# Next-Generation Hot Strip Mill Control Model for Roughing and Finishing Mills (RoFi)

Koen Schutte[1], Erik Gillebaart[2], Peter Gelten[1], Arnout Boelens[1], Richard van Dok[2], Mustapha Bsibsi[1]

[1]Tata Steel Nederland Technology B.V.
P.O. Box 10000, 1970 CA IJmuiden, the Netherlands
Phone: +31 2514 96081 / +31 2514 98804 / +31 2514 95136 / +31 2514 97384
Email: koen.schutte@tatasteeleurope.com / peter.gelten@tatasteeleurope.com
arnout.boelens@tatasteeleurope.com / mustapha.bsibsi@tatasteeleurope.com

[2]Tata Steel IJmuiden B.V.
P.O. Box 10000, 1970 CA IJmuiden, the Netherlands
Phone: +31 2514 94570 / +31 2514 95037
Email: erik.gillebaart@tatasteeleurope.com / richard.van-dok@tatasteeleurope.com

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## INTRODUCTION

Hot rolling is a key process in modern steelmaking. In a conventional hot rolling mill, slabs with typical gauges of 200 to 260 mm are reheated in a furnace to temperatures in the range of 1150°C to 1250°C. After drop-out from the furnace, the slabs pass through one or more roughing mill stands to be transformed into a transfer bar. The transfer bar is thereafter passed through multiple finishing mill stands (typically five to seven), before it is cooled down in a controlled manner on the run-out table and coiled. Typical hot-rolled strip gauges vary between 1.5 and 25 mm and coils have a width of 700 to 2100 mm. Most hot strip mills produce a large variety of steel grades to many different dimensions and therefore product changes during production are very frequent. As a result, good models with predictive power are required to set up the mill from product to product.

Most of the Level 2 models that are in use at Tata Steel IJmuiden have been developed in-house by the R&D department. This is also the case for the Level 2 automation of the roughing and finishing areas of the Hot Strip Mill (HSM2). The current generation of the models used dates back to the 1980's for the roughing area and the late 1990's for the finishing area. After having served for such a long time-span, the limitations of these systems have become more and more restrictive in the present operational context of the mill (e.g. rolling more and more advanced steel grades to wider dimensional windows). In particular, because of limited computer power available back in the day, the current models only allow for the use of a limited set of pre-determined reduction patterns in the roughing mill.

To accommodate various future needs, R&D is developing a new Level 2 automation that will take over the setup, control and adaptation from the existing systems in the roughing and finishing mills. This new model is called RoFi (**Ro**ughing**Fi**nishing). RoFi will have the following advantages over the existing models:

- Better ability to produce novel products in an automated way, by allowing for arbitrary slab and transfer bar gauges without manual intervention.
- Increase of the maximum coil weight by calculating bespoke reduction patterns for every coil, instead of pre-defined reduction patterns that put restrictions on the maximum slab length because of the inter-stand length limits in the rougher mill.
- Increased mill productivity by better utilization of mill hardware capability (being able to approach the physical installation limits for e.g. power more closely) and by allowing for arbitrary stand dummying orders in the finishing mill.
- Improved product quality due to better ability to control the time-temperature path throughout the mill and reduced reliance on operator interventions.
- Easier maintainability and better scalability due to an object-oriented core-shell programming approach.

RoFi also has the capability to control a transfer bar cooling installation in the future.

 

## MODEL DESCRIPTION

At present, we focus on implementing RoFi in the roughing mill of HSM2, followed by an extension to the finishing mill. For that reason, we also focus on the RoFi rougher mill setup in this paper. In future, RoFi should also be suited for use in thin slab casting and rolling lines (such as the Direct Sheet Plant in IJmuiden) with relatively minor modification.

### Material Representation

Throughout its transformation from slab to strip[1], the material is represented by discrete elements. In the length direction of the strip, the discrete elements are referred to as *samples*, and they are distributed equidistantly along the length of the strip. While the physical properties of different samples can differ from each other, each sample is assumed to have similar properties along its own length and therefore can be represented by one material state (e.g. gauge, width, temperature, etc.). Other than being physically connected (and thus moving correspondingly), interactions between the samples are neglected (viz. we do not consider any heat flow along the length of the strip). This is a reasonable assumption, because of the vastly different length scales in the length and thickness direction: the typical sample length to thickness ratio is much larger than one, also in the rougher mill.

Each sample is discretized in the through-thickness direction by a staggered grid finite difference discretization scheme, in which the temperature and heat flux nodes are offset by half a grid cell spacing. Coarser cells are used near the strip centre than at the top and bottom surface, with a constant multiplication factor between the cell spacing of adjacent cells. A schematic representation of the representation of the strip is given in Figure 1.

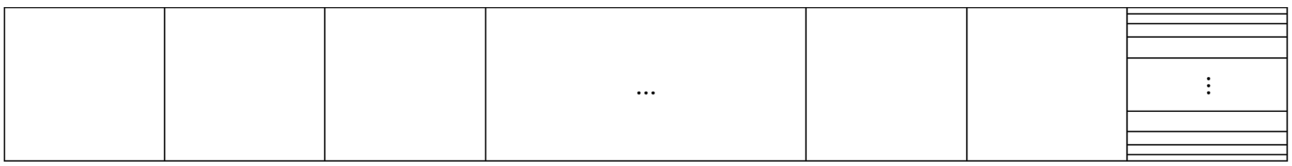

Figure 1: Schematic representation of strip discretization (side view).

### Predictive Material Tracking Through the Mill

To describe the interactions between the strip and the mill, it is necessary to have accurate knowledge of which strip sample is interacting with which mill component when. An overview of these interactions is established by predictive material tracking calculations. In RoFi, the material tracking is based on the concept of *volume flows*. As a simplification, we assume the strip density to be constant during the hot rolling process and therefore at any given time instant the volume flow rate of strip is the same in every position in the installation. The 'volume' of each installation component is given by the local material cross section integrated over the component length. Volume flow rate multiplied by time equates to volume, and this links the motion of the strip to its future position. In the presence of mill components that change the strip width and/or gauge, in our experience, the volume flow approach is the easiest to make sure that all strip samples are properly transversed through the mill.

All changes in the volume flow rate are described by so-called time-speed rules. These time-speed rules are triggered when either the head or tail of the strip reaches a particular location in the mill (or after a specified delay after reaching such a location). We found that the following set of rule types allows for specifying any change in motion state we require:

- Acceleration rule: specifying the desired acceleration rate and either a desired duration, or a speed target (or both, in which case the acceleration is stopped by whatever is reached first)
- Freeze velocity rule: used to stop an acceleration rule when either target is reached
- Reverse rule: used for reversing rougher mill stands
- Delay rule: adds a certain time delay to all interactions between samples and mill components that are ongoing, without actually moving the strip
- Finish rule: stops the calculations

A special role is given to the first rule that is specified: this is the rule that kicks off the calculations and therefore must be of the acceleration-rule type. Every step of the material tracking calculations proceeds by determining which rule will be activated next. To this end, the for every rule that has not been activate yet, the volume flow that needs to occur until the rule would be triggered is calculated. The rule that becomes active next is the one with the smallest required volume flow. Subsequently, all samples of the strip are moved by this volume flow (with their motion state is still being dictated by the *previous* rule). For each sample it is checked which installation components the sample has interactions with during this time interval. These interactions are stored for subsequent use when modelling the physical interactions between the strip and the mill. The material tracking calculation step concludes by activating the next rule and calculating the corresponding new volume flow rate. This process repeats until the 'finish' rule is triggered.

[1] For shorthand notation, we will refer to the material as strip in this paper, unless we specifically intend to refer to a slab.

**Modelling of Physical Interactions**

The strip undergoes various physical interactions and processes during the rolling process. We will address how these are modelled in the coming subsections.

**Oxidation / Oxide layer**

The oxidation of the strip is explicitly taken into account in RoFi. One of the models for the growth of the oxide layer on the strip that can be used in RoFi is the classical paralineair model (e.g. [1]), but also other, internally developed growth models can be used. It is assumed that in the roll bite, the oxide and the underlying steel matrix have the same relative deformation. Every time the strip passes under a high-pressure spray, we assume that the oxide layer is completely removed.

**Stand**

In the roll bite of the stand, the balances of horizontal ($\sigma_x$), vertical ($\sigma_y$), normal ($\sigma_n$) and shear ($\tau$) stress are solved by discretizing the strip in a configurable number of segments in the rolling direction, see Figure 2. For the roll flattening, the Hitchcock formula for the deformed roll radius is used [2]. For the friction in the roll bite, we use Coulomb's law, with a constant friction coefficient for all steel grades, that may differ per stand. The strip temperature, strain, strain rate and (mean) flow stress are assumed to be constant throughout the roll bite. The pressure hill in the roll bite is determined iteratively by balancing the aforementioned stresses. All derived rolling parameters, like the neutral point speed, the rolling force and the rolling power are calculated from the pressure hill.

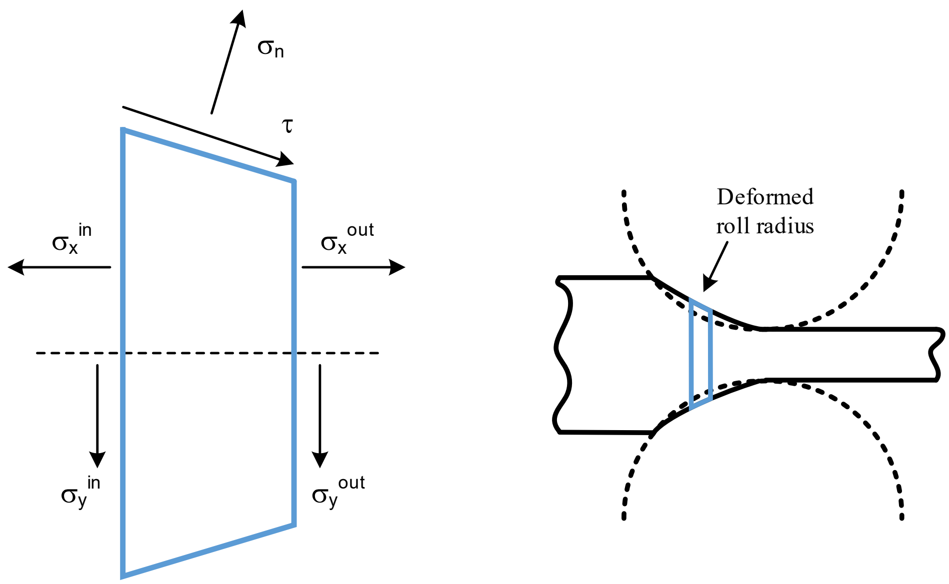


Figure 2: Schematic representation of the stress balance of a segment in the roll bite.

The deformation resistance of the material model is described by the mean flow stress that is calculated using the Misaka model, using an additional correction for non-carbon alloying elements by Kirahata et al. [3] that was retuned in-house. Different coefficients for this correction are used for four different steel grade families that are based on the chemical composition.

In addition to reducing the strip gauge, it is well known that passing strip through a stand also affects the strip width, especially when the width to gauge ratio is still modest. The width spread caused by the stand is modelled using the model that is proposed in literature by Shibahara [4].

**Edger**

Edger rolls are assumed to only influence the shape of the cross-sectional area of the strip; we assume any strip lengthening effects caused by the edgers to be negligible. It is well known from literature that the cross section of the strip after edger rolling represents the shape of a dog bone. This dog bone shape is not explicitly taken into account; instead, the strip is considered to be of a rectangular cross section with a representative gauge that is larger than the centreline gauge. During gauge reduction of a strip with a dog bone shape cross section, additional width spread occurs due to the flattening of the dog bone shape. Shibahara et al. [4] proposed equations for this effect as well and these are also used in RoFi.

To ensure a proper setup of the mill is made, we make predictions of the force, torque and power that are expected at the edger rolls during rolling. We follow the approached proposed by Zhang et al. [5] to find these parameters.

 

### Strip Temperature Calculations

As mentioned before, a finite difference discretization in the through-thickness direction is used to account for the strip temperature evolution throughout the mill. This allows for straightforward, accurate and consistent tracking of both the surface and mean bulk temperature of the strip.

In those regions were the strip predominantly cools due to radiation, we use the standard Stefan–Boltzmann law with an assumed emissivity of 0.83 to calculate heat flux at the strip top and bottom surface. To calculate the cooling effect of high-pressure sprays, the model by Breitenbach et al. [6] is used to calculate the heat transfer coefficient. Cooling of the strip by contact to the work rolls in the stand is modelled by (locally) extending the finite difference discretization scheme with cells that extend into the roll surface. At the cell interface that extend the furthest into the roll, a Dirichlet boundary condition at a temperature that is representative of the roll bulk is assumed.

Heating of the strip in the roll bite is modelled by assuming 100% of the deformation and tensions powers and 50% of the friction power contribute to the strip temperature increase.

### Setup Generation

Being presented with a slab that is dropped from the reheating furnace, the setup generator needs to come up with a suitable reduction pattern to achieve the desired transfer bar properties. In general, there is an infinite number of reduction patterns that can be used to arrive at the desired transfer bar geometry, so additional constraints are required to reduce the dimensionality of the solution space.

We attribute a *priority* to every stand and pass. Stands/passes with a high priority are expected to achieve a high reduction prior to work being offloaded to stands/passes with a lower priority. An example of such a priority pattern is given in the left-hand side of Figure 3.

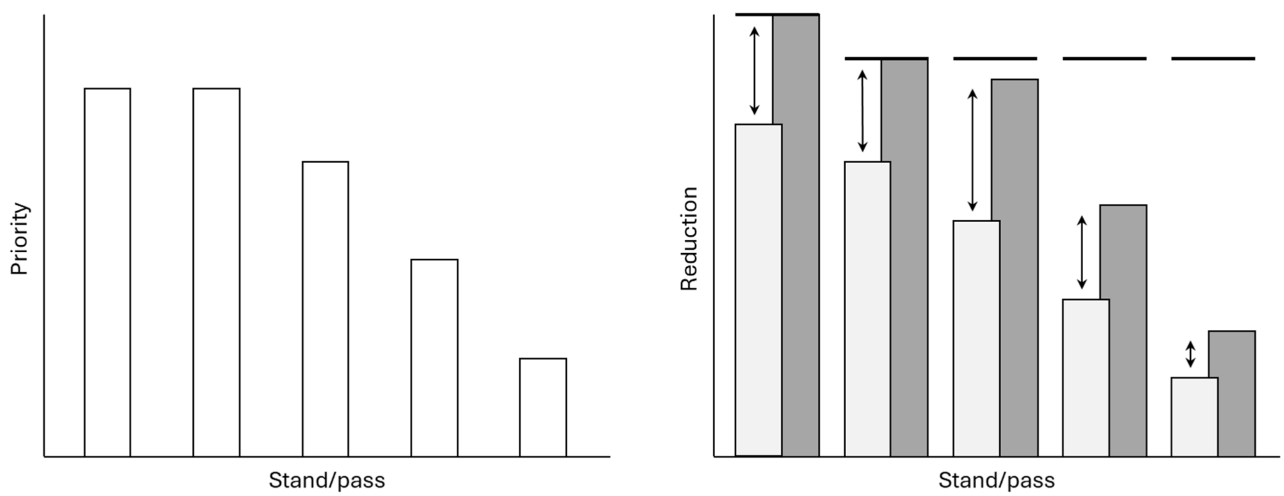


Figure 3: Example of priority pattern (left) and resulting reduction scheme (right). The black horizontal lines on the right indicate the upper reduction limits.

The chosen reduction per stand/pass is given by the priority times the (nominal) upper reduction limit on that stand/pass times a pre-factor, which is found iteratively. On the right-hand side of Figure 3, this iterative procedure is illustrated. When the pre-factor is chosen too low (light grey bars), the corresponding transfer bar gauge or width will be too large (since insufficient total reduction is done). When the pre-factor is increased (dark grey bars), the total reduction increases and thus the transfer bar gauge or width will decrease. Note also that when the reduction on any given stand/pass reaches an upper limit (indicated by the black horizontal lines), the reduction on this stand/pass no longer increases. Automatically, the other stands/passes that are not yet reaching their limits will take over the additional work from limited stands when the pre-factor is increased further.

For every coil, multiple reduction patterns are evaluated by starting the iterative procedure outlined above for different priority patterns. A cost function is used to determine which reduction pattern will be sent to the mill. A combination of multiple rolling parameters, such as processing time, transfer bar temperature and other transfer bar properties can be used in the cost function.

### Model Architecture and Scalability

The basic design principle used at Tata Steel R&D for making Level 2 models is that it should be easy to use and maintain the models for different production lines. One way of achieving this, is by using a core/shell structure. The core of each model is a library that contains all model 'intelligence' (e.g. description of physics, material tracking through the different installation components, logic to selection of setpoints to be sent to the installation, etc.). By itself, the core does not know anything about the installation it is controlling. Such information is supplied to the core by the shell, that is bespoke for every installation the model is used for. The shell also ensures that all other inputs that are required by the core are gathered, and feeds back the output of the core to appropriate system in the mill. This ensures that the same core can be used in multiple production lines, thereby greatly reducing maintenance effort and allowing quick rollout of new features to all users of the model. Another key advantage of the core/shell architecture is that it allows to use the same core for online calculations and for offline simulations, thereby ensuring that both environments stay aligned without additional effort. Such an offline environment, which can be used for model and product development, was not yet available for the previous generation model.

An illustration of the RoFi core/shell partitioning is given in Figure 4. The coloured segments in the middle of the figure together make up the core of RoFi. For every application, be it online or offline, a bespoke shell is made, as is indicated in the outer ring of the Figure.

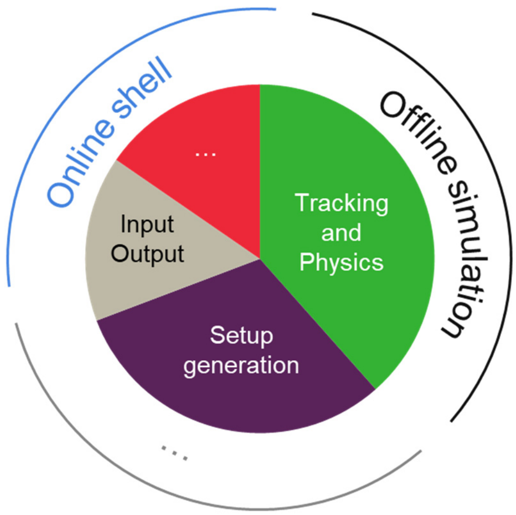


Figure 4: Core/shell architecture of RoFi.

## DISCUSSION

**Improvements Related to More Flexible Rougher Mill Operation**

As mentioned in the introduction, the limited set of pre-determined reduction patterns that are used in the current generation rougher mill setup model impose limits on the maximum coil weight that can be achieved as a function of strip width. Figure 5 shows an example of the improvement that can be achieved by switching to bespoke reduction patterns for every coil in RoFi. It is clear that the sawtooth in the maximum coil weight caused by the current model no longer seen when RoFi setups are used.

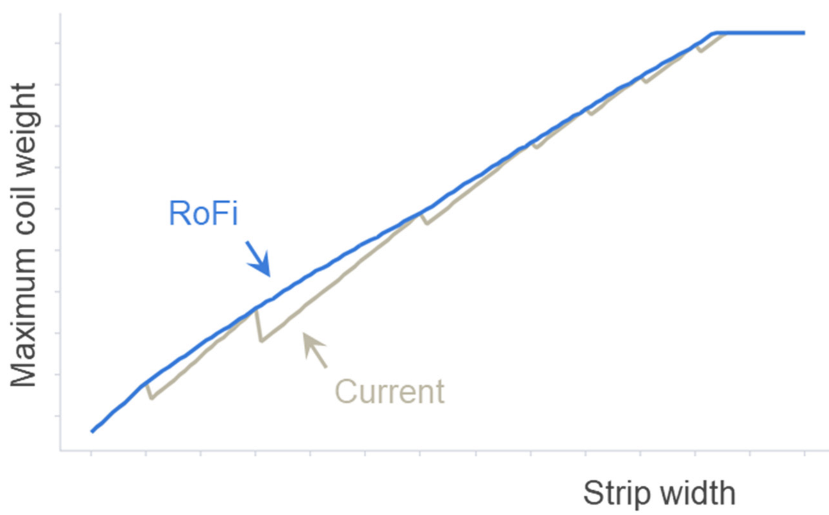


Figure 5: Example of maximum coil weight improvement potential as a function of strip width.

 

**Prediction Accuracy of Rofi Compared to Current Generation Model**
Figure 6 shows a comparison of the accuracy of the power predictions in the rougher mill between RoFi and the current generation model that is in use in HSM2. It is clear that the RoFi predictions are more accurate than the current generation model for most of the steel grade families and stands. The only exceptions (stand 3 for families that are indicated by "Brown" and "Jones" in the figure) occur in those places where the prediction accuracy was already very good in the existing model and still remain below the "nice to have" threshold for RoFi.

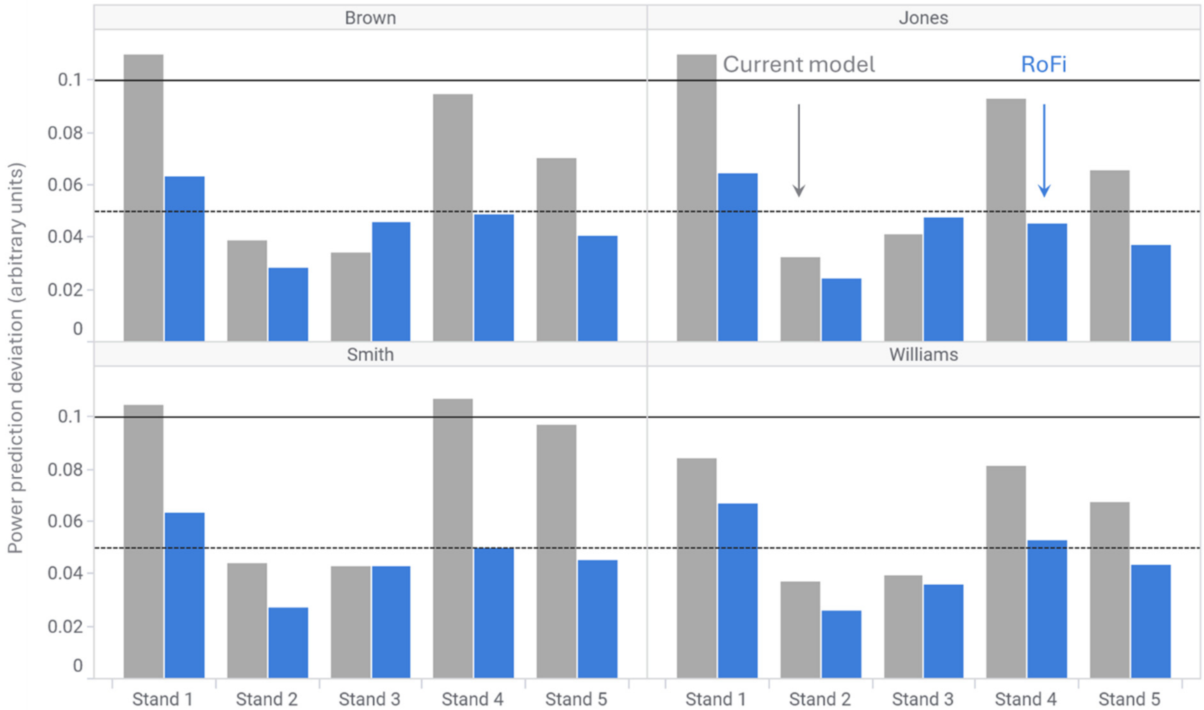


Figure 6: Comparison of power prediction accuracy between current generation model and RoFi. Results are shown for four different steel families that are defined based on the chemical composition, indicated by fictive names shown on top of the subfigures. Lower values are better, with the value of zero corresponding to perfect predictions. The horizontal lines indicate the performance levels that are considered to be necessary (0.1) and nice to have (0.05) respectively.

Figure 7 shows a comparison of the accuracy by which the transfer bar width can be computed between RoFi and the current generation model. The standard error of the RoFi predictions is about 25% lower than that of the current generation model.

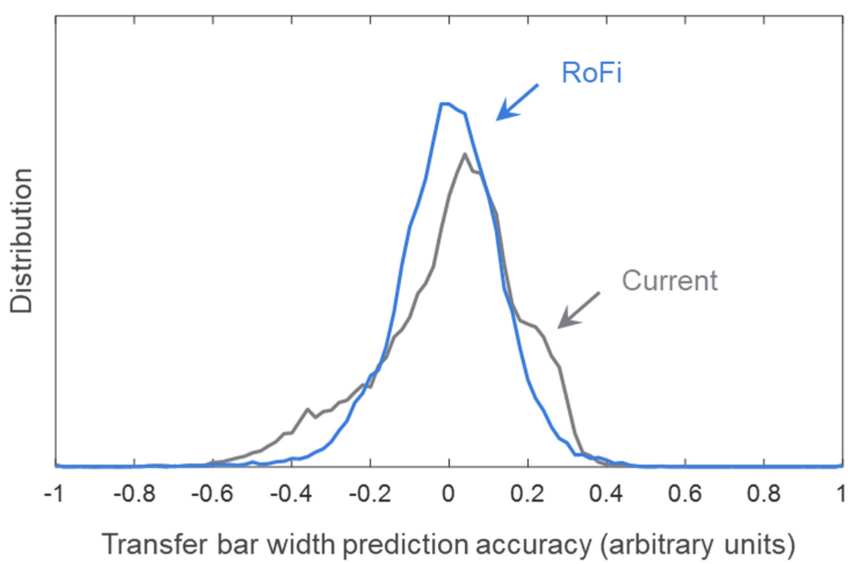


Figure 7: Comparison of the transfer bar width prediction accuracy between RoFi and the current generation model.

## CONCLUSIONS

We have presented a next generation control model for roughing and finishing mills for use in Tata Steel Hot Strip Mills. Compared to the previous generation model, the new model offers better ability to roll novel products in an automated way, by allowing for arbitrary slab and transfer bar gauges without manual intervention. It also allows for increases of maximum coil weight by calculating bespoke reduction patterns for every coil, and offers increased mill productivity by better utilization of mill hardware capability and by allowing for arbitrary stand dummying orders in the finishing mill. It is expected that the model will be commissioned in the IJmuiden HSM2 later this year.

## ACKNOWLEDGEMENTS

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