STEEL PRODUCTION INVOLVES A number of stages, such as melting, casting, rolling, and forging, that entail complex chemical and thermic reactions as well as intricate mechanical operations. Because these processes do not lend themselves to exact mathematical modeling, steel manufacturers must turn to techniques for reasoning with incomplete and uncertain data. Their decisions often rely on the experience of individual experts. Nearly all steelmakers worldwide now use expert systems, fuzzy logic, and neural nets to improve quality assurance and production efficiency. This special track of IEEE Expert looks at several typical, successfully fielded systems.

For many years, the steel industry's main objective has been to maximize production by automating processes and streamlining plant organization. As with the Republic of Korea's Kwangyang Works, steel manufacturers have been erecting new plants from scratch, locating them near the sea to make the delivery of steel from blast furnace to final shipment as direct as possible. Because they restricted the diversity of their products, such new plants have become very competitive. Asia's steel industry, in particular, used these approaches in the 1980s to produce high-quality steel cheaper than its Western competitors. (See the sidebar for historical overview of steel production.)

However, the continuing improvement of substitutes for steel has raised the demand for even higher-quality steel with dedicated characteristics. By using different alloying metals and various heat and surface treatments, steelmakers now can offer a manifold of products. Ongoing research into new steel qualities has produced a broad range of products, which present many new control problems. Although other industries reflect the same tendency toward processing in smaller lot sizes, the steelmaking environment shows more diversity than most because of the particular characteristics of its material and manufacturing technology. Furthermore, the capital-intensive nature of the industry can make unanticipated violations of technological constraints extremely costly. A look at several typical factors will illustrate these considerations.

Most steelmaking processes are temperature-sensitive. For each process, the steel must have a prescribed temperature, and any time it spends waiting on the next processing step will incur a costly reheating. Moreover, because chemical reactions depend on temperature, any loss of heat during processing may degrade the steel's quality. If the prescribed solidification temperature profile is violated, an incorrect internal structure of the steel might result.

Although process times are difficult to predict precisely, steelmakers do exercise some degree of control. Treatment time in furnaces depends on the temperature, which can be controlled through heat input, generally sub-
Comparing these constraints, steelmakers can also control casting and rolling times to some extent by varying the speed at which they run the caster or rolling mill. By slowing a process down if it appears that an order will arrive too early at the next aggregate, or speeding it up if it appears it will arrive too late, they can also use real-time process control to meet requirements for synchronicity. (An aggregate is a common steelmaking term for machine.)

Technological considerations in the production of higher grades of steel impose requirements on the sequence in which orders are produced. Chemicals added to steel to achieve certain characteristics react with the steelmaking aggregate. Residuals remain in the aggregate and may be absorbed by one of the next orders, which may be corrupted by this infiltration. The width and thickness of the steel product also constrain sequences in the casting and rolling processes. Production-run engineers will avoid some obviously incompatible sequences, but sometimes schedule incompatible ones anyway for lack of a closed tractable causal model that would prevent them from doing so. Afterward, causal models can explain these errors, and this negative experience will lead to a modification of the production process.

**Automating production**

The nature of these problems that complicate production control—the vagueness and always-changing nature of the knowledge—has prevented steelmakers from making closed control loops for steel production. This industry has always been very innovative in the application of new production technologies and the latest computer technology. It was one of the first, for example, to apply fault-tolerant computer systems to fulfill the high requirements for availability and reliability of control systems. Despite this rapid automation, the process operator has remained an important link in the production process, and with the introduction of these new control systems, operators are being overladen with process data. (See the modern steel production sidebar, next page.)

The steel industry adopted expert systems relatively early for further automating production. The five leading Japanese steel companies reported the first successful applications. The designers of the Schecplan scheduling system, for instance, claimed that its operation saved $1 million a year by reducing the time that ladles carrying hot steel to the casters must wait. 2

Although quality optimization and energy consumption are important aims, the most important motivation for applying expert systems seems to be production standardization. In the steelmaking plant, for example, it is more important to have a safe and continuous supply of the blast furnace than a high, but irregular, supply. Because there is so much freedom in production decisions, it is better for quality assurance purposes to have formal rules about how to proceed, even if they are less than optimal. Having an expert system that acts as a consultant or even as a decision maker will make decisions more transparent.

**Applying expert systems**

Steelmakers apply expert systems instead of conventional software because the controlling software has to reason with existing uncertainties and master the inherent complexity of typical control problems. The control of the blast furnace illustrates issues motivating the implementation of expert systems.

The main focus of the blast furnace quality improvement effort is hot-metal silicon variability. This is controlled by the heat levels inside the furnace. If the furnace is too hot, the silicon will increase; too cool, silicon levels will decrease. Unfortunately, it is impossible to measure the temperature inside the furnace, so hundreds of sensors on the walls indirectly measure the hot metal's temperature.

Existing expert systems address two problems:

- predicting abnormal situations such as slips (abnormal and sudden descendings of the raw materials charged in the furnace) and channeling (the heated gas reaches the top of the furnace without reaction) and
- keeping the thermal condition stable.

Operators can adjust furnace heat levels and hot-metal temperatures by manipulating such variables as ore-coke ratios, blast temperatures, fuel-injection levels, and blast moisture levels. If the hot-metal silicon falls below the desired value, the hot-metal temperature will also be below its goal. The operator will need to increase the heat level. The problems in controlling this process are the long reaction times and the different reactions of human operators. Individual operators use different actions, start them at different times, and apply different magnitudes of changes. They also frequently use old data from previous cases to decide reactions.

Most blast furnaces managers therefore aim not to optimize but to standardize this control. The uncertainty of many data values makes it difficult to find a simple control algorithm. An expert system lets manufacturers build a model of the physical and chemical process in the furnace with symbolic values, abstracting from the thousands of
Modern steel production and control

Steel production requires different groups of processes often involving different plants. In the iron-making stage, steelworkers charge iron oxide (pellets, sintered ore, or iron ore), coke, and limestone into a blast furnace to produce pig iron. Typically, a blast furnace can hold several thousand cubic meters and operates continuously for about 10 years before shutting down for repairs.

Starting at the top of the furnace, the charge takes about eight hours to descend through the shaft. Solid, liquid, and gas coexist in the blast furnace, with heat exchanges and reduction reactions governing the phenomena inside. These are expressed in terms of furnace conditions and heat. Changes in the properties of the raw materials and the changing profile of the furnace body disturb the furnace’s operation. The process consumes huge amounts of energy.

Special torpedo cars transport the liquid pig iron tapped from the blast furnace (up to 10,000 tons of hot metal per day for large blast furnaces) to the steelmaking shop. Here, basic oxygen furnaces (BOF) refine the iron steel to the desired composition by blowing oxygen into the hot metal, which oxidizes impurities. During each run, or heat, the processing of up to 300 tons of pig iron takes about 20 to 30 minutes.

Steelworkers must control molten steel’s composition and temperature. Such control is especially critical in the oxygen-blowing step. Recently, because of the increased use of continuous casting and widespread use of hot-metal pretreatment, the requirements for blowing control have become stricter. If no direct charging from the blast furnace is possible or if huge amounts of (cold) scrap iron are charged, plants must use electric arc furnaces to smelt the metal, a process that requires a huge amount of energy and takes considerably longer than the BOF converter process.

Next comes ladle refinement, where the liquid steel is poured into ladles, before cranes transport it to various refinement aggregates (machines). In making the various grades of steel that customers order, these aggregates eliminate further impurities and add further alloying metals.

The last stage in the steelmaking shop either uses continuous casters to cast the steel into billets, blooms, or slabs, or a more traditional process that involves making ingots, soaking the ingots, and passing them through a slabbing/blooming mill.

In continuous casting, real-time control is very important. Fluctuations in the level of molten steel in the mold of the caster cause inclusions of gas in the metal and surface defects. Heating the cast products up to 1200°C in a reheat furnace eliminates surface defects and prepares them for hot rolling. This process also poses many control problems, both in combustion efficiency and steel exit temperature.

Steelmakers control the reheating process with mathematical models, linear programming, and expert systems. The control of the reheating process is closely linked with the hot-metal process.

Other steps involve rolling the cast goods in the rolling mills, first rolling the steel warm and then cold to achieve high accuracies in surface structure, dimensions, compression, and impact strength. These stages each involve several passes. The rolling process greatly affects the quality of the final product, so the thickness, shape, and chemical properties of the rolled steel require highly accurate control. Controlling the pace of the mill presents another problem, one that involves determining the optimum reheating furnace discharge interval to allow the hot rolling mill to run continuously.

Finally, the rolling mill produces a variety of steel products. Batch or continuous annealing completes the processing of the steel and determines the properties of the final products. Here, the mill heats steel products to a predetermined, closely controlled temperature for a given length of time to obtain the desired quality. The final stage may involve a variety of operations such as pickling (descaling coils with acid), tempering, or coating of the produced coils, pipes, wires, and plates, before shipment to customers. (Figure A shows the cross section of a typical high-grade steel.)

![Figure A. Cross section (x600) of K100 steel produced at Austria’s Bohler Uddeholm plant. An acid-treated austenite, it contains 1.23% carbon, 0.4% silicon, and 12.5% manganese.](image)

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measured data values. Rules allow the specification of certain standards—when and how an operator should react.

One of the first well-described systems in this domain was Nippon Steel's Artificial and Logical Intelligence System (ALIS), which controls several blast furnaces. Comparisons between human and expert system performance showed that in 25% of the cases studied, the expert system performed better and only in 7% did the human excel. Furthermore, the system is continually modified to improve its competence.

This issue

Today, as the latest conferences on production control in steelmaking show, almost every steelmaker—from developing countries to the traditional steelmakers—applies expert systems. One great challenge now facing the steel industry is to improve the self-adapting capabilities of expert systems. As mentioned, modifications of the production process are quite regular, and the tendency is to adopt even more flexibility. Intelligent steelmaking aggregates that adapt themselves to new steel compositions and requirements for the produced good are important research topics now. Research into intelligent organizers that can learn new strategies if the manufacturing objective or
the production technology changes is also ongoing. The first article,
by Nicolas Pican, Frédéric Alexandre, and Patrick Bresson, addresses
this issue. They have developed a system that incorporates an artifi-
cial neural network to preset the parameters of a steel temper mill.
They also show that a combination of AI and conventional techniques
often solves industrial problems best.

An intermediate step in self-learning systems are systems that
assist human experts. Because users of expert systems are not
familiar with expert system techniques, they need simple techniques
to adapt a system to new production facilities and strategies. The ar-
ticle by Jürgen Dorn and Reza Shams describes experience along
these lines and makes propositions for improving this capability.

A focus of future research is the cooperation between expert sys-
tems in the steel industry. At the moment, expert systems are single-
user, front-end computer systems dedicated to one function. Their
integration with the existing organization is very simplistic. Most
systems couple to a process computer or a production-planning sys-
tem to obtain required input data. However, stronger coupling would
increase the benefits of expert systems. The simplest solution is an
expert system that performs this cooperation as its main task. How-
ever, a more generic approach would let expert systems cooperate in
an open framework.

For example, a steelmaking shop scheduling system should re-
ceive knowledge of the status of the blast furnace, because the sup-
ply situation will influence the scheduling strategy. More useful
would be cooperation between a scheduling system and an intelli-
gent machine such as a caster that can decide which sequences are
good and when maintenance operations should occur. Negotiation
are also necessary between a steelmaking plant and its customers
the rolling mills and other plants. Because these plants operate under
different sequencing criteria, a best sequence for one plant is not nec-
essarily good for the other.

Despite even more pervasive automation in the future, human ex-
erts will remain unavoidable for production control in the steel in-
dustry, because new production failures that cannot be handled ade-
quately by a system occur quite regularly.

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