Engineering Materials

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Steel 4.0

Digitalization in Steel Industry

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Preface

Steel is produced continuously from natural raw materials or recycled materials through a series of steps that ultimately result in finished goods, such as slabs, sheets, or coils. Steel is one of the most important input materials used in many industries, including construction, machinery, and the automotive industry. Thus, the steel industry plays a crucial role in the economy by providing jobs, supporting other industries, and contributing to infrastructure development.

Steel is a highly versatile material that can be molded into different shapes and forms. It has high strength and durability, making it an ideal material for structures that need to withstand heavy loads, extreme weather conditions, and other challenges. Moreover, steel is one of the most recycled materials globally since its recycling process is efficient, and recycled steel keeps its strength, contributing not only to cost savings but also to sustainability efforts.

However, the process of steel making is rather complex. Steel production involves managing variations in the quality of raw materials like iron ore and coal, which directly impact properties of the final products. Steel making requires extremely high temperatures, especially in processes using blast oxygen or electric arc furnaces. Managing these temperatures and ensuring uniform heating across large furnaces is a complex task. Numerous chemical reactions occur during steel production, each requiring careful control to achieve the desired composition and properties in the final product. Consistency in steel quality is crucial. Achieving precise chemical compositions, controlling impurities, and maintaining proper mechanical properties demand sophisticated control systems and monitoring.

This is why digitalization in steel making is highly important. Digitalization allows for real-time monitoring and optimization of processes, leading to increased efficiency in production. This can result in energy savings, reduced waste, and improved resource utilization. Additionally, gathering and analyzing data from various stages of steel production enable better decision-making. Predictive analytics can help anticipate maintenance needs, optimize production schedules, and improve overall operational performance. Digital technologies enable continuous monitoring of product quality. Automated systems can quickly detect deviations in parameters, ensuring that the final steel products meet stringent quality standards.

Against the backdrop of this, with this book we intend to shed light on the digitalization efforts in steel making. For this, we focus on topics reviewing the current state, with chapters on the current state of electric arc furnace based recycled steel making (chapter "Planning and Scheduling of Electric Arc Furnace Based Steelmaking"), steel surface defect detection methods (chapter "Systematic Review of Steel Surface Defect Detection Methods on the Open Access Datasets of Severstal and the Northeastern University (NEU)"), and decision support systems (chapter "Decision Support Systems for Steel Production Planning—State of the Art and Open Questions"). Additionally, simulation modeling of steel making is presented (chapter "Volatility and Synchronization in Steel Manufacturing—A Simulation Study of a Modern Steel Mill"), before algorithmic approaches are addressed, with chapters on the comparison of crossover operators in genetic algorithms (chapter "A Comparison of Crossover Operators in Genetic Algorithms for Steel Domain") and a comparative study of genetic algorithms for steel production planning under different order backlog circumstances (chapter "Comparative Study of Two Genetic Algorithms for Steel Production Planning Under Different Order Backlog Circumstances"), a comparison of cross-entropy loss functions in steel defect detection (chapter "Effect of PolyLoss Function on Steel Defect Detection"), and eventually a novel genetic algorithm for simultaneous scheduling of two distinct steel production lines (chapter "Novel Genetic Algorithm for Simultaneous Scheduling of Two Distinct Steel Production Lines").

Thus, the book contributes to a better understanding of both the state of the art in steel making and novel algorithmic approaches in planning and monitoring of steel making.

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Introduction

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Abstract Steel is being created from natural raw materials or recycled materials in a continuous process through a chain of consecutive stages that ultimately lead to finished goods, such as slabs, sheets, or coils, that are being used in many industries, such as automotive, machinery, construction, etc., as one of the most important input material. This chapter gives an overview of the current state of steel making technology as well as the state of the art of planning and scheduling in steel making by means of a widely used IT system.

Keywords Steel making technology · Scheduling · ERP system

1 Steelmaking—State of the Art

Steel manufacturing is at the center of many developed and emerging economies [1, 2] as steel continues to be a highly demanded material [1] in various industries (e.g. construction, automotive, mechanical/electrical engineering, etc.; see [2]).

In the past 150 years, technology employed in steelmaking has changed dramatically. Some stages, such as Bessemer, became completely obsolete and were replaced by other methods whereas some other stages, such as Electric Arc Furnaces (EAF),

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Hot Strip Mills and Basic Oxygen Furnaces (BOF) are being elaborated continuously and are likely to remain intact and in place in future.

Steel is manufactured via a chain of processes and stages. Based on their production routes, modern steel plants can be categorized into two types, i.e., Integrated Steel Plants (ISPs) and Mini Steel Plants (MSPs). ISPs are relatively large and consist of BOF route of steelmaking with series of processes which can provide several steel grades with capacity size of 1–5 Mt per year while MSPs are relatively small with module capacity of 0.5–1 Mt per year and mainly use EAF steelmaking with captive direct reduced iron (DRI) producing units. Downstream processes, such as Continuous Casting (CC) and Rolling or Milling, are common in both facilities [3].

When discussing different steel grades, it becomes essential to delve into the classification of steel products. Steel is categorized based on the amount of carbon (C) and other elements. Consequently, steel grades are generally divided into two primary groups: Plain Carbon Steel and Alloy Steel [4].

More than 90% of the steel produced globally falls under the category of plain carbon steel. This particular type of steel features a very low concentration of magnesium (Mg) and other elements. Regarding the carbon content, Plain Carbon Steel can be further divided into three sub-groups: low carbon (0–0.2% C), medium carbon (0.2–0.6% C), and high carbon (0.6–1.5% C) steel [4].

On the other hand, Alloy Steels are typically manufactured in Mills or Steel Plants and incorporate alloying elements such as nickel (Ni), chromium (Cr), molybdian (Mo), and cobalt (Co). These alloy steels are classified into three distinct classes based on the percentage of alloying elements: low (up to 5% alloying elements), medium (between 5 and 10% alloying elements), and high (above 10% alloying elements) [4].

The integrated steelmaking has two major stages, reduction (ironmaking) and refining (steelmaking). In the following, these two processes will be discussed in more detail.

1.1 Ironmaking—Reduction Stage

In the ironmaking stage, the primary objective is to eliminate oxygen and other unwanted elements from iron ore, transforming it into metallic iron, which contains a relatively high carbon content (around 4%). This resulting product is referred to as "hot metal." Ironmaking serves as the initial step in integrated steel production and is widely regarded as the most capital and energy-intensive process in the entire steel manufacturing industry, as it primarily involves the removal of undesirable substances from iron ore [3].

There are three primary routes for ironmaking: the blast furnace/basic oxygen furnace (BF-BOF), direct reduced iron/electric arc furnace (DRI-EAF) and smelting reduction/basic oxygen furnace (SR-BOF) [3].

The blast furnace route stands as the most prevalent method of steel production, accounting for over 70% of global steel output. In the blast furnace, coke is utilized as the primary energy source and reducing agent. The second common steelmaking route involves recycling and melting steel scrap in the electric arc furnace (EAF). In DRI-EAF, natural gas is used as both the energy source and reducing agent. The third steelmaking route is smelting reduction, which relies on the combustion of coal without agglomeration [3].

In the following, the most common method, i.e. blast furnace, will be discussed.

1.2 Blast Furnace

The modern blast furnace is a massive structure, reaching heights of up to 100 m, with a cone-shaped furnace shell extending up to 30–40 m in height. The process within the blast furnace unfolds as follows: raw materials are introduced into the furnace from the top, and iron and slag are subsequently extracted from the bottom. An air blast, supplemented with auxiliary fuels, is delivered through tuyeres [3].

The furnace is primarily charged with iron ore (Fe_2O_3) in various forms, such as sinter, pellets, or lumps, along with coke as a reducing agent. Limestone or dolomite is added to balance the chemical properties of the slag. To maximize the furnace's efficiency, the quantities and proportions of all raw materials are carefully controlled, and the order in which they are charged is meticulously executed [5].

Once the furnace is charged, it undergoes three main stages: blowing, reduction, and tapping.

In the blowing stage, high-pressure oxygen gas is injected into the molten steel to reduce the carbon (C) content. At the top of the furnace, there is a recovery turbine that maintains the pressure of the off-gas. This blower can supply up to 6500 m^3/min and operate at pressures of up to 400 kPa. In the smelting process, turbo-blowers elevate the temperature of the air to 900–1200 °C before it enters the furnace's combustion zone through copper nozzles [3].

The reduction stage begins by preheating iron ore as it descends from the furnace hopper. During this stage, the combustion of coke and additional fuel is absorbed by the iron ore. This process lowers the melting point of the iron ore from 1537 °C to approximately 1150 °C. The temperature at the core of the furnace reaches around 1550 °C, which is sufficient to ensure the fluidity of the iron and slag. It is crucial to accurately control the proportion of raw materials at this stage since it can impact the melting point of the slag and the fluidity of the iron [3].

In the tapping stage, after the molten iron is separated from the slag using a skimmer, it flows into a transfer ladle. Smaller furnaces have one taphole, while larger furnaces may have several. This operation is repeated every two hours, and in each casting, the amount of tapped iron obtained can range from 250 to 800 tons, depending on the furnace's capacity [3].

The ladles are constructed from thick steel and are designed to hold up to 300 tons of molten steel. They are mounted on a railway and powered e.g. by a diesel locomotive, allowing them to travel between the blast furnace and the steelmaking shop. The product at this stage is referred to as "pig iron," and it can be used for a variety of purposes. In almost all steel plants, pig iron undergoes refining stages such as desulfurization before being used in steelmaking [3].

Alternative ironmaking methods, such as smelting reduction or direct reduction, are recommended in cases where raw materials are not readily available in the quality required for the blast furnace, or when fuel sources like natural gas or coal are considered expensive. Additionally, these methods are advantageous for steel plants with very small steelmaking capacities, offering a viable alternative to the conventional ironmaking process [3].

1.3 Direct Reduction

The process of removing oxygen from iron ore without reaching the molten stage is known as direct reduction. Direct reduction can yield three primary products: sponge iron, iron carbide (Fe_3C), and hot briquetted iron (HBI). Further refinement of direct reduction products is typically carried out through the Electric Arc Furnace (EAF). The reducing agent used in direct reduction can be derived from the reformulation of natural gas or coke, leading to two primary methods of direct reduction: gas-based and coke-based [5].

In the gas-based process, iron ore is heated and subsequently led to reactors where it is reduced with reformed natural gas. By eliminating the oxygen, the iron passes through a series of fluidized bed reactors and is later compressed into granules, which can be used in the EAF or even sold in the market [3].

In the coal-based process, a tilted horizontal cylinder with an internal refractory lining, known as a Kiln furnace, is employed. The Kiln furnace rotates and conveys iron ore with coal along its length, while combusted air circulates above this mixture. Gradually, this process assists in the reduction of iron ore, releasing carbon monoxide and hydrogen as the process unfolds. This method is particularly attractive to plants with an ample supply of high-quality iron ore but a shortage of natural gas [3].

1.4 Smelting Reduction

Bath smelting or smelting reduction refers to a method which make molten product directly from iron and coal. The output of this stage can be used for further refining to BOF or EAF. In this process iron ore and coal are directly added to molten slag and metal bath. Reduction of iron ore needs less raw materials than DRI or blast furnace methods due to high temperature of this operation. This method has the least environmental emissions and brings flexibility in terms of production. Also, agglomeration plants can be eliminated to approximately 99% [3].

1.5 Steelmaking—Refining Stage

In the refining stage, the primary goal is to reduce the carbon (C) content of hot metal to below 1% and introduce alloying elements to achieve the desired chemical composition through oxidation in a steelmaking furnace. Steelmaking can be accomplished through either the Basic Oxygen Furnace (BOF) or Electric Arc Furnace (EAF) routes. In the BOF process, pure oxygen is injected into the hot metal using a lance, while in the EAF, a mixture of scrap metal, sponge iron, and other iron units is heated using electricity. A general comparison of these two routes reveals that the EAF requires fewer chemical reactions for refining [5].

The steelmaking process comprises three primary stages, with two of these often occurring simultaneously: Oxidation, Charging, and Adding Alloying Elements [3].

Oxidation involves the removal of impurities such as silicon (Si), ferrous oxide (FeO), chromium (Cr), manganese (Mn), and phosphorus (P) from iron ore. This typically requires multiple oxidation steps, with silicon being one of the first elements to be removed. However, certain elements like nickel (Ni) or tin (Sn) cannot be oxidized [3].

In the charging stage, precise temperature control is crucial, and this is monitored through the thermally balanced charging of raw materials [3].

1.6 Basic Oxygen Furnace

The BOF features a barrel-shaped steel shell with an alkaline refractory lining, which is why it is termed "basic". In most steel plants worldwide, its capacity ranges from 100 to 250 tonnes, with a few having a capacity of 400 tonnes. This process converts iron into steel by introducing pure oxygen to remove undesired elements. The process begins with the weighing of hot metal and analyzing its chemical composition. This data, combined with the required steel grade specifications, is used to calculate the amount of flux, scrap, and oxygen required [3].

To start the cycle, the furnace is charged with metal scrap and hot metal brought by a ladle. A lance then blows pure oxygen at high velocity, igniting the process. To prevent the ejection of hot metal, which is referred to as "sparking" due to the impact of the oxygen jet, burnt lime and dolomite are added to form slag. Finally, fluorspar is added to make the slag fluid [5].

Between the end of the oxygen blowing process and tapping, a steel sample is taken for chemical analysis. The results reveal the chemical composition of the molten steel. Based on the desired steel grade, planners determine whether further adjustments are necessary.

The final operation involves lowering the temperature of the molten steel to the required tapping degree. Once it reaches the desired temperature, the furnace is tilted, and the molten steel is poured through the taphole into a ladle [3].

For some high-quality steel grades, a ladle refining stage is performed, involving certain operations similar to those conducted in the BOF, such as vacuum degassing. This stage creates a turbulent flow to minimize the presence of hydrogen and oxygen dissolved in the steel [3].

1.7 Electric Arc Furnace

Over the past 20 years, the Electric Arc Furnace (EAF) has seen global development and is renowned for its cost-effective and flexible approach to steelmaking. EAFs are equipped with either Alternate Current (3 electrodes) or Direct Current (single or twin electrodes), and the type of electrode used does not significantly affect the furnace's performance. These electrodes are crafted from special materials to ensure connectivity and stable performance in high-pressure environments. However, electrodes are consumed during the process and require continuous replacement. The electrode voltage is automatically determined, ensuring that the necessary energy is supplied for melting iron. This is achieved by continually measuring impedance and making voltage adjustments as the operation progresses [3].

One of the primary advantages of EAF is its ability to accept direct reduced iron (DRI), metal scrap, and molten iron in various proportions. Oxygen is also used in EAF to eliminate impurities, while lime is used to create a foamy slag on top of the molten steel, facilitating the removal of unwanted elements and improving energy efficiency. Once the molten steel reaches the desired quality and temperature, it is tapped into a ladle for further modification [3].

After charging the EAF, the initial stage, known as pre-heating, involves raising the temperature of the molten iron through the combustion of natural gas. This is followed by the initial melting stage when the electrode tips enter the furnace and their voltage steadily increases. Typically, high voltage is used at the start of the operation, and as the molten steel nears completion, the voltage is reduced to prevent damage to the furnace walls. When oxygen is introduced into the molten steel to form carbon monoxide, other impurities react with oxygen to form slag. This slag also shields the arc and protects the furnace walls from radiation. The operation concludes after determining the temperature and carbon content of the molten steel, reaching the desired levels. The molten steel is then poured into a ladle for downstream processing [6, 7].

2 Production Planning of Steelmaking—State of the Art

Although digital technologies [1, 2, 8–18] such as artificial intelligence (AI), big data analytics, cloud computing, cyber-physical systems (CPS), internet of things (IoT), and simulation promise optimized production processes/resources [2, 15, 19], better cost, energy, material efficiency [2, 15, 16, 20], added flexibility [2, 15, 16], more customer-centric production [2, 16], larger profits/revenues [2, 15], enhanced product quality [2, 15], and improved sustainability [2, 15, 18, 21] digitization is rather underdeveloped in the steel industry [15, 16, 19]. Steel companies tend to be suspicious towards the technologies laid out in the literature because they question the applicability of these technologies in real-life production situations [19]. Hence, digitization efforts are often triggered by external stakeholders (e.g. customers or suppliers; see [2, 22]).

Supply chain management in the modern steel industry reveals many challenges. Current planning and execution systems, such as SAP's state-of-the-art execution system (SAP S/4HANA) or its best-of-breed planning systems like SAP Integrated Business Planning for Supply Chain, offer an enormous range of options to support best-in-class supply chain management in general. However, a wide variety of aspects must be considered that are industry-specific and therefore require, at least partially, different approaches than in other manufacturing industries.

Three different categories of industry-specific framework parameters can be identified which play an important role in supply chain management of the modern steel industry:

1. Customers/Markets
2. Products
3. Planning and execution processes.

2.1 Customers/Markets

The clients in this industry require customer-specific goods. For example, the dimensions and steel grades differ from customer order to customer order, and therefore the routings for production need to be composed individually in each case.

2.2 Products

One difficulty that is encountered both in the planning and execution parts of supply chain management is the mapping of the actual conditions of reality into the systems environment.

Additionally, the mapping of customer-specific requirements results in a corresponding configurability of the respective products. This means that the products and other master data required for supply chain management cannot—unlike in other industries—be created in advance and made available for simple retrieval in the event of a specific customer order. Rather, the specifics with which the configured material is defined are not known until the creation of the customer order itself happens. This results in the need to use configurable materials that are finally defined by means of characteristic evaluation in the customer order. In the steel industry—even more extremely than in most other manufacturing industries—this requires the use of multi-level configuration (characteristics-based planning).

2.3 *Planning and Execution Processes*

The framework parameters of steel industry listed under Customers/Markets or Products clearly have a limiting effect on the options applicable in planning and execution of supply chain management. However, with the latest SCM functions provided by SAP, mapping in the most recent planning and execution systems (SAP S/4HANA and SAP Integrated Business Planning for Supply Chain) is possible.

A distinction can be made between the following approaches:

- Push approach
- Pull approach
- Combined Push/Pull approach.

2.3.1 Push Approach

Within the push environment the fundamental approach consists of bringing respectively pushing quantity projections into supply chain management using a forecast as signal and initiating production and procurement quantities on this basis.

But the framework parameters described above lead to the fact that existing functions must be used in a certain way, in order to be able to take them sufficiently into account. A standard approach that could be useful in most other industries, such as consumer goods or mechanical engineering industry, is not feasible in the steel industry due to the described multi-level characteristics-based planning approach. Therefore, the following sequential approach should be chosen for supply chain planning in a push environment (Fig. 1).

From the historical sales orders, the characteristics used in variant configuration are passed on as attributes to SAP Integrated Business Planning for Supply Chain (IBP). That means that planning is carried out on the basis of a product representative.

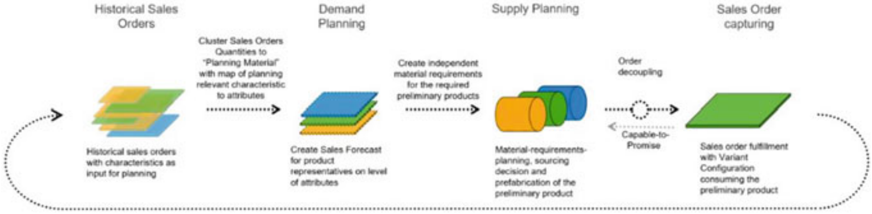

Fig. 1 Push approach

In SAP IBP, demand planning is then performed at this attribute level. In a more detailed approach, this can also be extended optionally to a Sales and Operations Planning (SOP) approach.

The derived projected product requirements are then passed on to operational supply planning, which is carried out in SAP S/4HANA with embedded Production Planning and Detailed Scheduling (ePP/DS). Specific product heuristics such as length-based planning can be applied here, other options would be provided by Production Planning Optimization (PPO).

Dedicated detailed scheduling based on characteristic-based planning can be achieved here as well, on the one hand, via the detailed scheduling-based optimization of ePP/DS. On the other hand, sequence planning based on the functions of block planning can also be realized. Furthermore, ePP/DS additionally offers the possibility to connect external optimizers via the Optimization Extension Workbench, which can explicitly perform optimizations based on dimensions, temperature, or other criteria.

The final step of planning can be seen in sales order capturing, which is performed in the core of SAP S/4HANA. Here, it can make sense to use the advanced functions of the availability checks, for example with capable-to-promise functions (Supply-Creation based Confirmation SBC), in order to obtain a correspondingly high quality in the determination of the confirmation data, which can also be—in addition to the described projected requirements from Demand Planning—another input for operational supply planning.

The planning data generated in this way can then be transferred to the classic execution functions in the core of SAP S/4HANA.

2.3.2 Pull Approach

However, pull approaches are also suitable for the steel industry, especially if they take into account the bottleneck-oriented Theory of Constraints (ToC) approach. This is an approach in which all decisions to be made as part of supply chain planning are subordinated to the bottleneck capacity. In this way, a consistently feasible, i.e. executable, production and procurement plan with the minimum of work-in-progress inventories is created. This includes decisions like inventory positioning and sizing and the postprocessing of supply planning run. Finally, it also affects the sequencing in execution.

Due to the characteristics of the manufacturing process in the steel industry with resources like furnaces or road mills, the alignment of the supply chain planning (and with it the execution) to the bottleneck capacities makes a lot of sense. In addition, the prevention of unnecessary work-in-progress, which automatically happens as result of ToC-related planning, is another major advantage of this pull-based planning philosophy in this industry.

However, the extensive use of configurable materials required in the steel industry in particular reveals some challenges in terms of using a pull-based approach. This is due to the fact that anchoring the stocks that are obligatory in the pull procedure is not easily possible with characteristic-based configuration compared with the procedures in other industries.

Here, the functions of the SAP SCM Consulting Solutions (SCM CS) of the Theory of Constraints (ToC) can be used in connection with flexible master data levels to achieve customer-specific make-to-stock production.

2.3.3 Combined Push/Pull Approach

It is also feasible to combine the two approaches. In this case, the supply chain planning aspect would be handled by the ToC functions of SCM CS, while the push-based approaches described in historical sales order consideration, and the demand planning aspect would be executed based on push basis. It is also possible to utilize advanced sales order confirmation within this approach and to hand-over the results of planning to execution in SAP S/4HANA.

As described above, the characteristics of the steel industry pose a variety of challenges for supply chain management that are often perceived as limitations. With the latest SAP supply chain management functions, however, these can be overcome in a push—as well as in a pull-based or in a combined environment.

3 Outlook

Very few topics in steel manufacturing have received as much attention from the mathematical modeling and algorithmic optimization literature as the scheduling of customer orders. Usually, scheduling customer orders means to group them into distinct batches called sequences and arrange the individual constituents of these sequences in a meaningful way [23]. In general, steel production schedules are characterized by the degree to which they satisfy a set of (i) technological and (ii) commercial objectives. Among these objectives are, for example, (i) the minimization of geometric as well as chemical transitions between successively processed customer orders during Compact Strip Production (CSP) as well as (ii) the maximization of logistics-related key performance indicators (KPIs) such as machine utilization, inventory performance, and due date reliability [23, 24]. In the past, schedule optimization problems have been modelled as mixed integer programming (MIP), linear programming (LP), and Travelling Salesman Problem (TSP) variants [25]. These problem formulations have in common that they evaluate production schedules via so-called cost functions that are essentially linear combinations of several objectives or KPIs. In practice, it is a common complaint that commercial objectives (e.g. logistics-related KPIs) are rarely implemented in these cost functions since they are frequently dominated by technological objectives instead. See [25, 26] for a detailed review of this field.

In spite of the high academic level of the theoretical studies in this field, there is a striking discrepancy between the rich formalisms invented and their practical