



## Digital Twin for Bell-Less Top Charging: Accelerating Blast Furnace Start-up and Stability

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### Abstract

Blast furnaces are central to pig iron production, where efficient operation directly impacts productivity, hot metal quality, and overall cost-effectiveness. A key factor in this performance is the charging system, which significantly influences furnace stability. This paper presents the development of a Digital twin for a new bell-less top charging system. The solution integrates the Rockwell process control system with the Siemens SIMIT simulation platform and Primetals Level 2 and Expert system. This Digital twin was used for testing, training, and scenario evaluation, contributing to a rapid and stable blast furnace start-up following relining.

Digital twin

Bell-less top charging system

Siemens SIMIT

Rockwell supervision and control system

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ARCHIVAL RECORD

# Digital Twin for Bell-Less Top Charging: Accelerating Blast Furnace Start-up and Stability

Mr. Ronaldo Schittini Gardoni Junior<sup>§\*</sup> and Pedro Sampaio Cotta<sup>§</sup>

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## Abstract

Blast furnaces are central to pig iron production, where efficient operation directly impacts productivity, hot metal quality, and overall cost-effectiveness. A key factor in this performance is the charging system, which significantly influences furnace stability. This paper presents the development of a Digital twin for a new bell-less top charging system. The solution integrates the Rockwell process control system with the Siemens SIMIT simulation platform and Primetals Level 2 and Expert system. This Digital twin was used for testing, training, and scenario evaluation, contributing to a rapid and stable blast furnace start-up following relining.

**Keywords:** *Digital twin, Bell-less top charging system, Siemens SIMIT, Rockwell supervision and control system*

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## 1. Introduction

Digital twins are among the key technologies in the industry 4.0 landscape, offering significant benefits by merging the physical and digital worlds to address industrial challenges, as described by Amthiou et al. [1]. Before the advent of Digital twins, understanding the behavior of physical systems relied solely on physical testing. Today, Digital twins are used not only for system representation but also for optimization, as explained by Bettinger et al. [2], with a strong impact on productivity and cost reduction.

According to McKinsey [3], a Digital twin is a virtual replica of a physical object, person, or process that can be used to simulate its behavior to better understand how it works in real life. Digital twins are linked to real data sources from the environment, which means that the twin updates in real time to reflect the original version.

The Siemens simulation platform (SIMIT) enables extensive possibilities for developing and optimizing Digital twins, as it specializes in industrial simulation and virtualization. It allows engineers to create detailed digital models of equipment, incorporating physical properties, geometry, and operational parameters, as explained by Siemens [4].

As part of the relining process, the blast furnace was equipped with a bell-less top charging system, a system designed to distribute the ferrous burden and coke into the blast furnace, detailed by Geerdes et al. [5]. A comprehensive automation package was implemented to ensure a smooth start-up and optimal utilization of the new equipment. This package is anchored by a Basic Automation (Level 1) process control system, which works in close coordination with a Process Automation (Level 2) process optimization system. This optimization technology for the blast furnace process employs a closed-loop expert system, sophisticated process models, and artificial intelligence, all supported by an

extensive knowledge base developed in collaboration with industry leaders, as mentioned by Primetals [6].

In this context, a Digital twin was developed to serve as a training and testing environment for operators and process specialists. A virtualized simulation platform was created to test application software and visualize results before deployment in production. By simulating process values, setpoints, actual values, position feedback, and speed feedback, the behavior of the plant and equipment could be replicated, enabling validation of control logic and system response. Equipment malfunctions could also be manually simulated to assess the automation system's reaction. Additionally, the system proved effective for training operators and process engineers, allowing practice without risk or disruption to the actual plant.

Figure 1 illustrates the core concept proposed for the project. The Level 2 process optimization and specialist system calculates and sends setpoints to the Level 1 process control system. Level 1 then decomposes these targets into specific setpoints for individual equipment. These values are transmitted to Siemens SIMIT, where the simulation is executed. As a result, simulated feedback and actual field values are returned from SIMIT to Level 1, which in turn provides feedback to Level 2, thus closing the control and simulation loop.

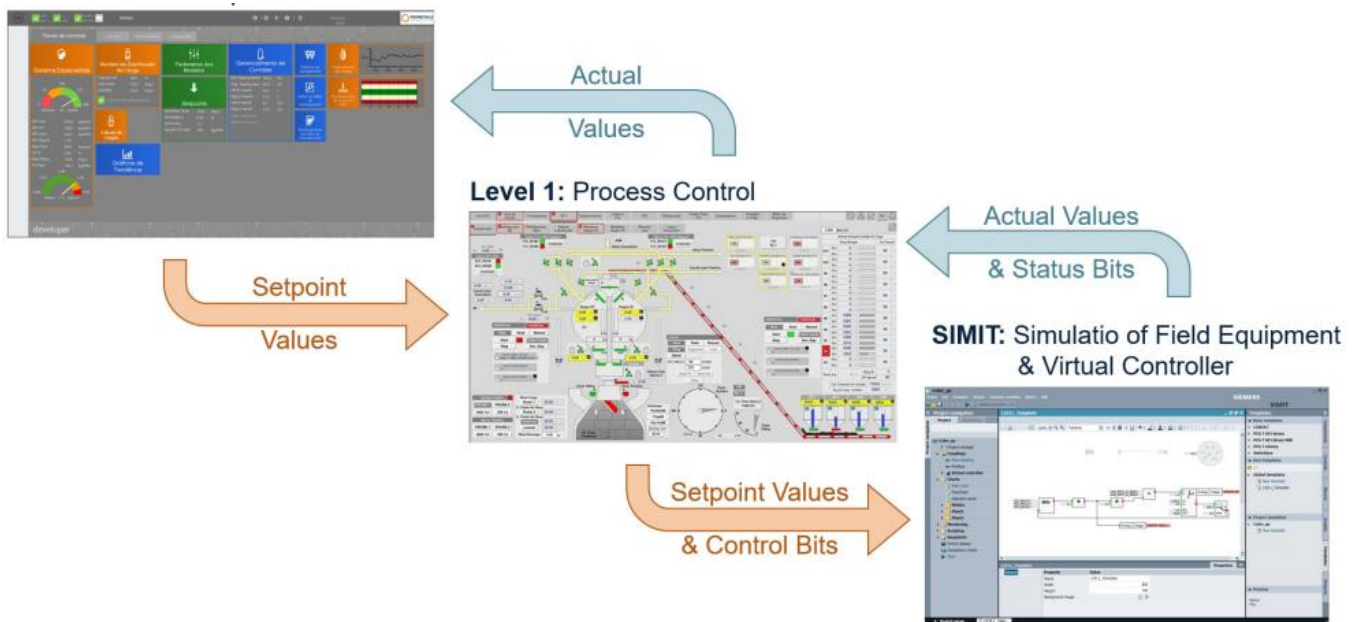


Figure 1. Basic flow of information between systems

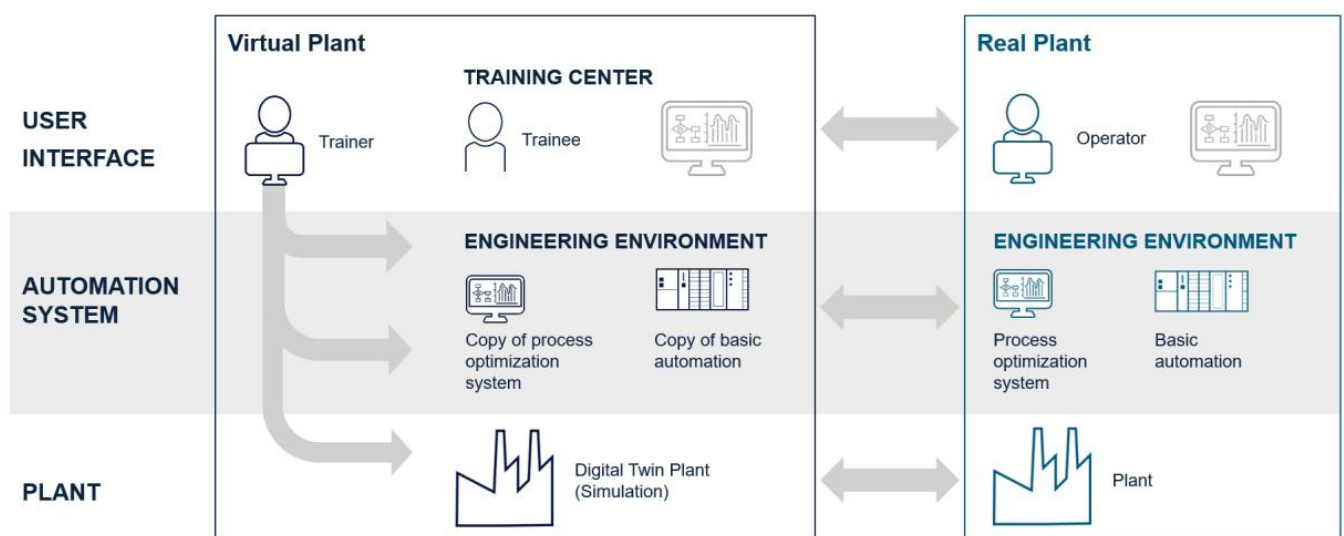


Figure 2. Digital twin structure

The structure of the Digital twin for test and training center is illustrated in Figure 2.

The functionalities of the Digital twin can be summarized as follows:

- The test and training system prepares operators for blast furnace operation through simulated scenarios;
- It provides hands-on training, simulates start-ups, emergency shutdowns, and abnormal situations;
- Operators become familiar with the new bell-less top and practice decision-making under different conditions.

## 2. Development

The Digital twin concept involves the creation of a virtual environment in which operators can simulate material charging using

different batch types and test the functionalities programmed into the process control and optimization systems. To implement this concept, the development within SIMIT focused on simulating device signals, equipment responses, and overall process behavior.

### 2.1. Devices signals simulation, equipment response and process simulation

The signal simulation covers the behavior of instruments and actuators and includes Field Level (Level 0) of the plant by simulating field devices and sensors in accordance with their expected operation. The following simulation strategies were employed:

- Digital movement supervised by digital feedback was simulated through a time-delayed generation of the expected feedback signal (e.g., flaps, locks, latches, lifts);

- Digital movement supervised by analog feedback was simulated using an integrative function block that generates increasing or decreasing feedback. In cases involving counter feedback, the signal was converted accordingly (e.g., pumps);
- Analog movement supervised by digital feedback was simulated by integrating the movement and comparing the resulting value with predefined limit values (e.g., tanks);
- Analog movement supervised by analog feedback was simulated using an integrative function block that generates increasing or decreasing feedback. The slope of the integration was determined by the analog setpoint value.

Process simulation was used to model material transport throughout the plant. The material position was generated based on the simulated actual speed, which served as input to an integrative function block.

Based on the material position, tracking sensors such as detectors and light barriers were simulated. In the case of pyrometers, a fixed temperature value was simulated while the material was present.

## 2.2. Configuration overview

Communication between the ControlLogix Process Programmable Logic Controller (PLC) and the SIMIT was established using the SIMIT External Ethernet/IP Coupling Add-on. This interface module facilitates the exchange of setpoints and actual values between the automation system and the simulation environment in SIMIT as illustrated in Figure 3.

In this configuration, the Digital twin virtual machine is hosted within the same virtualization cluster as the Level 1 and Level 2 servers and communicates through a dedicated Virtual Local Area Network (VLAN) with the Rockwell PLCs, operator stations, and

engineering stations. Figure 4 illustrates a simplified view of the network architecture and its main components.

## 2.3. Level 1 automation

The Level 1 Process Control System for the Digital twin was composed of the following equipment:

- Level 1 operator station with dual screen;
- Level 1 server in a non-redundant configuration;
- PLC for the stockhouse (material handling), and a separate non-redundant safety PLC;
- PLC for the bell-less top (top Charging), and a separate non-redundant safety PLC.

There is no difference between the Level 1 software used in the production system (online system) and the Level 1 software used in the simulation system (offline system).

### 2.3.1. Stockhouse

The Digital twin solution within the Level 1 process control system for the stockhouse included the following process areas:

- Material bins for minerals;
- Material bins for coke;
- Material discharge and tracking to Intermediate bins (BC1, BC2, TM1, TM2);
- Intermediate bins weighing (BC1, BC2, TM1, TM2);
- Material transport and tracking to top charging system (bell-less top BLT).

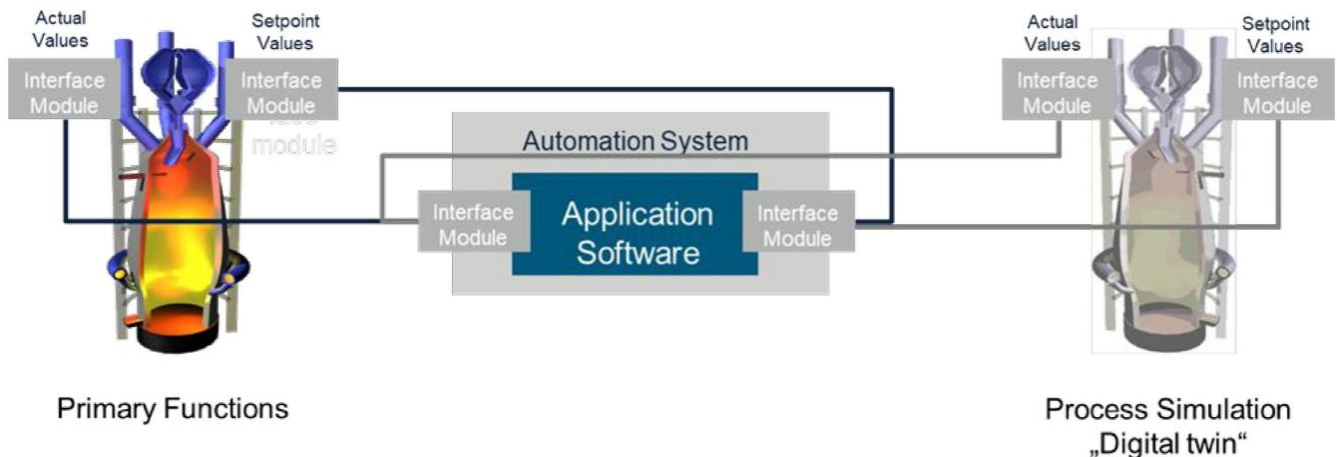


Figure 3. Configuration overview

### 2.3.2. Bell-less top

The Digital twin solution within the Level 1 process control system for the bell-less top includes the following process areas:

- Tilting chute and tilting rocker;
- Lock hopper systems 1 and 2 including material flaps and seal valves;
- Equalizing system (pressurizing/depressurizing sequence);
- Material flow gate;
- Chute rotation and tilting mechanisms;
- Nitrogen-cooled gearbox;
- Water cooling system;
- Hydraulic and Greasing system;
- Burden level measurements (stock rods) for actual stockline.

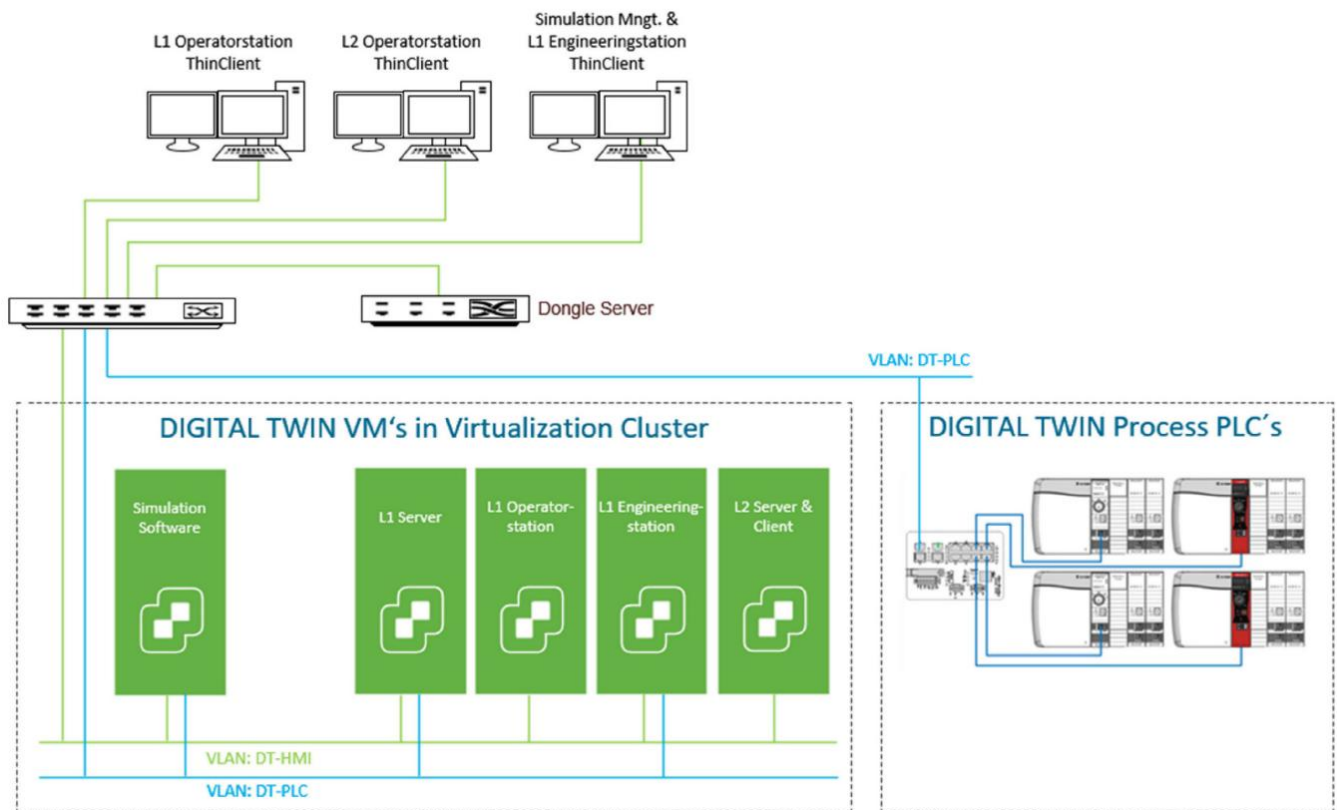


Figure 4. Network basic layout

## 2.4. Level 2 process models

The following process models were included in the Digital twin plant simulator solution:

### 2.4.1. Burden control model

The Burden Control model is typically used by operators and process engineers in the control room to calculate new setpoints for the charging system, as illustrated in Figure 5.

### 2.4.2. Burden distribution model

The Burden distribution model is used to simulate material distribution in the upper part of the blast furnace, based on charging conditions and burden parameters.

### 2.4.3. Shaft simulation model

The shaft simulation model is a background model used to automatically perform a mass balance of all materials charged within a single charge, including both coke and ore layers, as illustrated in Figure 6.

## 2.5. Communication coupling to Level 1 and Level 2

Communication between the ControlLogix Process PLCs and the SIMIT simulation platform is based on the industrial standard OPC UA, using the Kepware OPC Connectivity Suite. A tag list containing all functional field I/O's (e.g., digital inputs/outputs as well as analog inputs/ outputs) was exported from Rockwell Automation Studio 5000 and transferred to the SIMIT simulation platform.

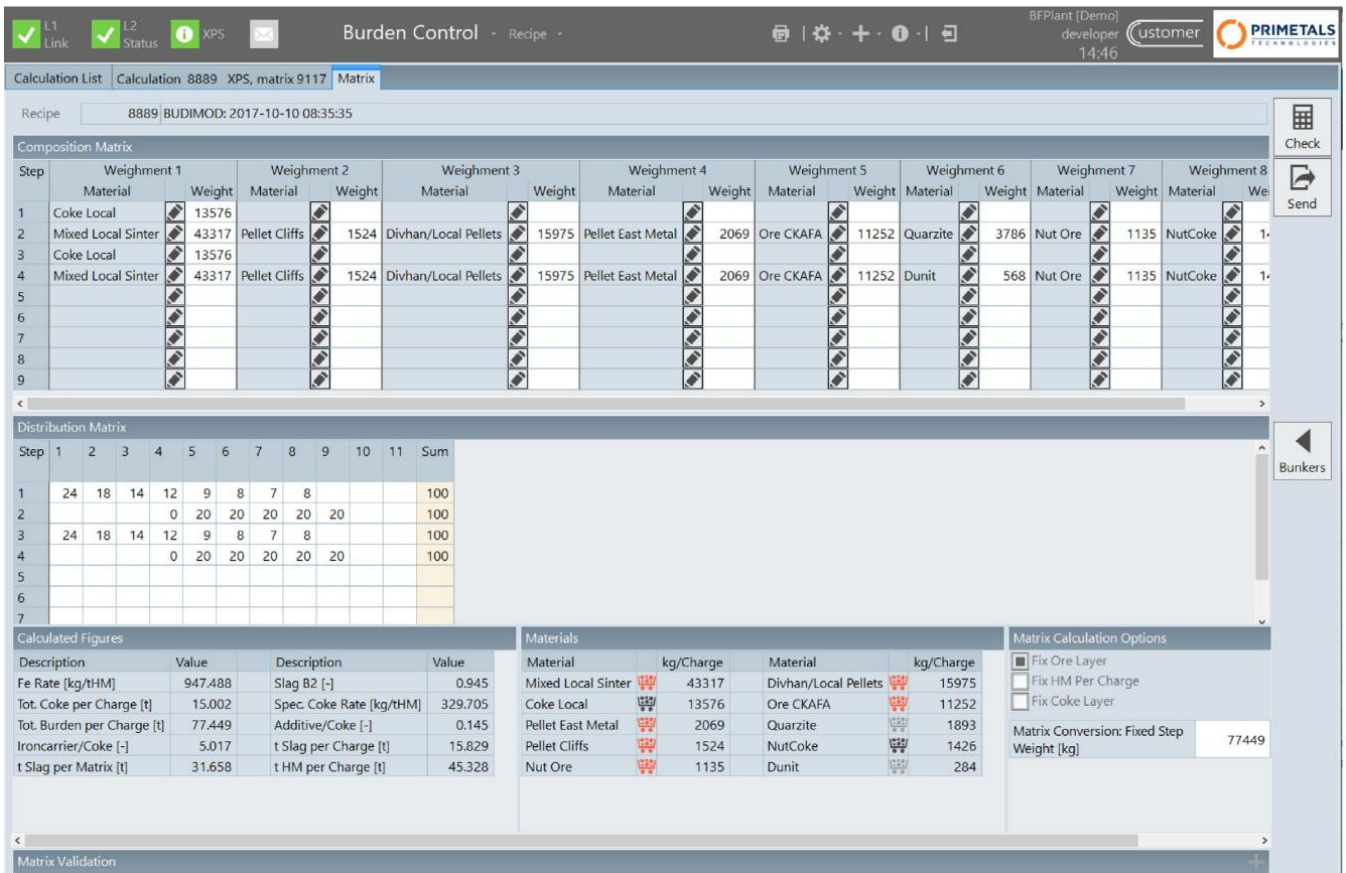


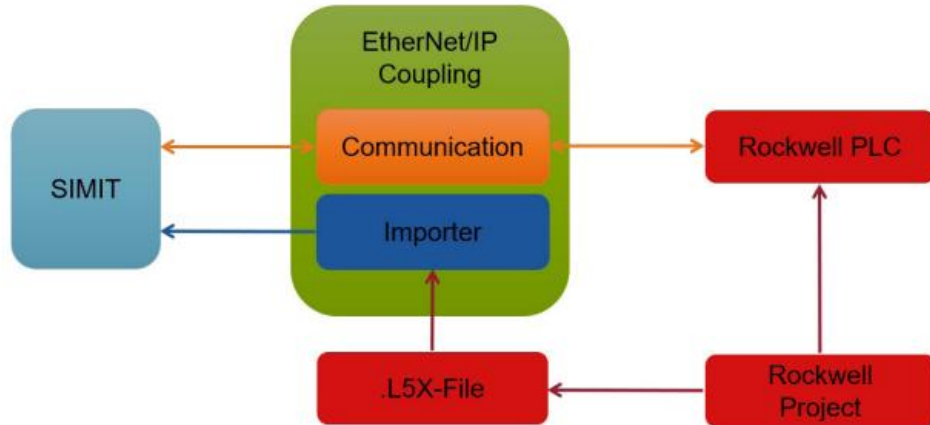
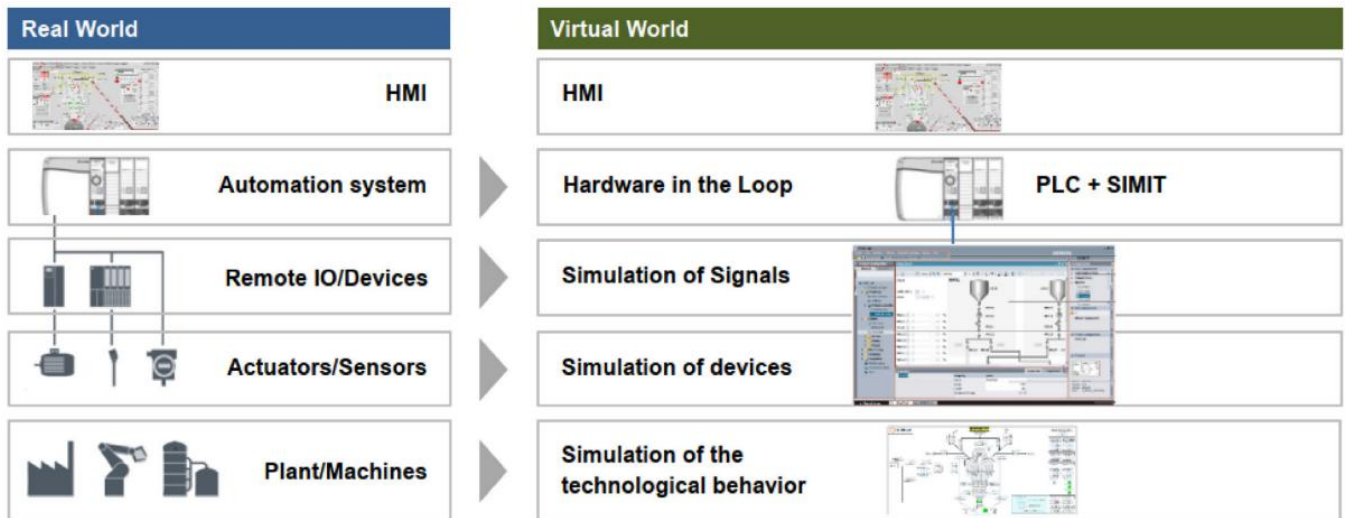
Figure 5. Burden Control Matrix



Figure 6. Shaft simulation model

**Table 1.** Signal assignment between OPC and SIMIT

| OPC DA server (General)            | OPC UA server (General)                                  | OPC UA server (SIMIT) | SIMIT   |
|------------------------------------|----------------------------------------------------------|-----------------------|---------|
| BOOL, UI1                          | Boolean                                                  | Boolean               | binary  |
| I1, I2, I4, I8, UI1, UI2, UI4, UI8 | SByte, Int16, Int32, Int64, Byte, UInt16, UInt32, UInt64 | Int32, Int64          | Integer |
| R4, R8                             | Float, Double                                            | Double                | analog  |

**Figure 7.** Ethernet/IP Coupling between SIMIT and Rockwell**Figure 8.** Software structure comparison between real and virtual world**Table 2.** Mapping of inputs and outputs based on OPC read/write access

| OPC           | OPC UA server (SIMIT)       | SIMIT  |
|---------------|-----------------------------|--------|
| Readable      | CurrentRead / Current-Write | Output |
| Writeable     | CurrentRead                 | Input  |
| readWriteable | CurrentRead                 | Input  |

The same data link used by the Level 1 system was employed to exchange process data and setpoints with Level 2, as communication between Level 1 and Level 2 had already been established.

### 2.5.1. Mapping of signals and data types of an OPC server

SIMIT supports only binary, integer, and analog signal types, with both integer and analog signals having a data width of eight bytes. In contrast, an OPC server can provide signals in a broader range

of data types. Table 1 presents the mapping between OPC data types and the corresponding data types used in SIMIT.

Signals from the OPC server can be configured as read-only, write-only, or read/write. In SIMIT, these signals are interpreted as inputs or outputs depending on their access type, as illustrated in Table 2.

A graphical user interface is provided to import tags from a Rockwell Logix Designer project exported as an L5X file, as illustrated in Figure 7. Signals can be imported and selected either from an existing L5X file exported from Rockwell Logix Designer or via XML files.

During simulation, SIMIT periodically reads and writes the imported tags. The standard time slice used in the project was 100 ms. Fast applications operated with a time slice of 20 ms while slower or specialized applications used 1000 ms.

## 2.6. Software technical concept

For each control system, four simulation areas were prepared in SIMIT. In Figure 8, there is a comparison between the real and virtual environment software structure.

### 2.6.1. Controller

The Rockwell controllers installed in the hardware-in-the-loop configuration served as the interface between SIMIT and the plant's human-machine interface (HMI). Through the controllers, all input and output signals (I/O signals) of the automation system were exchanged with SIMIT using OPC UA communication.

### 2.6.2. Field level

Simulation of drives, valves, and measuring points was performed, including components such as a relief valve, as illustrated in Figure 9.

### 2.6.3. Process level

Simulation of process values was performed, including examples such as a pressure signal, as illustrated in Figure 10.

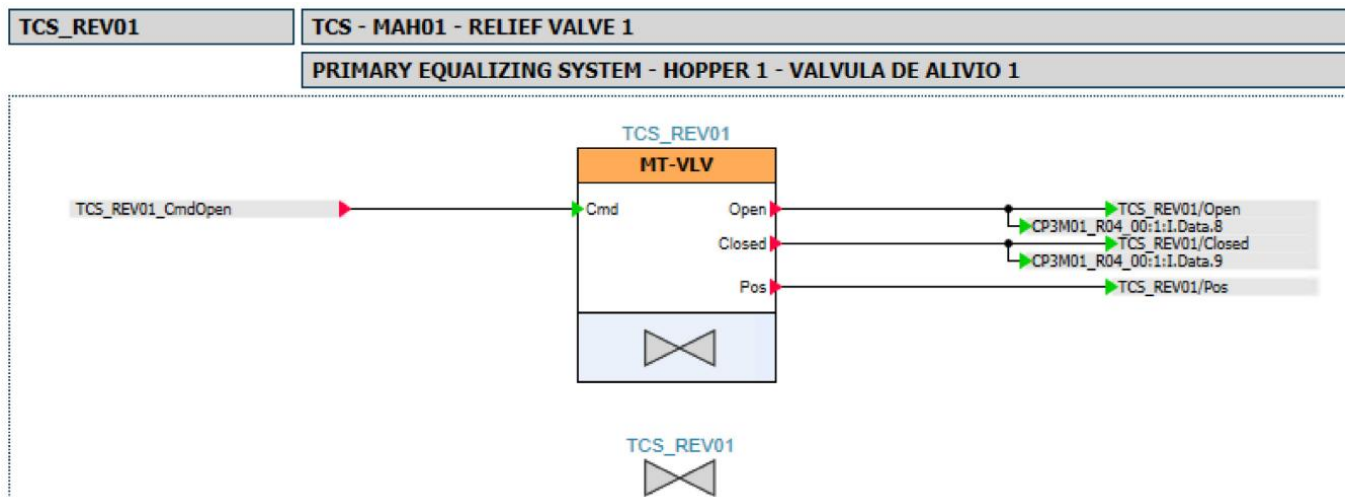
#### 2.6.4. Control level

A graphical display of SIMIT elements at the field level was created based on the background picture of the HMI, as illustrated in Figure 11.

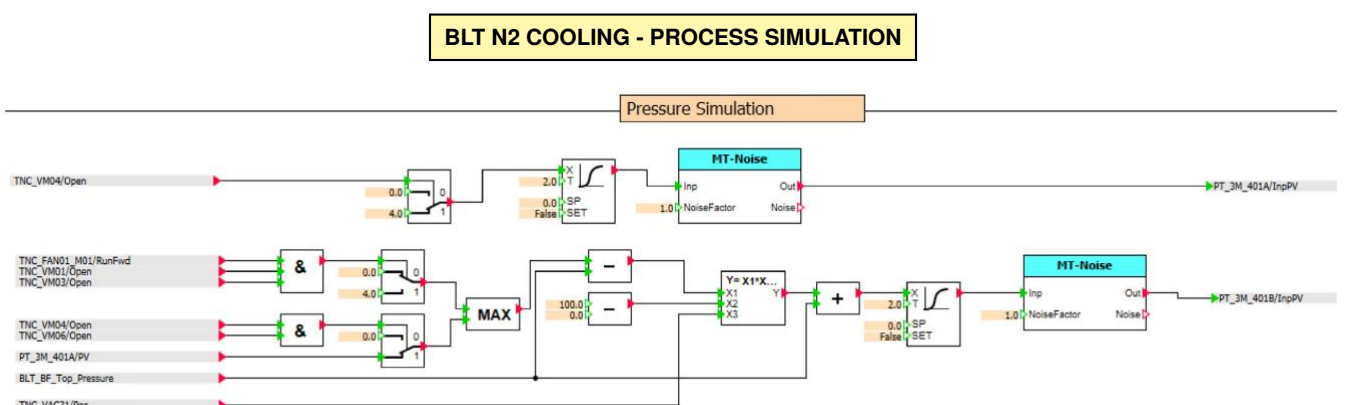
### 3. Results

The final system comprised controllers running a replica of the Level 1 software, virtual machines hosting the HMI visualization, Level 2, and Expert System. At the core of the Digital twin was an engineering station equipped with the simulation application.

This configuration enabled the engineering team and the customer to conduct a realistic Factory Acceptance Test (FAT), validating all agreed functionalities. Operators were able to configure and execute training scenarios using the same HMI screens as those in the actual plant, allowing early familiarization with the new control system months before start-up.



**Figure 9.** Chart example with a valve simulation



**Figure 10.** Chart example with a process pressure simulation



During the ramp-up phase, one of these insights led to a significant modification in the charging system software. The development and validation of this change took three weeks in the Digital Twin, and it was deployed directly into the production environment—without requiring a furnace shutdown. Without

- The simulation system served as a “flight simulator” for both new and experienced operators, supporting training for normal operations and fault conditions.

By integrating these elements, blast furnace operators were better equipped to manage the new bell-less top charging system, ensuring reliable production, improved fuel efficiency, and consistent hot metal quality.

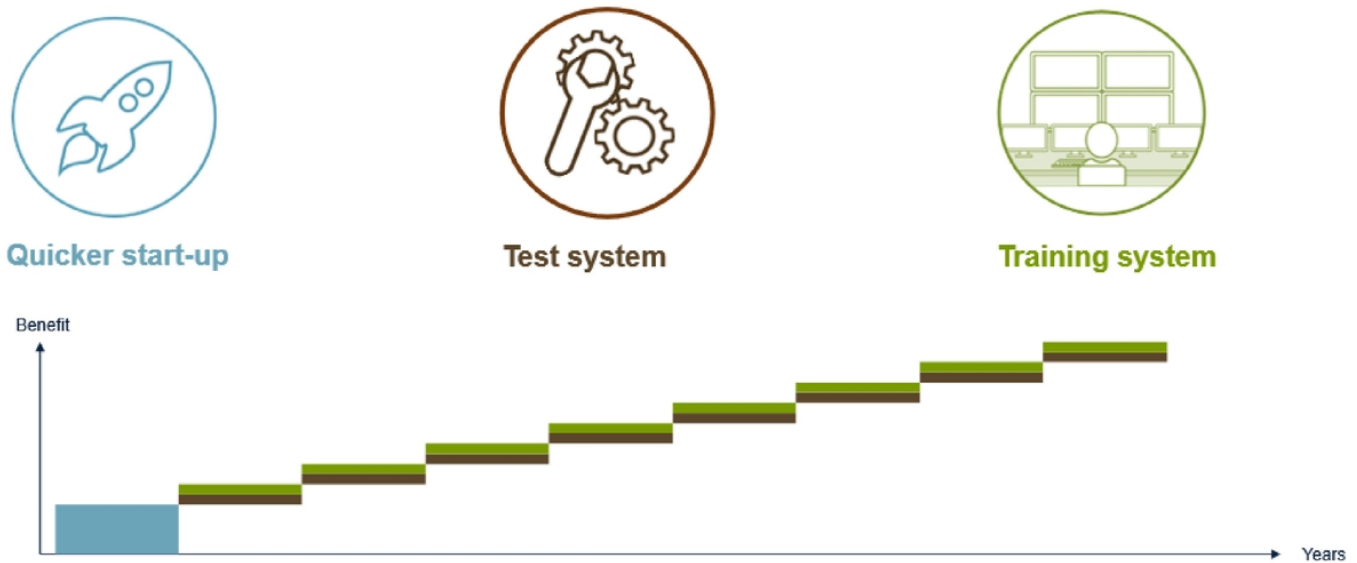


Figure 12. Cumulative benefits expected from the system

Future development opportunities include expanding the Digital Twin to other areas of the Blast Furnace, thereby enhancing its scope and operational relevance. Another key improvement involves strengthening the integration between the production system and the Digital Twin engineering environment, enabling seamless and real-time updates. Furthermore, the implementation of fault scenario simulations would allow operators to test and prepare for undesirable situations, contributing to improved decision-making and operational tests.

#### 4. Conclusion

The implementation of a Digital twin for the blast furnace bell-less top charging system proved to be a highly effective strategy for enhancing operational readiness, system validation, and personnel training. By integrating Siemens SIMIT with Rockwell's process control and Primetals' Level 2 systems, the project team successfully created a virtual environment that mirrored real plant behavior with high fidelity.

This environment enabled comprehensive testing of control logic, simulation of equipment responses, and validation of process sequences well before commissioning. Operators and maintenance personnel were able to familiarize themselves with the new system, rehearse critical scenarios, and gain confidence in handling both routine and abnormal conditions months ahead of the actual start-up.

The Digital twin also facilitated a robust Factory Acceptance Test, ensuring that all functionalities were verified in a controlled setting. During commissioning, the system continued to serve as a valuable tool for training and troubleshooting, minimizing risks and reducing the learning curve.

The benefits of this approach are clear: faster and smoother start-up, reduced downtime during lifecycle changes, and improved preparedness for critical situations. As demonstrated, the Digital twin is not only a technological innovation but also a strategic enabler for safer, more efficient, and more reliable blast furnace operations.

Furthermore, the scalability of the Digital twin approach opens opportunities for broader adoption across other metallurgical

processes and industrial systems, enabling predictive control, enhanced training, and continuous process optimization.

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