Industrial Perspective of Digital Twin Development and Applications for Iron and Steel Processes

Digital technologies are transforming industry at all levels. Steel has the opportunity to lead all heavy industries as an early adopter of specific digital technologies to improve our sustainability and competitiveness. This column is part of AIST's strategy to become the epicenter for steel's digital transformation, by providing a variety of platforms to showcase and disseminate Industry 4.0 knowledge specific for steel manufacturing, from big-picture concepts to specific processes.

Authors

Yale Zhang (top row, left)
Principal Consultant, Digital, Hatch Ltd., Mississauga, Ont., Canada
yale.zhang@hatch.com

Mitren Sukhram (top row, right)
Senior Process Metallurgist, Hatch Ltd., Mississauga, Ont., Canada
mitren.sukhram@hatch.com

Ian Cameron (bottom)
Principal Metallurgist – Ferrous. Hatch Ltd., Mississauga, Ont., Canada
ian.cameron@hatch.com

Alvaro Rozo
Global Director, System Integration, formerly with Hatch Ltd.

Iron- and steelmaking processes involve various levels of complexity from continuous to batch operation, from physical deformation to chemical reactions, and from reduction to oxidation, just to name a few. Every day, plant managers, process engineers and operators must make timely decisions to address production, quality and cost issues that are often contradicting each other, while adhering to a high standard of safety and environmental requirements. It is not an easy task even with assistance of today's advanced process control systems.

A blast furnace is the most significant asset in an integrated steel plant in terms of its value to build, complexity to operate and significance to production. It counts for about 75% of the total cost of final steel products. Nowadays, most ironmakers are facing one or more of the following challenges:

- Blast furnace integrity and safety is the No. 1 concern for both plant management and operation teams. Health, safety, and environmental risks need to be continuously monitored, assessed and managed.
- Many in-house or vendor-developed applications are deployed over decades across different process areas of the blast furnace for production management, process monitoring and control purposes. The poor integration between these modern and legacy computer systems creates many data "silos," across which data are not shared and thereby cannot be fully utilized to provide timely knowledge by applying the latest machine learning (ML) and artificial intelligence (AI) technologies. Siloed data can also cause a fragmented (rather than holistic) view of the hot metal and steel value chain, leading to missed opportunities from integrated optimization of raw material procurement, logistics/inventory management and production planning.
- Due to an aging workforce, more and more plants are encountering difficulties in maintaining process knowledge and transferring them to the next generation who are more technology-oriented and not interested in "old-fashioned" jobs. In many cases, plant engineers get stuck firefighting daily operating issues and little effort can be allocated for continuous improvement of furnace performance. Additional expert support is often required.

Over the past five years, Industry 4.0[1] has been an attractive subject among many articles, conferences and research studies. Industry 4.0 is no longer just a buzzword — the convergence of market pressure, technology innovations and industrywide acceptance of digitalization is truly driving transformation in steel manufacturing. Among many emerging disruptive technologies, digital twins receive a higher adoption rate due to the steadily growing maturity of the Internet of Things (IoT), cloud infrastructure and increased number of successful applications. This paper presents Hatch's vision and approach of developing a blast furnace digital twin, named Blast Furnace 4.0, with the intention to at least partially address the aforementioned challenges. Combining real-time data with Hatch's extensive ironmaking process expertise, Blast Furnace 4.0 can predict furnace conditions, conduct scenario analysis, and provide consistent and timely guidance to achieve stable and economic blast furnace operation. Its benefits are illustrated by two industrial use cases: blast furnace casting guidance and thermal control.

Hatch's Vision on Digital Twin Technology

Although the concept of digital twin has been around for many years, its first clear definition was given by NASA[2] in 2010:

"A digital twin is an integrated multi-physics, multiscale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its flying twin."

Several key components of the digital twin have been derived from this definition, including integrated simulation, models, sensor updates and historical information.

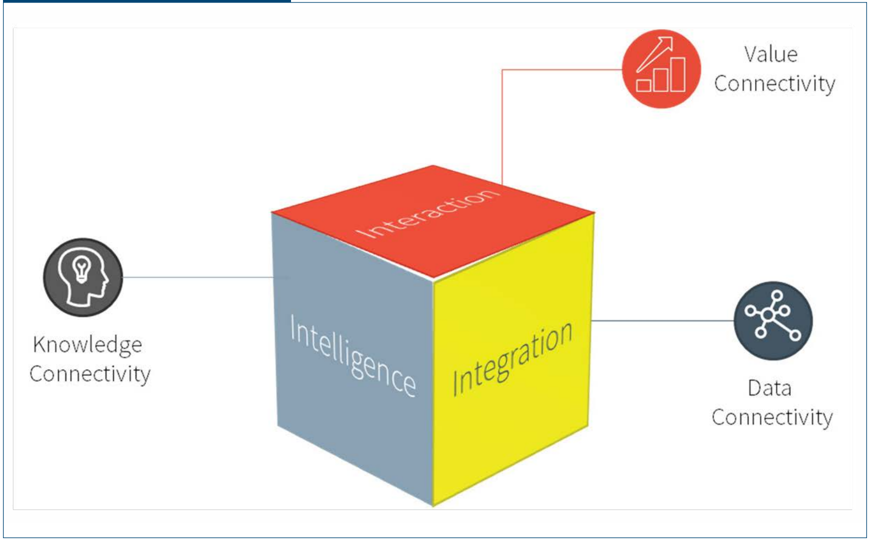
With recent technology development, especially in the fields of edge and cloud computing, IoT, ML/AI, virtual reality (VR) and augmented reality (AR), the concept of digital twin is also evolving with many different viewpoints. A digital twin is a dynamic, digital representation of physical asset(s) that combines multiple modeling technologies (i.e., first-principle models, data-driven models and engineering design models) and real-time data to draw meaningful insights and help improve human decision-making. An effective digital twin should consist of integration, intelligence and interaction, as depicted in Fig. 1.

Data Connectivity by IoT integration — Within an augmented visualization environment, a digital twin integrates all sources of data from process operation, equipment maintenance and product quality together with a high-fidelity 2/3D asset design model based on a pre-defined asset hierarchy framework. It establishes real-time data exchange with its physical twin and therefore creates a "single version of truth" to present on-demand, contextualized information and ensure information transparency for all designated users through a secured public or private cloud infrastructure.

Knowledge Connectivity With Built-In Intelligence — A digital twin must have its built-in intelligence, which is its key differentiator from widely applied business intelligence (BI) dashboards — no matter if it is presented in a 2D or 3D environment. A digital twin provides an analytical platform to effectively combine first-principle models, big data and ML/AI technology to generate actionable insights and make intelligent decisions related to the physical asset's safety, reliability, efficiency and profitability. The digital twin has the capability to consolidate various types and sources of knowledge and know-how, including those generated from other systems.

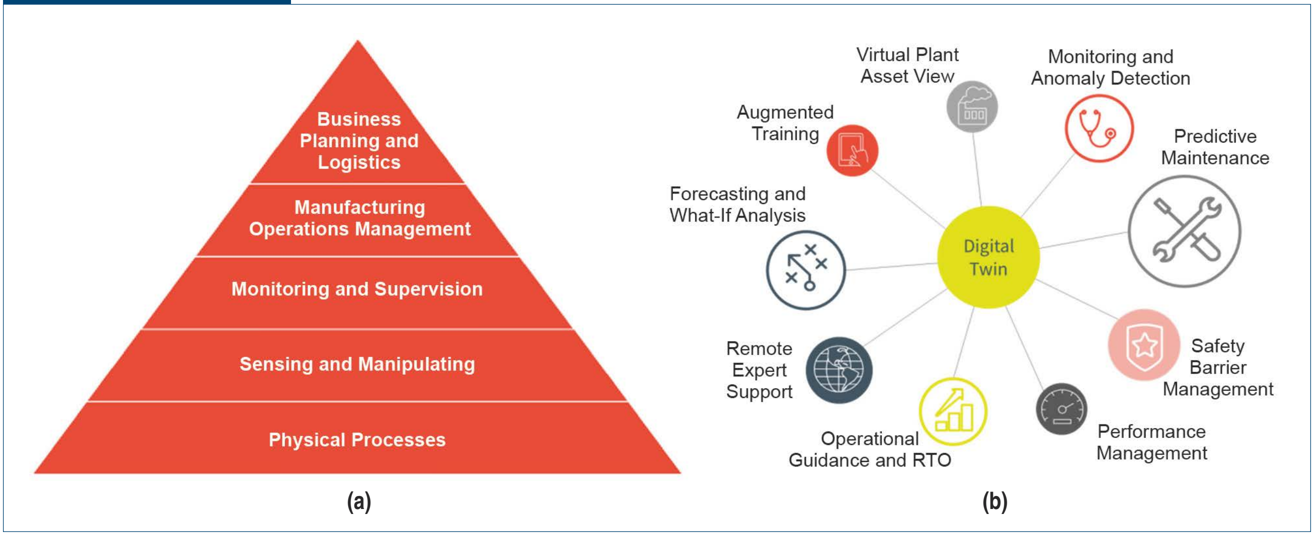
Value Connectivity Through Interaction — A digital twin adds value to business by interacting with humans or machines through various digital twin services, predictive maintenance, scenario analysis, augmented training or remote expert support, just to name a few. The emergence of digital twin may fundamentally break through the pyramid hierarchy of ISA-95 model for the integration of enterprise and control systems as shown in Fig. 2a, leading to a new model, where the digital twin is centralized by various extended services (Fig. 2b). The advantages of this new digital twin approach are that it will share information across all silos and promote a completely new way of collaboration among operation divisions, functional departments (e.g., financial, procurement, business planning, logistics and so forth) or even with external parties such as original equipment manufacturers and service providers.

Figure 1



Three key aspects of a digital twin: integration, intelligence and interaction.

Figure 2



ISA-95 pyramid model (a) and digital twin services (b)

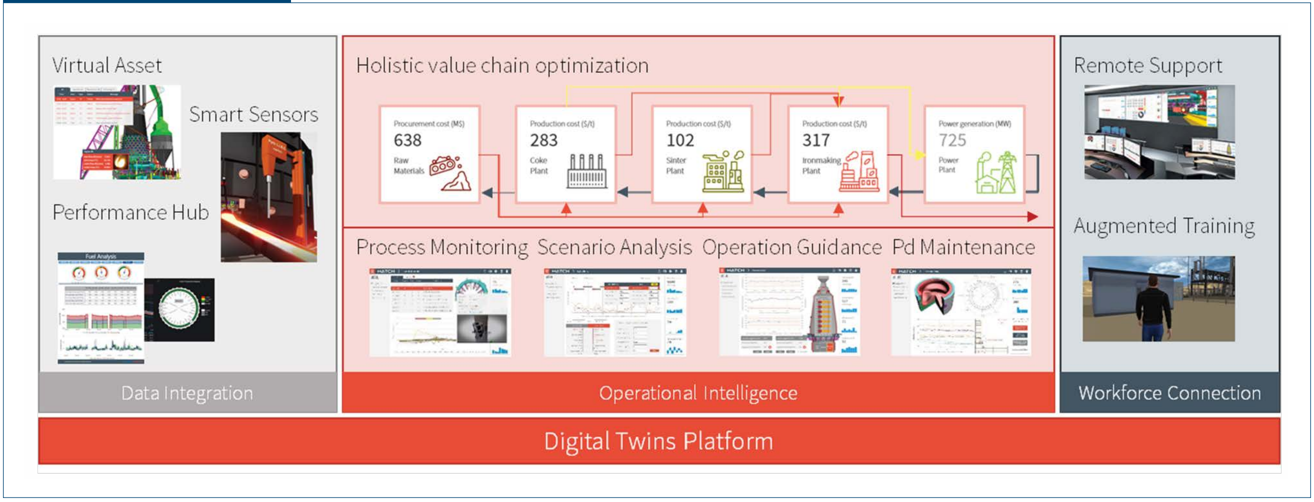
Following this vision, significant efforts have been made on design and ongoing development of the Blast Furnace 4.0, which will be described in detail in the next section, together with a few industrial case studies.

Development of Blast Furnace 4.0

Hatch Blast Furnace 4.0 was developed based on a digital twin platform, in which it has three main pillars: data integration, operational intelligence and workforce connection. Each pillar consists of various digital twin services, as shown in Fig. 3.

Data Integration — The goal of data integration is to establish a single source of truth for the blast furnace, providing trustworthy information to the right people and at the right time when needed. The blast furnace is among the most significant assets in the value chain. Modern blast furnaces are well instrumented, from the burden charging system, hot blast and fuel injection systems to casthouse operations and overall furnace cooling equipment. A typical blast furnace, with an inner volume of 3,000 m^3, is equipped with thousands of sensors. Due to technical limitations, harsh operating conditions, a technically complex process and many other reasons, blast furnace operators and engineers have not yet mastered the complete truth of

Figure 3



Blast Furnace 4.0.

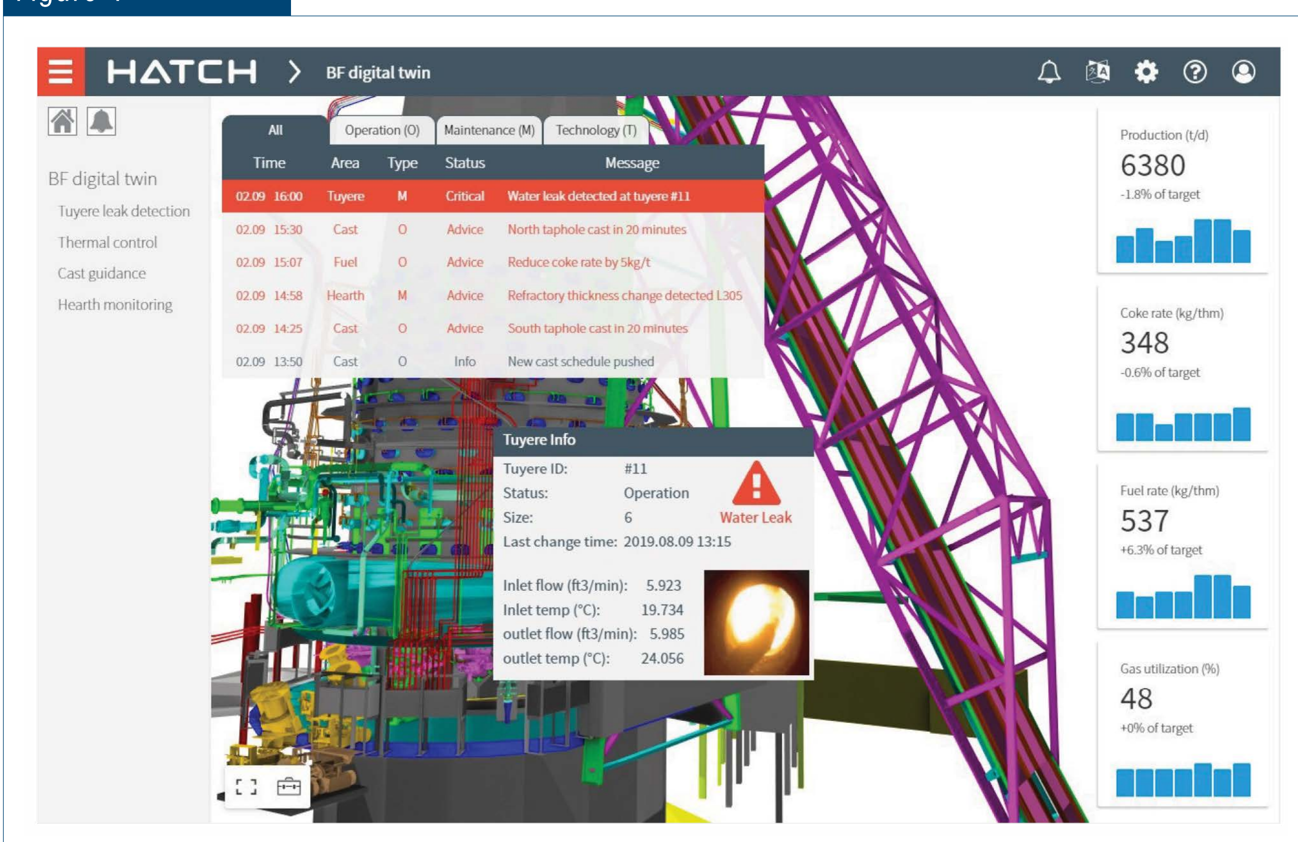
blast furnace. They are always interpreting the blast furnace's internal state, and to do so, engineers rely on deep data analysis and off-line lab sample analysis to control hot metal quality. The lack of necessary information in real time negatively affects their ability to sense and analyze operating conditions and make right decisions accordingly and at the right time.

Recently Hatch has been partnering with National Research Council (NRC) of Canada to develop and commercialize a new smart sensor technology, PyroLIBS, which uses laser-induced breakdown spectroscopy to continuously measure the chemical composition of hot metal while the blast furnace is casting and provide immediate feedback to control systems for real-time process optimization.[3] This technology will enrich blast furnace single source of truth by adding new critical data and can have a large impact on both productivity and quality control.

After obtaining the data, either from regular/smart sensors or other enterprise information systems, the next challenge to achieve a single source of truth is to orchestrate and present data in a contextualized way, making the data and associated information transparent to all stakeholders and to be at their fingertips. A digital twin serves perfectly for this purpose, which integrates all data sources, real-time operational data, equipment downtime and maintenance records, raw materials and product quality, etc., together into a high-fidelity blast furnace 3D model. The digital twin creates a dynamic, digital image of an operated blast furnace in a virtual space, as illustrated in Fig. 4. Through a 3D web user interface (UI), the blast furnace can be viewed from different angles. When one zooms in and selects one tuyere, for example, all structured data (tuyere size, operating status, cooling water flows, etc.) and unstructured data (tuyere camera images for raceway monitoring) related to this tuyere are immediately available to the operator. This is done by an underlying data model that is used to manage an asset hierarchy framework and link to corresponding data sources. Operation intelligence can also be integrated — in the example shown in Fig. 4, a tuyere water leak has been detected based on a Hatch proprietary data analytical algorithm.[4]

Given the blast furnace single source of truth, it becomes relatively easy to develop any type of performance dashboards. Fig. 5 shows a few blast examples of furnace dashboards Hatch has developed in Microsoft Power BI.

Figure 4



Blast furnace asset twin.

Figure 5

Examples of blast furnace performance dashboard.

Operational Intelligence — By laying a solid foundation, data integration becomes a significant enabler to achieving operational intelligence, which is the core value of Blast Furnace 4.0. The operational intelligence is built upon Hatch's extensive ironmaking experience and combination of advanced first principle and data-driven modeling technologies. Among many others, five value-added themes of use cases have been identified.

Process Monitoring: Blast Furnace 4.0 continuously monitors process operation in real time and detects abnormal process drifts and upsets, allowing operators to respond promptly and bring the process back to normal. The previously mentioned tuyere water leak detection is a typical use case in this theme. Upon receiving a water leak alert, operators will first verify the alert by performing a "gas test" and then determine whether and when the tuyere needs to be replaced to prevent potential increase of fuel rate, refractory damage and further production loss. Other use cases include real-time tracking of blast furnace burden descent, and on-line mass and energy balance calculation to monitor blast furnace operating window for fuel and oxygen injection.

Scenario Analysis: Process engineers use Blast Furnace 4.0 as a blast furnace digital twin to simulate blast furnace operations, conduct what-if analyses under various operating scenarios and/or conditions, and make or adapt production plans accordingly. For instance, through burden distribution simulations, process engineers can search the best distribution matrix (i.e., angles and rings) to achieve the desired ore-to-coke ratio curve. The blast furnace operator can test and adjust future casting schedule in response to higher-than-expected iron and slag levels in the hearth, thereby ensuring stable operation and consistent hot metal supply to downstream.

Operation Guidance: With enough information and built-in intelligent logic, Blast Furnace 4.0 provides actionable recommendations to operators. This is indeed the very first step toward blast furnace autonomous operation. One example is blast furnace thermal control, which will be discussed in more detail later in this section.

Asset Predictive Maintenance: Predictive maintenance is a typical digital twin service. Blast Furnace 4.0 uses a thermal assessment model to monitor hearth refractory temperature and thickness on-line. Once high-risk spots have been detected, predictive maintenance measures (such as ilmenite point charging) could be performed to protect the refractory wall.[5]

Holistic Value Chain Optimization: The blast furnace is not a stand-alone operation; in fact, it is linked to many other upstream and downstream operations such as coke plant, sinter/pellet plant, steelmaking shop, or even a power plant through complicated material and energy flows, which represents a hot metal value chain. Blast Furnace 4.0 analyzes this value chain in a holistic way, identifies raw material, production and quality constraints, and furthermore minimizes hot metal production cost subject to these constraints. This helps steelmakers respond quickly to market condition changes and improve their competitive advantages.

Two industrial examples are presented in the following sections to demonstrate the significant value added by Blast Furnace 4.0 through its operational intelligence.

1. Blast Furnace Casting Guidance — Casting is an important aspect of blast furnace control and stable operations. Matching the continuous nature of producing molten iron and slag to the intermittent process of casting the blast furnace is often challenging for operators. Ideally, the rate of hot metal and slag removal would exactly match the rate at which iron and slag are smelted.[6] Under such conditions, there is no accumulation of the liquids in the blast furnace hearth. Once liquids accumulate, they can exert back-pressure on the tuyere raceways, distort the gas flow in the blast furnace and make a negative impact on furnace operation. Many small casts can also lead to unstable operations. Accumulating and then rapidly draining the hearth can lead to slow-fast-slow charging rates and stockline movement. A major accumulation of molten iron and slag can increase blast pressure and reduce the charging rate. In certain extreme scenarios when molten slag and/or hot metal are at an elevation closer to the tuyeres, a sudden shutdown of the blast furnace will lead to filling the tuyeres with slag and a delayed start-up to clean the tuyeres and remove the solidified slag. This is a major risk that should be avoided. Many blast furnaces follow casting rules enacted through experience but lack on-line tools to measure the liquid level in the hearth to confirm whether applying the rule is valid in the current operational scenario. To help operators cast the furnace and avoid the aforementioned problems, Hatch has developed a casting guidance model as part of Blast Furnace 4.0.

Most blast furnace operations meticulously record and log casting data for analysis and to improve casting performance. Important times that are logged include: start/end time of drilling, time when molten iron starts to flow, slag is seen and the taphole is plugged, etc. The casting guidance model uses this information along with other real-time process data to inform the operator how much liquids are retained in the hearth. The model also helps the operator process the data to perform scenario analysis and improve casting performance.

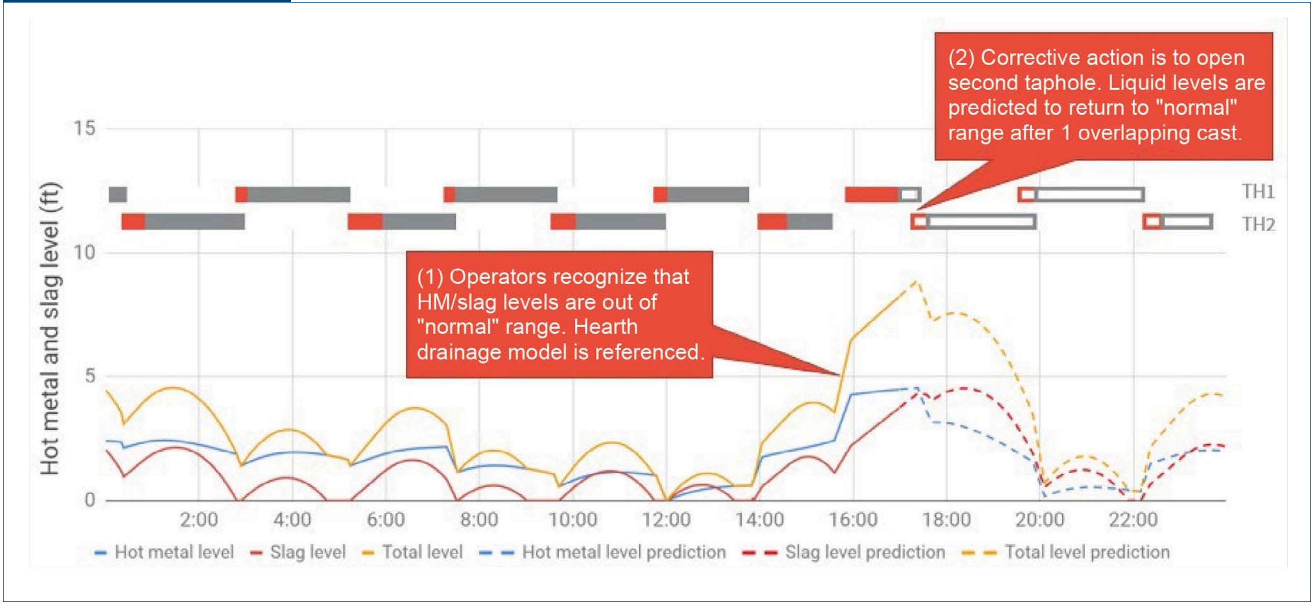
The casting guidance model is essentially a mass balance tracking the liquids entering and exiting the hearth. Comparing the molten iron and slag production to their respective casting rates allows for estimation for the liquid level in the blast furnace hearth. The blast furnace hearth can be modeled as a control volume being continuously filled and periodically drained. The filling comes from the production of hot metal and slag as the iron ore smelts. The periodic draining results from the casting practice employed by the blast furnace operators. Knowledge of these material flowrates at any given time, as well as blast furnace geometry and material properties, allows for hearth liquid levels to be estimated.

Calculating the mass of molten iron and slag produced is accomplished by performing the on-line mass balances and pulling this information from the blast furnace data historian. Although multiple techniques exist for measuring both hot metal and slag casting rates, they are often not suitable for use in the casting guidance model. The reason is that a delay exists between liquids exiting the taphole and a flowrate measurement is available. These techniques provide a good reference check of the alternative "real-time" methods. An alternative technique involves using a modified version of Bernoulli's equation to calculate total casting rate based on taphole geometry, blast pressure, liquid head and friction factor assumptions. Accumulation of liquids in the hearth is simply the result of mass of liquids into the hearth subtracted by the mass of materials cast from the hearth. The casting guidance model employs these mathematical techniques to determine the liquid level.

With such information in place, the irregular nature of casting rates compared to production rates becomes evident. Also, the impact of liquid levels on blast pressure can be identified. With slag and liquid iron levels in the hearth available, the operator can better anticipate when a suitable countermeasure should be employed; for example, overlapping casts, changing drill bit diameter or reducing the production rate.

A dry hearth practice is when iron is tapped continuously and slag is tapped 95% of the time.[6] A dry hearth practice assures that increasing hearth liquid levels do not impact gas flow in the blast furnace by exerting pressure on the raceway regions, ensures smooth descent of burden as iron and slag do not accumulate in the hearth, and allows for the blast furnace to be rapidly shutdown at any time without fear of filling the tuyeres and blow pipes with molten slag and iron. The following section demonstrates how the casting guidance model can help operators maintain a dry hearth practice.

Figure 6



Example results from the casting guidance model.

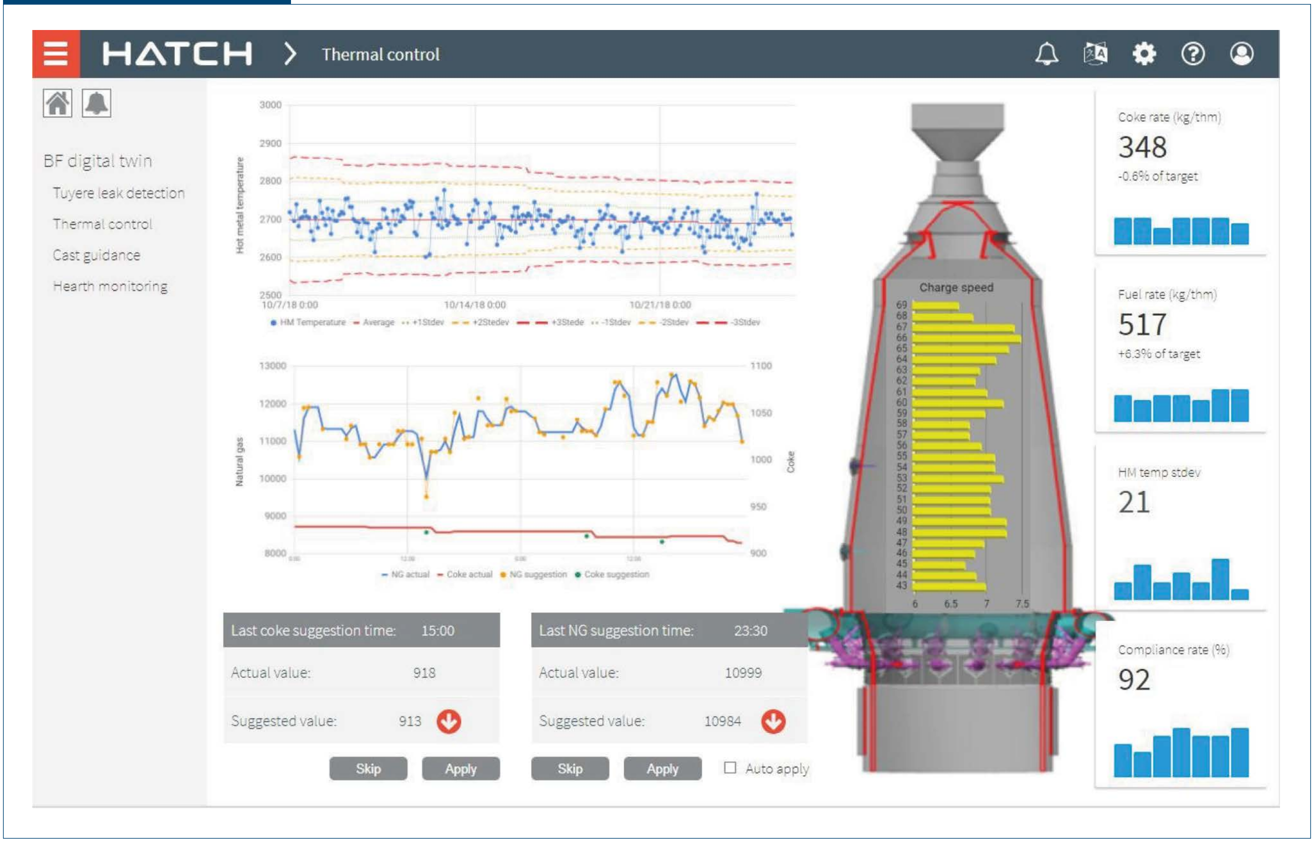
Fig. 6 plots example results from the casting guidance model and shows a typical casting practice on a two-taphole furnace. The trend plot shows the liquid level in the blast furnace hearth and the Gantt chart shows the casting of taphole 1 and 2, respectively, and their time when the hole is opened, slag is seen, and the hole is closed. Just before 1600 hours, the casting guidance model shows that there is an accumulation of liquid in the furnace. This tool prompts the operators to take corrective action to reduce the liquid levels in the hearth. There is a predictive function built into the casting guidance model to predict future hearth liquid level by adjusting the casting schedule and/or parameters. In this case, opening taphole 2 at 17:10 and overlapping the cast on the subsequent taphole will drain the furnace to maintain a dry hearth practice. The casting guidance model is effective in helping operators manage the casting practice while multitasking at the many responsibilities they perform at the blast furnace.

2. Blast Furnace Thermal Control — Thermal control of the blast furnace is another important aspect that intends to control hot metal temperature (or silicon content) around the right target to realize an efficient and stable blast furnace operation. Low hot metal temperature may cause some casting problems, whereas high hot metal temperature will lead to unnecessary fuel being consumed with an increased operating cost. The goal of thermal control is to decrease the variations in hot metal temperature and make it possible to lower the target temperature and total fuel consumption without hampering blast furnace productivity.

The blast furnace has two sources of fuel: metallurgical coke charged in batches from the top of blast furnace, and pulverized coal and/or natural gas injected continuously through tuyeres. Compared to the coke charge, fuel injection is a quicker way to manipulate the energy input to the blast furnace, which is used to control raceway flame temperature, provide additional hydrogen in the bosh zone to facilitate iron reduction, and reduce coke consumption. A challenge of blast furnace thermal control is to coordinate the injected fuel rate together with the coke rate and deal with the slow response of hot metal temperature to any fuel changes, which could be up to 6–8 hours. To accomplish this, a thermal control model was developed as part of Blast Furnace 4.0. Within this model, an instantaneous hot metal production rate is calculated from the top gas analysis and minor element reduction, which allows for a rapid adjustment of the injected fuel rate according to ever-changing reduction conditions inside the blast furnace and maintaining a relatively constant target of total fuel rate. The thermal control model provides suggestions on both coke rate and fuel injection rate for operator's guidance to reflect the actual fuel demand and reduce hot metal temperature variation, as illustrated in Fig. 7.

In this specific example, the hot metal temperature needs to be controlled and reduced in order to avoid other operational problems contributed by high hot metal temperature. The thermal control model consists of two interlinked loops. The inner loop was executed every 30 minutes, where the natural gas injection rate was given based on the current assessment of

Figure 7



Example results from the Hatch thermal control model.

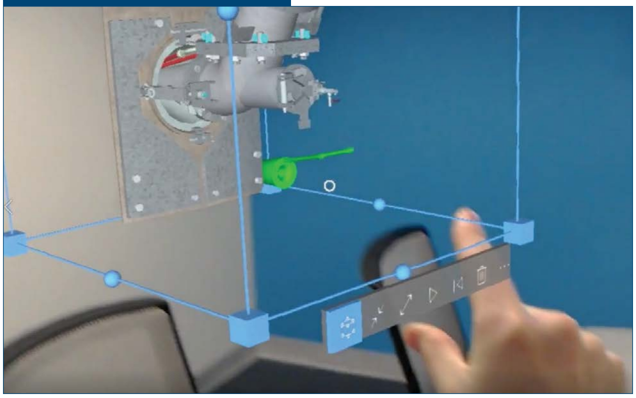
thermal state as well as the calculated instantaneous production rate as previously described. The outer loop was executed at every cast, where the blast furnace thermal state was reassessed based on newly available hot metal temperature. A statistical analysis approach was used here to help better understand the hot metal temperature trend and determine the appropriate thermal state of the blast furnace. Then a simple decision tree model was applied to determine the required coke rate change. As shown in the top trend plot in Fig. 7, both hot metal temperature average value and standard deviation were reduced by about 10°F and more than 20%, respectively. This improvement was seen after the first month of operation of the thermal control model.

Workforce Connection — Finally, a well-designed blast furnace digital twin can be shared through a secured cloud infrastructure and made accessible to a wider group of specialists and engineers for remote technical support and augmented training purposes. Fig. 8 shows an example where VR/AR technology has been integrated into Blast Furnace 4.0 to provide an interactive and visual standard operating procedure for blast furnace tuyere replacement when tuyere water leak is detected. Significant benefits are foreseen in implementing these tools in the blast furnace workplace as the technology matures in the next few years.

Implementation Approach

The blast furnace is a complex process and challenging to operate at world-class performance level. It is impossible to look in the furnace and examine precisely what is occurring at any moment in time — the operators and engineers must interpret the available information from their control systems. Developing a digital twin requires a deep understanding of the blast furnace process and operations. Following the design thinking principle, Hatch proposed an agile approach for Blast Furnace 4.0 development. According to different blast furnace characteristics and requirements, the use cases that are most critical and valuable to furnace safety, operation efficiency and cost are chosen, and then the implementation is expanded to include other features/functions based on the achieved operational improvements. The approach consists of five steps, as shown in Fig. 9. Hatch shares the same approach for developing digital twins of other processes such as smelting furnaces, autoclaves, alumina tube digestion, etc.

Figure 8

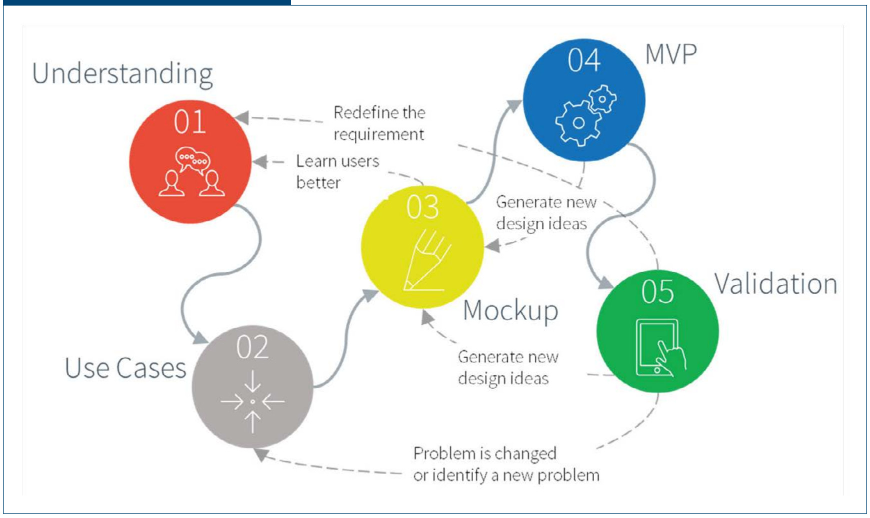


Augmented reality to show tuyere replacement procedures.

- Understanding requirements: In this first step, attention is focused on understanding user needs through expert interviews and information gathering. A wide range of needs is taken into account without pre-judgment and then grouped into various categories such as functional requirements, data requirements, user experience requirements, or security requirements and so on.
- Developing use cases: Based upon the above requirement analysis, the next step is to develop use cases (for example, blast furnace thermal control and casting guidance discussed previously are two different use cases). For each use case, Hatch identifies the goals, who the key users are and what their pain points are, and most importantly, prioritizes these use cases based on their potential benefit and implementation cost.
- Prototyping: This step is to propose a solution for high-priority use cases. During this process, an interactive mockup/prototype system is used as a communication tool to visualize different digital twin ideas and solicit stakeholders' feedback.
- Delivering the Minimum Viable Product (MVP): MVP is the first version of the proposed digital twin solution with enough features and functions to satisfy early adopters but at the same time to bring direct benefit. A quick delivery of MVP is targeted from the prototype and continuously improved during the following development.
- Verifying: This is the most crucial step in the entire process. Hatch compares with the original requirements and ensures all needs are fully satisfied by MVP or its further improved versions. Verification often serves as a new round of innovation process that may lead to further design improvements. The five-step digital twin development approach is not a simple linear process. At each step, the understanding of a user's objectives are deepened, new needs are defined and new pain points are addressed. This brings the process back to previous steps and promotes innovative ideas or solutions, continuously enriching digital twin services.

Blast Furnace 4.0 has large potential benefits for ironmakers, but best practices for implementation need to be considered and put in place to mitigate potential risks, as discussed in the following section.

Figure 9



Agile development approach.

Flexible On-Premise and/or Cloud Deployment Options: Blast Furnace 4.0 is typically implemented in a secured cloud infrastructure, either based on Microsoft Azure or Amazon Web Services (AWS). The operationalization of Blast Furnace 4.0 needs to take into consideration operations environment as well as various requirements from stakeholders. Should actions be real-time critical and required to be integrated with control layers (such as hearth iron/slag level prediction, burden descent monitoring, etc.), parts of the Blast Furnace 4.0 will need to be deployed at edge devices as close as possible to the control systems; whereas non-time-critical functions (for example, burden distribution simulation, casting guidance, and data storage) are performed in the cloud for data visualization and rich user interaction through web user interface. Should the interaction be directly with operators, Blast Furnace 4.0 needs also to consider high-performance human-machine interface and reduce visual fatigue to operators. Even though cloud computing is a core part of the Blast Furnace 4.0, in any case, where there is a requirement for a complete on-premise installation due to corporate IT strategy, Blast Furnace 4.0 has provisions to meet the requirement.

Collaborative Partnership to Avoid "One System Fits All": Each ironmaker has their own philosophy to operate blast furnaces. Instead of providing "one size fits all" type of solution, Blast Furnace 4.0 intents to build a digital twin to reflect owner's operating philosophy through close collaborative partnership. Blast Furnace 4.0 is a customizable and open platform that can also incorporate the user's own knowledge and know-how.

Change Management Support: Change management is crucial to any new technology adoption, including Blast Furnace 4.0. To sustain long-term success and benefits, Hatch can provide change management support by a cross-functional team combining ironmaking subject matter specialists with digital and advisory experts, which may include effective training and knowledge transfer, on-site operational support, asset management tools, communication and greater client engagement.

Post-Implementation Performance Monitoring: As with many model-based operational technologies in the market, such as advanced process control, simulation, etc., a Blast Furnace 4.0 strategy needs to consider how these models will be monitored and maintained. Typically, changes (known-knowns, unknown-knowns, unknown-unknowns) in performance of the process or assets may impact the effectiveness of the models which will need to be tuned. Hatch can provide continuous monitoring and services to ensure that the performance of models deliver value to the operations of the blast furnace over time.

Conclusions

With the advanced development of Industry 4.0, there is no doubt that more and more steelmakers will transform their traditional operations toward digital intelligence. Hatch's experience indicates the digital twin is a very good starting point of this journey due to its capability of (1) orchestrating data to a single source of truth to increase data transparency and user engagement; and (2) converting data into actionable intelligence and improve human decision-making through various digital twin services. Blast Furnace 4.0 is a great example of digital twin application and can bring significant benefits to operations as illustrated by industrial case studies. Significant efforts have been put into blast furnace model development and progress has been made in implementing some of them on-line with partner steelmakers. Hatch appreciates more collaborative development partnerships to continue improving Blast Furnace 4.0 or digital twin development for other processes to make this technology a powerful contributor to digital transformation for the steel industry.

Acknowledgment

The authors thank Luke Boivin, Janice Bolen, Erin Du, Rishi Midha, Sava Stosic and Ezra Widajat for their contributions to this paper.

References

1. Forschungsunion and Acatech, "Recommendations for Implementing the Strategic Initiative INDUSTRIE 4.0," Acatech Deutsche Akademie Der Technikwissenschaften, April 2013.
2. M. Shafto, M. Conroy, R. Doyle, et al., "DRAFT Modeling, Simulation, Information Technology & Processing Roadmap Technology Area 11," NASA, November 2010.
3. B. Shahriari, J. Bolen, et al., "Development of the PyroLIBS Sensor: Direct and Real-Time Measurement of Molten Material Composition," *AISTech 2020 Conference Proceedings,* 2020.
4. Y. Ghobara, R. Pula, I. Cameron, et al. "Successful Deployment of a Tuyere Leak Soft-Sensor at USS Blast Furnace No. 14," *METEC 2019.*
5. J. Entwistle, I. Cameron, et al., "Hearth Temperature Control at USS Blast Furnace No. 14," *AISTech 2019 Conference Proceedings,* 2019.
6. I. Cameron, M. Sukhram, K. Lefebvre and W. Davenport, *Blast Furnace Ironmaking: Analysis, Control and Optimization,* Elsevier, Amsterdam, 2020. ✦

AISTech
This paper was published in the AISTech 2020 Conference Proceedings. AIST members can access the AISTech 2020 Conference Proceedings in the AIST Digital Library at digital.library.aist.org.