Optimizing Supply Chain of Plate Rolling Mill Process: A Digital Twin System

Authors

Matheus Henrique Lemes Faria,
Digital Twin Specialist, ENACOM, Belo Horizonte, MG, Brazil
matheus.faria@enacom.com.br

Matheus Botelho Menezes dos Santos, Digital Twin Developer, ENACOM, Belo Horizonte, MG, Brazil
matheus.botelho@enacom.com.br

Felipe Augusto Cardoso Pereira,
Digital Twin Specialist ENACOM, Belo Horizonte, MG, Brazil
felipe.augusto@enacom.com.br

Matheus de Oliveira Mendonça,
Digital Twin Manager, ENACOM, Belo Horizonte, MG, Brazil
matheus.mendonca@enacom.com.br

Gustavo Rodrigues Lacerda Silva,
Chief Technology Officer, ENACOM, Belo Horizonte, MG, Brazil
gustavo.lacerda@enacom.com.br

Douglas Alexandre Gomes Vieira,
Chief Executive Officer ENACOM, Belo Horizonte, MG, Brazil
douglas.vieira@enacom.com.br

Gueider Franz Becker, Production Scheduling Technician, Gerdau, Belo Horizonte, MG, Brazil
gueider.becker@gerdau.com.br

Rafael Franco Moraes, Supply Chain Specialist, Gerdau, Belo Horizonte, MG, Brazil
rafael.moraes@gerdau.com.br

Luciana dos Santos Ribeiro, Supply Chain Specialist, Gerdau, Belo Horizonte, MG, Brazil
luciana.ribeiro@gerdau.com.br

Maurício Martins Pereira, Process Specialist, Gerdau, Belo Horizonte, MG, Brazil
mauricio.pereira@gerdau.com.br

Flávio Viana de Freitas, Metallurgical Engineer Specialist, Gerdau, Belo Horizonte, MG, Brazil
flavio.freitas@gerdau.com.br

Bruno Alvares, Supply Chain Tech Manager, Gerdau, Belo Horizonte, MG, Brazil
bruno.alvares@gerdau.com.br

Bruno da Silva Breder, Tech Manager – Industry 4.0, Gerdau, Belo Horizonte, MG, Brazil
bruno.breder@gerdau.com.br

The rolling mill has a complex scheduling process, with many logistic and operational constraints while attempting to produce plates on the correct due date of the final client. Between these constraints are the availability of the slab to be rolled and the parameters that two subsequent slabs must share or have close values, such as type of steel, temperature, thickness and width. A digital twin system is developed to assemble the next coffins that follow all the operational and logistic restrictions, while attempting to minimize the delay in demands. Coffins created using the digital twin are 12% larger and included 1% more delayed demands on average than manually created ones.

Introduction

The optimization of processes in large-scale industrial plants is fundamental to ensure high levels of productivity and to minimize the occurrence of undesired scenarios.[1] In steel production, computer-assisted optimization has proven to be of great benefit to different steps in the manufacturing of steel products.[2] In particular, the technology of digital twins is widely employed in optimization tasks in several industries,[3] and the benefits of its usage in steel production are well documented, leading to increases in productivity and a higher level of predictability in the supply chain.[4]

Rolling mills are used to refine certain products into more usable forms.[5] They receive products manufactured by casting machines and apply rolling cylinders and cutting devices to reshape and split them.[6] The necessity to optimize operation scheduling in a rolling mill arises naturally from the desire to maximize production, minimize wearing of machine parts and avoid delays in product deliveries. This article presents a solution to the scheduling problem of the Gerdau rolling mill in Ouro Branco.[7]

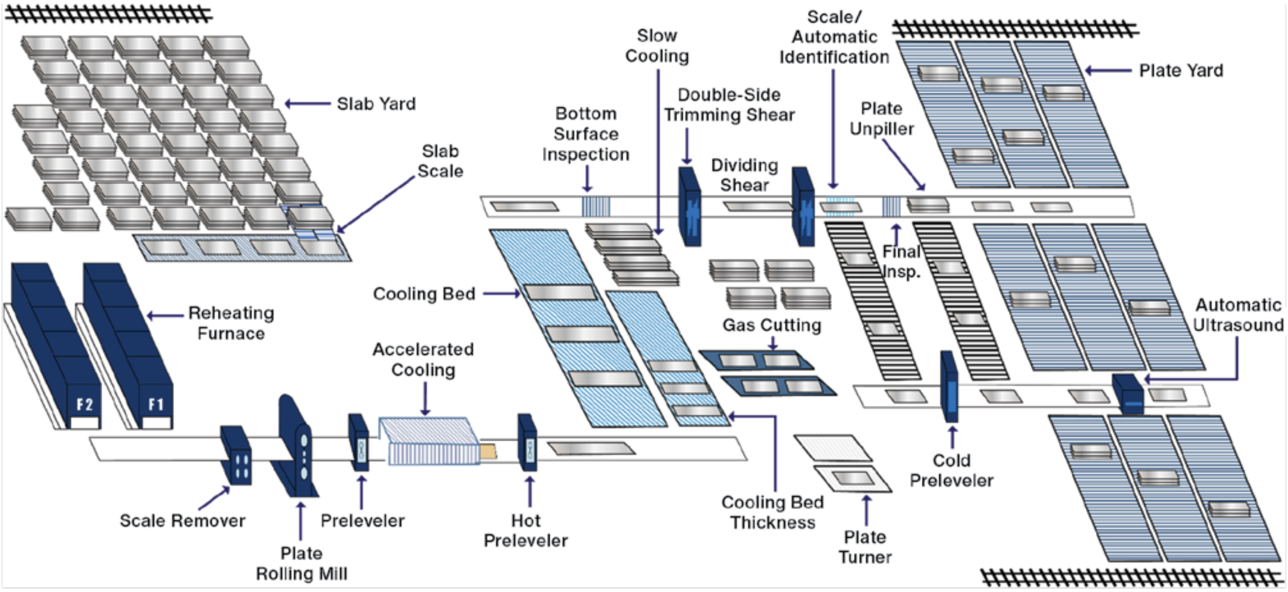
The rolling mill on which this work is based receives steel slabs as its raw material and produces steel plates as the final product. Its process starts with the reheating of input slabs, which are then rolled into the desired thickness by rolling cylinders, becoming steel roughs. The roughs then undergo cooling and leveling before being cut into a series of plates and moved to a storage yard for later distribution after its careful inspection. Fig. 1 contains a high-level schematic of the rolling mill as described.

The working roll cylinders in the rolling machine sustain wear after every operation, which means they must be replaced constantly after processing a certain set of slabs. A list of scheduled slabs to be rolled consecutively with the same working cylinders is called a coffin.[6] The mill, therefore, operates one entire coffin at a time before undergoing a cylinder change for the next coffin.

The scheduling algorithm employs heuristic methods to design the coffin, combined with digital twin technology. The main benefit of using a digital twin is that it executes a moment-to-moment simulation of the rolling mill based on the current data, providing useful information for every step of the process, including data on storage occupation, resource availability and key performance indicators (KPIs), to assist in the task of decision-making by the operational and supply chain departments.[4]

Figure 1

Rolling mill schematic.



Discussion

Problem Definition

The rolling mill scheduling problem revolves around the construction of coffins by determining the demands that will be included in the coffin, and in which order the slabs must be rolled. The process must take into account both logistical constraints, such as the demand due dates and the availability of the slabs, and physical and technical constraints, such as temperature, width and thickness differences between subsequent demands, steel quality, and coffin stage.

In the sequence, a high-level description of the scheduling problem solved by the algorithm is presented. It starts with a description of the problem's input and output, followed by the objective function and restrictions.

Input and Output: The problem's input, in simple terms, is a list of pending steel rolling demands and parameters related to operational restrictions. It includes information such as:

- Rolling demands: Either already associated with a slab in the storage yard, or requiring a slab that has yet to be cast by the steel mill.
- Current storage yard status: Listing slabs and plates in the plant's yards.
- List of planned unavailability of the rolling mill: Periods in which the mill will stay idle for maintenance or routine checkups.
- Tolerance of the rolling parameters difference between subsequent slabs.

Given the input information, the algorithm selects demands to be processed, schedules the rolling of the demands into a timeline, and provides a step-by-step simulation with the digital twin.

The output of the algorithm contains the scheduled demands separated into coffins, as described in the introduction. Several rules and restrictions apply to the construction of proper coffins, which will be detailed better in this article.

The output of the algorithm contains:

- A list of coffins ordered by starting time: Every coffin contains a list of demands, also ordered by starting time.
- Unallocated demands, including:
  - Rejected demands: Valid demands that were not allocated in any coffin.
  - Invalid demands: Demands with some pending parameters to be manually evaluated by the user.
- Simulation data, including:
  - Start and end time of every demand's processing.
  - List of constraints broken by solution.
  - Amount of steel rolled per day.
  - Data on delayed demands.
  - Status of each sale order.
  - Occupation in the plate yard and in the intermediate buffers.

Hard Restrictions: The hard restrictions for the scheduling problem pertain to coffin construction and time allocation. Coffin construction is the focus of the algorithm.

- Coffin stages:
  - The demands that compose a coffin can be partitioned into stages. For a slab to be eligible for a stage, it must be inside the allowed parameter intervals for the stage, which include:
    - Minimum and maximum width and thickness.
    - Allowed resistance classes.
  - Furthermore, stages in a coffin must also verify other restrictions, including the following:
    - Every stage is associated with a list of possible next stages, listing the stages that can follow it. The last slab in each stage must necessarily be followed by a slab from a stage in the list.
    - Stages have a maximum and minimum number of slabs they must contain.
    - There exists a maximum negative and maximum positive width delta parameter for every stage, determining how much the width between two consecutive elements in a stage may vary.
  - Coffins must always start in a special stage called the opening stage. The parameters for that stage determine the kinds of demands a new set of working roll cylinders must start with.
  - Fig. 2 contains an example of a coffin partitioned into stages.
- Unfurnacing temperature: Every demand has a parameter that determines to what temperature their corresponding slab must be reheated before rolling, called the unfurnacing temperature. The unfurnacing temperature of two subsequent slabs must be smaller than a threshold. Also, the temperature must follow a unimodal profile in the coffin (increasing first and then decreasing), with a tolerance for small fluctuations (i.e., a decrease of 5°C would not end the increase phase if the tolerance is 10).
- Hard parameter grouping: For some demand parameters, there is a number n such that demands with the same value on the parameter must be placed in consecutive groups of at least n slabs within a coffin. Examples include:
  - Steel family: steel types with similar rolling routines.
  - Rolling strategy: defines whether the slab uses normal or controlled rolling.

Soft Restrictions: Soft restrictions are not necessary for a solution to be considered acceptable, but are desirable to make solutions that are better aligned with the attendance of the final client and promote a better functioning of the rolling mill and its plant (other equipment and processes included).

- Avoiding short coffins: A coffin whose number of slabs is below a given minimum value is considered short. Short coffins are undesirable, as they

Figure 2

Example of a coffin. Every vertical bar is an individual slab, and colors indicate coffin stages.

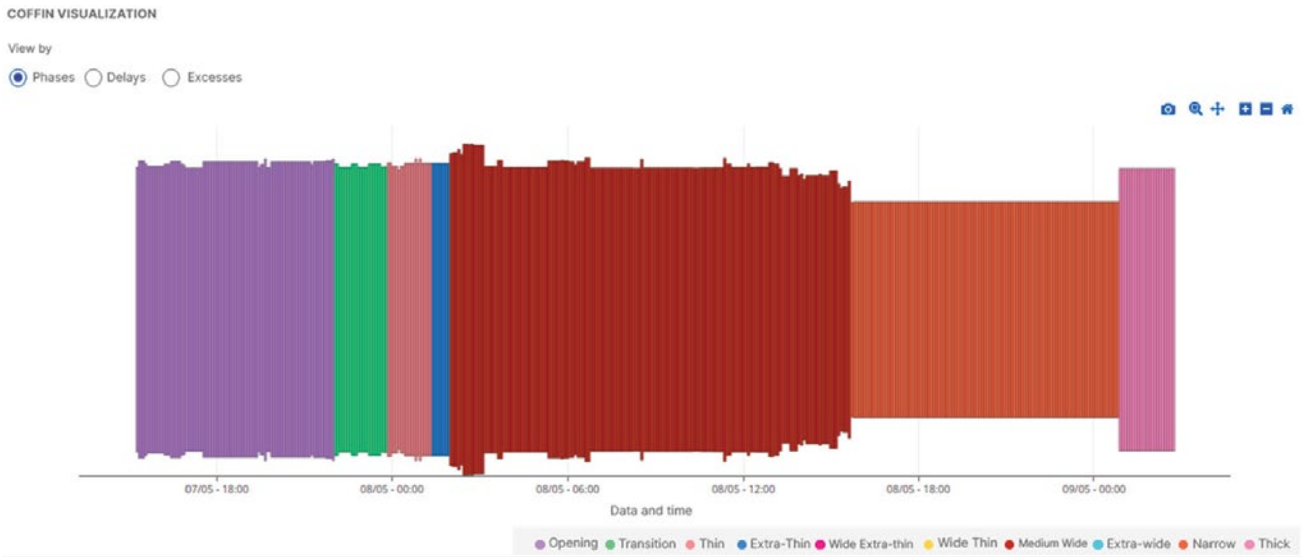
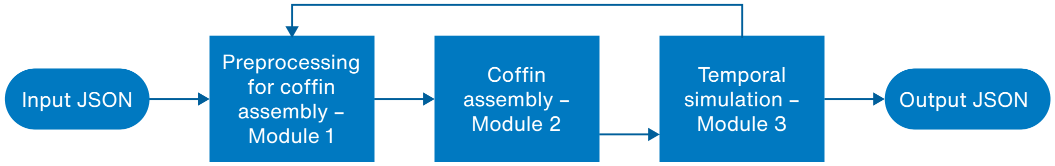


Figure 3

High-level algorithm flowchart.



incur more cylinder changes for smaller amounts of processed slabs.

- Soft parameter grouping: Some less critical parameters such as rolling way and slab width should be grouped when possible but can be made separated in case of conflict with some more important parameter.

Temporal Simulation Restrictions: Besides the restrictions on the coffin assembly, the digital twin temporal simulation of the system also must follow a set of hard restrictions, independent of the coffin assembly procedure:

- Demand processing times: The processing time of a given demand depends on several factors, including its width, the number of times it must be rolled before it is in the desired thickness, which cutting process it must undergo, and the transit times between different machines in its processing route.
- Unavailability of machines: During certain time intervals, machines within the mill may be unavailable, due to maintenance or routine check-ups. During these intervals, demands that depend on the machine cannot be processed.
- Working roll cylinder change time: Between the end of one coffin and the beginning of the next, there must be an idle period for the change of roll cylinders in the rolling machine.

Main Algorithm

The main components of the algorithm, as shown in Fig. 3, are the preprocessing routine, the coffin construction and the temporal simulation. The last step characterizes the system as a digital twin, providing detailed information for the decision-making process by simulating the processing of the scenario and calculating valuable metrics over the solution.

Preprocessing: The preprocessing receives the input data and set the scenario configuration from it, such as start date, maintenances, stage configurations and tolerances. It also preprocesses the demands, removing demands with missing information or with slabs unavailable during the coffin construction.

After the first loop, the preprocessing updates the available demands and slabs considering the last iteration coffin assembly time, adding the slabs that arrive at the yard while the coffin was being assembled.

Coffin Construction: The construction of coffins uses graph theory heuristics to build large coffins in a reasonable amount of time. It starts by grouping available demands into sets called clusters. Clusters are sets of demands that have similar or equal values in certain parameters, including:

- Unfurnacing temperature.
- Earliest possible stage.
- Rough's width.
- MULPIC strategy.
- Thickness.

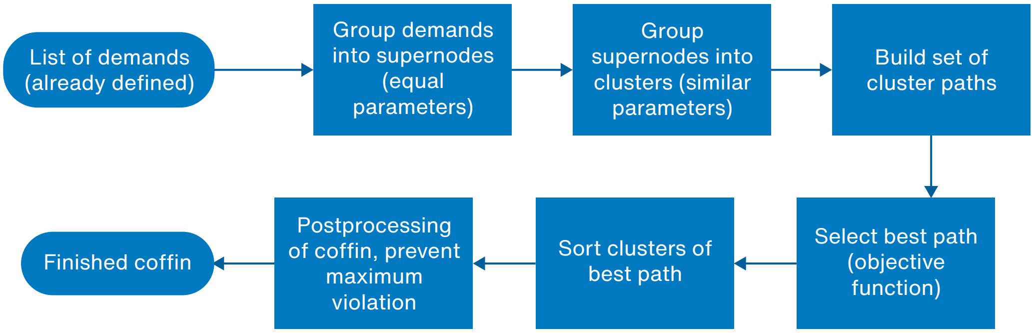
The algorithm uses a simple recursive method to search for the best directed path of clusters. A path is an ordered sequence of clusters that respects the following rules for gradual path composition, starting with an empty path:

- If the current path is empty, select a cluster that is eligible for the opening stage and add it to the path. Set that cluster's stage to opening.
- If the current path is not empty, let C be its last cluster, and S the stage of C, i.e., the current stage that a coffin made using this path would be. Another cluster that does not belong to the path can be inserted at the end of the path after C only if:
    - The addition of the slabs in the new cluster after C in the coffin will not violate any hard restriction.
    - The possible stages for the new cluster include at least one stage that can follow stage S (including S if the maximum size was not violated).
- If there is no possible cluster to be added, the path is completed.

The best path is chosen using an objective function that is composed of a priority list of several elements, including:

Figure 4

High-level coffin construction flowchart.



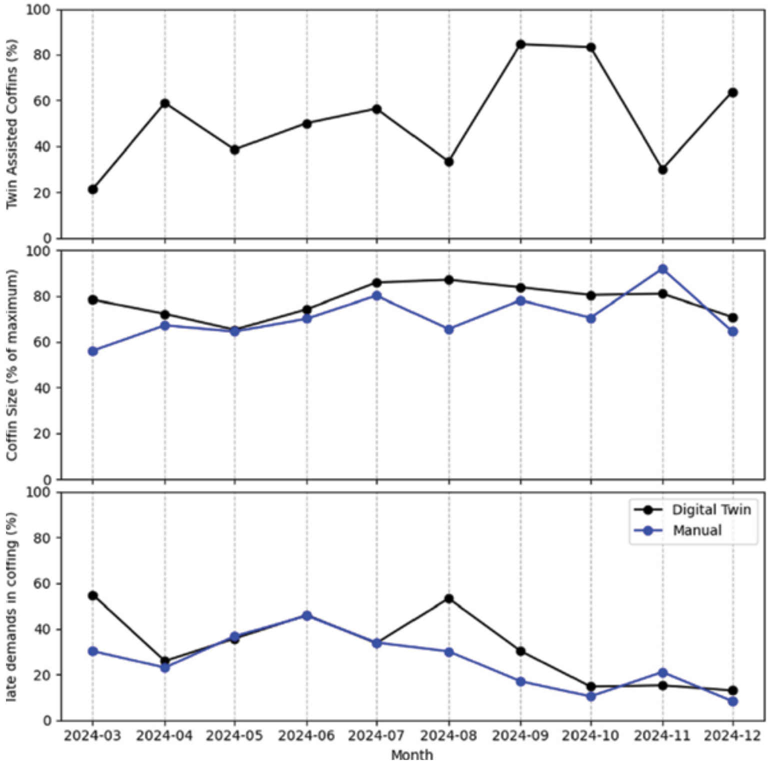
- Number of remaining unallocated late demands (i.e., late demands that are not in any coffin, nor within the clusters of the current path).
- Number of unallocated timely demands (a demand is timely if its due date is close to the current time).
- Difference between sum of cluster sizes and desired slab amount in a coffin.

Once the recursive method returns the best path found, its clusters are reordered according to a priority list of stages. After that, a new coffin is constructed. The construction of the coffin starts by adding every demand from every cluster into a new, initially empty coffin, in the order given by the path.

Afterwards, a postprocessing routine adjusts the coffin to ensure no hard restrictions are broken. The most important step in the postprocessing is removing demands from the coffin if their selected stage already exceeds the maximum amount determined for the stage.

Figure 5

Evolution of digital twin usage and performance parameters.



Temporal Simulation: With the coffin assembled, the digital twin simulates the whole rolling mill operation, from the moment that each slab leaves the reheating furnace to the moment the plate leaves the yard. The simulation considers the time spent in each machine (and waiting for the machine if it is unavailable) for each demand, respecting the restrictions listed earlier, and, with that, the duration of the process of assembling the coffin.

After the temporal simulation, the process may start again, as the preprocessing stage can update the available demands by adding the ones that became available while the coffin was being assembled.

Experimental Results

The software is currently being used by the supply chain team in the routine to define the next coffins to be produced. The current section shows an analysis considering a comparison between coffins that were constructed with the aid of the digital twin, and coffins constructed manually (using the "as is" strategy, before the system implementation). The use of the digital twin usually consists of a first run of the optimization code and then subsequent runs with manual changes to adjust the day-to-day operation detail.

These adjustments are then simulated in the digital twin; the adjusted coffins are not bound by the hard restrictions of the digital twin optimization algorithm and thus can have many broken restrictions, which are considered acceptable or not by the supply chain team.

Fig. 5 shows the digital twin usage data from March 2024 to December 2024, with a little more than 50% of the coffins being made with the digital twin aid during the whole period. The average amount of slabs in coffins generated with the digital twin are larger than the ones constructed manually for almost all months. On average, a digital twin–aided coffin had 12% more slabs than one made manually, which allows better cylinder usage and less operational time taken to swap the cylinders, allowing the rolling machine to work more time.

Another important data is the fraction of late demands in the coffin. As the optimization minimizes the number of delayed demands not included in the coffin, those constructed with aid of the digital twin tends to have, on average, a slightly larger fraction (about 1% more) of late demands in it.

System's Capabilities

The optimization result screen focuses on providing useful information about the solution to the optimization problem, including detailed data on the simulated execution of the scenario.

Fig. 2 contains a screenshot of one of the optimization result screens provided by the digital twin system. It includes a timeline with the slabs of each coffin. Fig. 6 shows another screenshot, illustrating the evolution of the unfurnacing temperature, width and thickness of demands in a coffin. On the topic of KPIs, Fig. 7 shows one of the main ones. It informs the expected tons of delay for each day of the scenario, as well as details of where this delay is happening.

Other screens exist with more information but were omitted for brevity.

Integration of Existing Systems: The Gerdau steel plant from the city of Ouro Branco uses several different systems to keep track of the plates in its yard, steel works outputs and rolling mill demands, which often work independently from one another. Fig. 8 shows a tab from the software with the integration of the systems that send data to the digital twin.

Before the implementation of the current digital twin system, the interface between those systems was limited, which led to some disruptions in the supply chain, such as overproduction of certain demands, and surplus plates being left idle in the distribution yards without ever being allocated into a sale item. Thanks to the system's better integration, 25 excess pieces weren't produced in the interval of 3 months.

Conclusions

The digital twin system, and the solution algorithm implemented within it, enable better decision-making on the part of the rolling mill production planners. The coffin construction algorithm can check a plethora of different restrictions while providing large coffins and

Figure 6

Evolution of thickness, width and temperature along a coffin.

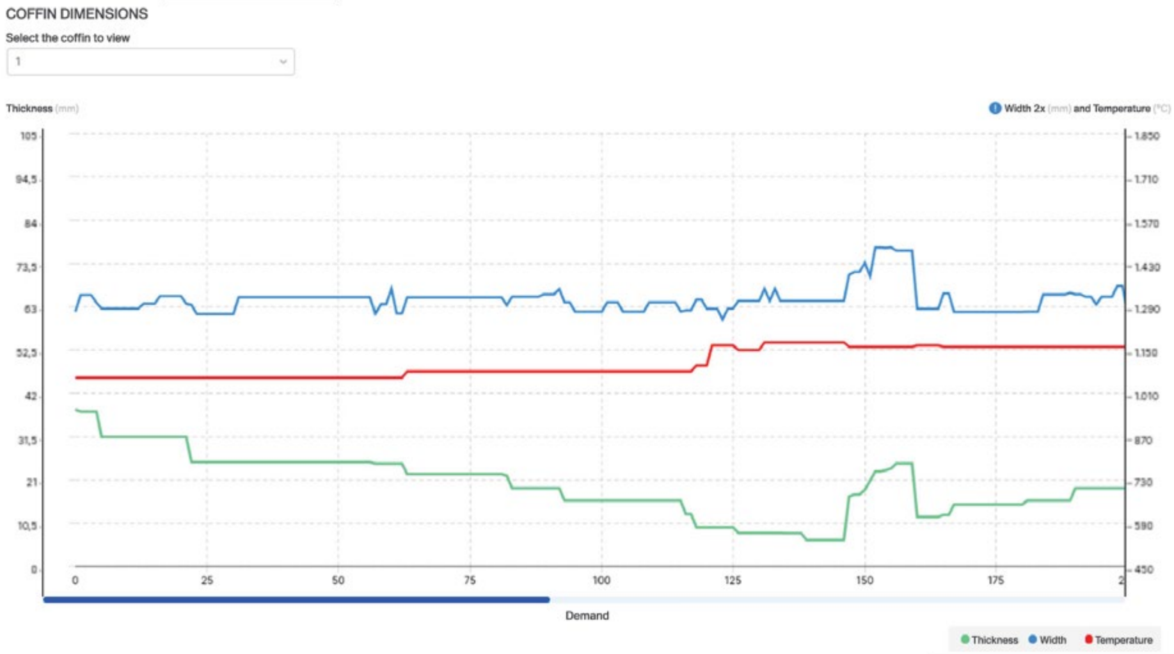
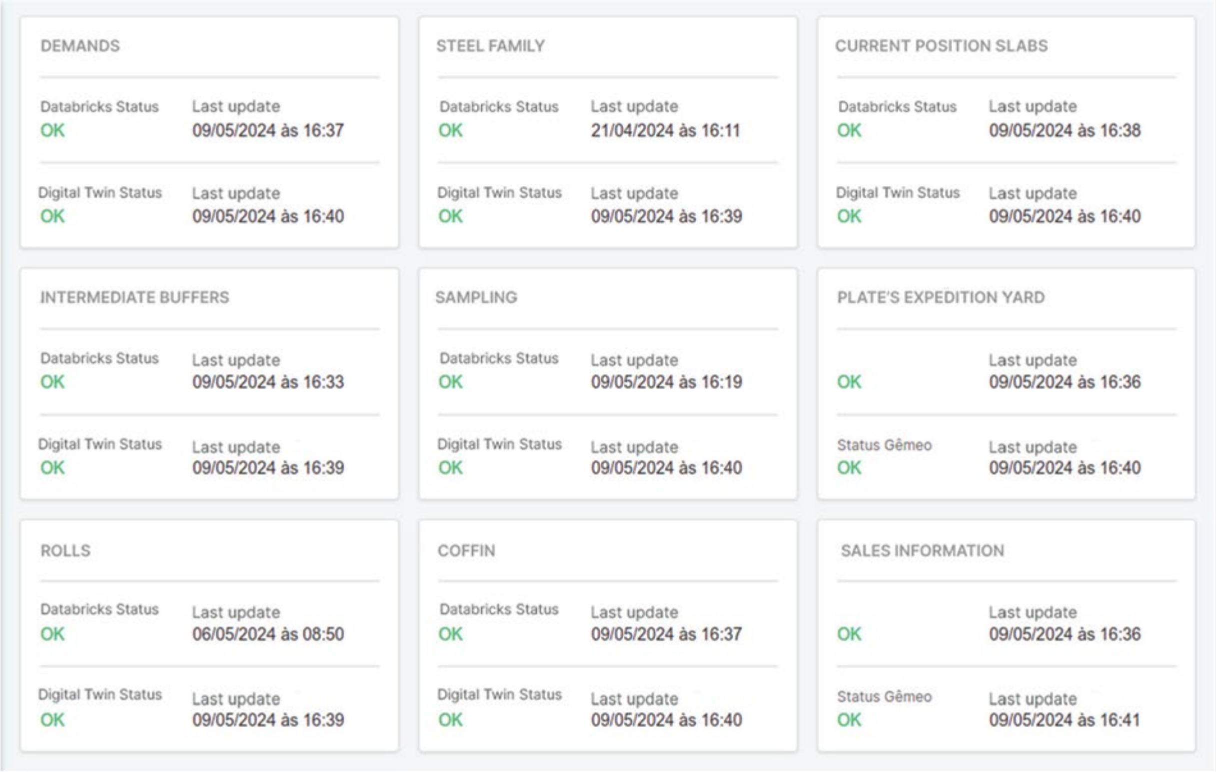


Figure 7

Evolution of delay behavior in a scenario.

Figure 8

System integration screen.



DEMANDS

Databricks Status OK — Last update 09/05/2024 às 16:37

Digital Twin Status OK — Last update 09/05/2024 às 16:40

STEEL FAMILY

Databricks Status OK — Last update 21/04/2024 às 16:11

Digital Twin Status OK — Last update 09/05/2024 às 16:39

CURRENT POSITION SLABS

Databricks Status OK — Last update 09/05/2024 às 16:38

Digital Twin Status OK — Last update 09/05/2024 às 16:40

INTERMEDIATE BUFFERS

Databricks Status OK — Last update 09/05/2024 às 16:33

Digital Twin Status OK — Last update 09/05/2024 às 16:39

SAMPLING

Databricks Status OK — Last update 09/05/2024 às 16:19

Digital Twin Status OK — Last update 09/05/2024 às 16:40

PLATE'S EXPEDITION YARD

OK — Last update 09/05/2024 às 16:36

Status Gêmeo OK — Last update 09/05/2024 às 16:40

ROLLS

Databricks Status OK — Last update 06/05/2024 às 08:50

Digital Twin Status OK — Last update 09/05/2024 às 16:39

COFFIN

Databricks Status OK — Last update 09/05/2024 às 16:37

Digital Twin Status OK — Last update 09/05/2024 às 16:40

SALES INFORMATION

OK — Last update 09/05/2024 às 16:36

Status Gêmeo OK — Last update 09/05/2024 às 16:41

aiming to minimize delivery delays to the final client, empowering better productivity and keeping the supply chain functional.

Furthermore, the digital twin provides the user with a full report of its simulated execution, including a timeline of processed demands and several performance indicators, allowing an analysis of multiple production scenarios to aid in the decision-making process.

The information provided by the system is also currently used to avoid overfilling of storage yards, and overproduction of plates when not necessary, resulting in an improvement in space, time and resource efficiency.

Future works include the implementation of new restrictions and objectives, such as aiming for hot furnacing; as well as applying digital twin technologies and optimization algorithms to other rolling mills, considering the particularities of each one; and allowing a thorough integration of the system with other digital twin systems in the same plant, e.g., communication between this system and a previously implemented steel mill digital twin.[8]

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