Adaptive dimension models for optimization of long products rolling
This paper presents the ABB ADMTM tool for optimization and simulation of long products rolling. Cornerstones of the tool are state-of-the-art optimization and model learning techniques, along with unique, simplified mechanical and physical models.

The everyday work of a rolling mill operator can be truly wearisome. It may indeed be timeconsuming to find one’s way out of situations where unstable rolling results in downtime, less yield, and cobbles often having to be cut and removed. The path followed in order to regain stable rolling is based on the long experience of individuals for whom process parameter settings are a form of “secret art” representing the very core of their professional pride. After a while, the production is back on track — however, not until time has been spent on a trial-and-error procedure involving analyzing a number of trial billets for dimensional accuracy, producing scrap and costing energy in the meantime. An unsuccessful product change (PrC) procedure may result in production delays of more than one hour, whereas a successful one is completed in a matter of minutes. The result of this challenge is a unique operator’s on-line software tool based on state-of-the-art rolling models and optimization, simulation and statistical methods for guiding the operator to optimal process parameter settings for stable and dimensionally accurate rolling.

Models for Optimization, Simulation and Calibration — The ADM tool advises the mill floor worker which parameter settings should be used to reach optimal conditions. This information is presented via an easy-to-use HMI, with the complex calculations taking less than a minute, and most often around 10 seconds or less. This tool can be accessed through an auxiliary PC located in the operators’ booth, alongside the regular ABB Rolling Mill Control (RMCTM) and Interstand Dimension Control (IDCTM) displays. One of the ADM window displays is shown in Figure 1. Here, the operator selects optimization objective, constraints, solution control parameters and updating procedure. Interstand Dimension Control (IDC) for Rolling Stability — The ABB IDC concept has been developed
for rod and bar mills to achieve tighter tolerances head to tail, and to improve product quality, yield and availability. In addition, it ensures fast product and dimension changes and obtains early indication of abnormal mill conditions, more consistent mill setup and improved pass schedules. The key component is the U-gauge™ for on-line bar dimensional measurement (Figure 2).

On-line information from drive systems and U-gauges is seamlessly communicated to the ADM tool. This data, combined with the operator's selection of only a few parameter settings for various process simulation and optimization tasks, forms tool inputs. The operator launches these tasks with little intervention and receives simulation and optimization responses in the form of adjustment lists, tables and charts — normally within a few seconds.

This configuration and high-speed algorithms allow for a great number of interactive process optimization tasks in a short period of time. Having identified parameter settings that meet the demands of the operator, these results may be stored as a new RMC rolling schedule for later retrieval.

Figure 1  ADM main window for optimization data entry.

Figure 2  U-gauge in operation for dimensional measurement.
The ADM tool requires only minimal configuration work on the PC before it can start to deliver useful results.

**Rolling Maximization and Minimization** — Again, maintaining stable rolling, defined by a continuous mass flowrate throughout the process line with minimal interstand stresses, in particular compressive ones, together with dimensional accuracy of the finished product, challenges the operator’s skills. The ADM tool provides additional capabilities to assist the operator in fully understanding changes to the current rolling state and to plan for the optimization of the coming production. Using this tool, one can ensure stability and product dimensional quality; a vast number of related aspects previously beyond reach but of nearly equal importance can be controlled. The core of the ADM optimization module permits the maximization or minimization of selected production aspects while keeping related and dependent aspects within permissible constraints.

A general nonlinear optimization problem may be expressed as:

$$\min_x f(x)$$

s.t. $c_i(x) \leq 0, \quad k = 1, N$

(Eq. 1)

Here, $x$ denotes the primary optimization variables, typically roll gaps and motor speeds. The objective function $f(x)$ to be minimized may be defined so as to involve any conceivable rolling process quantity of interest — total rolling power, power targets (load leveling), area/width (groove utilization), tension targets, to mention a few. Maximization of production speed may also be specified. The $N$ constraints $c(x)$ are used to specify permissible upper and/or lower bounds to process quantities, such as maximum available rolling power, groove utilization, speed, area reduction, etc. Equality constraints are automatically set for finishing width and height, but any process quantity may be subject to equality constraints.

An example of the maximization of bar finishing speed is shown in Figure 3. Real mill data is used, and constraints are defined for motor power, torque, speed, interpass tension, groove utilization and area reductions. For this particular mill configuration, it was concluded that, for one of the drives, the actual power requirement was close to the maximum allowable, which somewhat inhibiting the full potential of this optimization feature.

**Energy Consumption Minimization** — Minimizing energy consumption is another optimization choice available to the operator. Power modeling follows Reference 2, and it should be noted that the sum of stand powers most often deviates little with respect to the actual mill power when using the model updating approach described here. It is also believed that the model, according to Reference 2, provides accurate enough power gradients, which has been concluded from extensive FE simulations.

A real 10-stand (intermediate and finishing stands for 20-mm rounds) example is solved in less than 10 seconds on a regular PC. The starting point in Figure 4 (iteration “0”) corresponds to the actual mill process parameter settings, and the iteration history illustrates the convergence of the ADM optimization procedure toward a total rolling energy, which is about 10% lower than at the outset. Here, the model error in the sum of stand powers is 2.5%. Furthermore, ADM optimizes an imaginary process line with 20 stands within 30 seconds.

Bar and groove geometries are displayed in Figure 5 in the Appendix.

**Interpass Tension Modeling** — In all optimization and simulation selections, the interpass tension plays an important role, and constraints assuringstable rolling without push may be specified as well as tension setpoints. A unique modeling feature is the way in which tensions change bar dimensions, both in the deformation and interstand zones, while at the same time the overall model maintains a continuous mass flow. This paves the way for a consistent analysis of endless rolling, in which bar dimension may be controlled by relatively high interstand tensions.

The core of the tension modeling approach is based on maintaining a continuous mass flow through the Nst stands, forming the setup at hand:3

$$\hat{m}_i^\text{NP} (x) – \hat{m}_i^\text{Entry, Exit} (x) = 0, \quad i = 1, Nst$$

(Eq. 2)

Here, the vector of Nst unknowns includes billet entry speed and interpass tensions, and this set of nonlinear, coupled equations may be solved using standard Newton iterative methods. Further, NP denotes neutral plane. There is also a logic for bar interstand dimensional changes, i.e., cases when the area and speed vary along the interpass stretch under conditions of relatively high tensions.

**Model Adaptation** — Optimization may be carried out either for the current production or for a coming one following a PrC procedure. In the former case, on-line drive system and U-gauge readings are used for model adaptation for enhanced model accuracy. The calibrated models may also be used in the PrC optimization, provided this rolling case does not deviate much from the one for which the model was calibrated. The logic of the ADM tool automatically decides the best adaptation scheme. It is well known that a rolling power model benefits
greatly from adaptation, and it carries over to the accuracy by which the energy consumption is determined.

The core of the adaptation logic is to use on-line U-gauge and drive information to tune bar spread and stand power models. As for spread, a general expression with dimensionless variables for an equivalent rectangle method is:

\[ g_i = g \left( h_i / h_p, b_i / h_p, h_i / R, D / B, \sigma_{1,2} / \sigma_{eff} \right) \]

where

- \( h \) = bar height
- \( b \) = bar width
- \( R \) = roll radius
- \( D \) = groove depth and
- \( B \) = groove width

Subscripts 1 and 2 denote stand entry and exit, respectively. The last terms represent the influence of interstand tensions. A few parameters in this expression are used in the updating procedure. Typical absolute mean, maximum, and finishing bar width model confirmation errors after updating are <2%, <4.5% and <1%, respectively, and these results are for real 8- and 10-stand configurations with oval, round and square grooves.

Rolling power, according to Reference 2, is also the subject of model updating in the ADM tool. The updating results in significant model error reductions, although experience is that an outlier may still reach a 20% error after updating. However, the sum of stand powers becomes very accurate, as mentioned above. In this context, it should be noted that even the most complex, uncalibrated FE model will have outlier errors of the same order. It appears from the extensive FE literature that the confirmation outlier error after FE model updating is still of the
order of 7–10%, which also conforms with the experience of the authors.

**Sensitivity Analysis** — This feature is very useful when analyzing the effect of small perturbations to the process parameters obtained in an optimization or to the results of a standard simulation. One sensitivity analysis task requires two to three seconds for a 10-stand configuration. A 20-stand configuration requires about 10 seconds.

**A Monte Carlo Approach With Uncertain Rolling Conditions** — In some circumstances, the operator may want to investigate safety margins with respect to unstable rolling. This provides valuable insights when, for example, a new material with uncertain properties, essentially its flow stress or resistance to deformation, is to be rolled the first time. The operator may then launch another simulation-based feature of the ADM tool — a statistical evaluation of the likelihood of interpass tensions exceeding allowable ranges. The core is here the well-known Monte Carlo (MC) approach. Results are in the form of probability of stable rolling for the configuration and process parameters at hand. In fact, all types of results pertaining to the bar, rolls and drives may now be expressed as confidence intervals with lower and upper limits, rather than as one specific value obtained in a regular deterministic simulation. This also improves prediction accuracy of the energy requirement, as this is very sensitive to bar materials’ deformation properties. On the whole, a statistical evaluation of model performance is extremely valuable, also when considering complex FEM simulations. An evaluation of MC interpass tension results, as shown in Figure 6, gives the operator information about the type:
- Stable rolling: probability of all tensions being in range 1: 0.9734.
- Unstable rolling: probability that at least one tension will be in range 2: 0.0078.

Here, “tension ranges” 1 and 2 may be specified by the operator.

**Future ADM Extensions**
Further reduction of optimization times toward just one or two seconds is within reach using the latest numerical optimization developments. The vision here is a fully automatic on-line procedure, in that the optimization and adaptation are carried out during the time the bar head travels between the first two stands. Model improvements will include simplified upper-bound 3-D solutions with thermomechanics and optimization for materials properties control. This also alleviates limitations inherent in simplified power models by the introduction of a more precise thermal flow stress modeling.

**Conclusions**
It is strongly believed that the ABB ADM tool will help assist a mill floor worker’s daily goal of production perfection. HMI ease of use, robustness and accuracy are cornerstones of the ADM optimization, simulation and adaptation logic. It also provides an excellent educational platform for a unification of the many different “secret art” PrC and process line fine-tuning philosophies that usually exist among mill operators.

**References**

**Appendix**
See Figures 3–6.
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