power term of the cost function
J_T : Tension term of the cost function
k : Yield stress
M : Motor power
P : Specific roll force
P_0 : Roll force for $R'=R$
P_E : Elastic deformation force
P_P : Specific force for plastic deformation
P_{E0} : Elastic recovery force for $R'=R$
R : Undeformed work roll radius
R' : Deformed work roll radius
s : Specific roll pressure
T : Total interstand tension ($T=\sigma W_S$)
V : Strip speed
V_R : Work roll peripheral speed
W_S : Strip width
δ : Strip thickness absolute reduction
η_G : Gear efficiency
η_M : Motor efficiency
μ : Coefficient of friction
ν_R : Poisson's ratio of the work roll
ν_S : Poisson's ratio of the strip
ϕ_n : Angle at neutral plane
σ : Tension stress
ε : Logarithmic reduction

Subscripts and Superscripts
1 : Stand input parameter
2 : Stand output parameter
$\bar{}$: Parameter mean value
i : Stand number
j : Interstand zone number

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