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Data driven modeling & optimization of industrial processes

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The PROMIMOOC Project

In the PROMIMOOC project, the two real-world use cases available are the production of steel coils (Tata Steel) and the stamping of car body parts (BMW). Together these two cases nicely reflect a complete industrial process, where we have a producer of steel coils on one hand and a consumer of these (and other) steel coils that in turn produces car body parts on the other hand. In this chapter both cases are explained in detail. In addition, a generic framework for data driven on-line control that can be applied to many of these industrial processes is proposed in Section 2.3.

2.1 Tata Steel

In the steel-making industry, iron ore and scrap are transformed into smooth steel coils of a few centimeters thick and many meters in length. The process consists of several steps, some of the steps being optional and some steps are sometimes executed multiple times.

Continuous Casting Liquid iron from the blast furnace is being cast into thick heavy slabs.

Hot rolling The slabs are being reheated by a walking beam or pusher furnace and go through several rougher and finishing mills. Each mill is reducing the thickness of the steel and increasing its length.

Pickling In the pickling line, the coils get cleaned.

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Cold rolling After hot rolling, most coils get cold rolled by several more reduction mills to get the dimensions the customer requires.

Galvanizer Some of the steel coils need a coating and further processing, this is what the galvanizer is for.

For the PROMIMOOC project, only the hot rolling process step of Tata Steel is taken into account since this is the step where surface defects start to occur and where machine parameters have a high impact on the final product. The hot rolling process can by itself be divided into a dozen smaller steps as can be observed in Figure 2.1. It consists of four furnaces, two walking beam furnaces and two pusher furnaces. Each steel slab will pass from one of these furnaces and will then go through five consequent rougher mills. After the rougher mills a cropper shear is used to remove any oxide from the steel surface. The steel then passes another seven finishing mills before it ends up at the roll-out table. At the roll-out table the steel cools down before it is being coiled by the coiler. At the roll-out table the surface inspection system takes images of each millimeter of steel, both of the upper and lower surface, and detects and classifies defects on the surface. These defects are classified into twenty-seven defect families.

2.1.1 Objectives

For Tata Steel, the main objectives are to accurately classify defects on the surface of the steel coils by using material measurements and machine parameters. Finding relations, possible causes and anomalies in the provided data is of great importance as this brings additional insight into the complex process of hot rolling and may lead to an improved production process.

Once surface defects can be classified and predicted using input material properties and machine parameters, model-based optimization of the machine parameters can be performed using optimization algorithms. These algorithms can give recommendations of near-optimal machine settings that can then be used by a domain expert in controlling the production process.

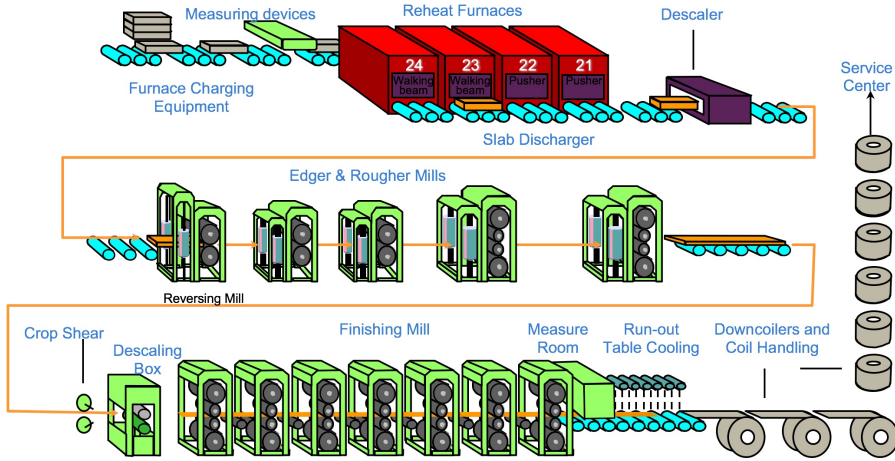


Figure 2.1: A schematic view of the hot rolling process at Tata Steel's hot strip mill 2 (HSM 2). Courtesy of Tata Steel.

2.1.2 Data

The data sets provided by Tata Steel contain measurements, machine parameters and defect information for roughly 20.000 steel coils processed by Hot Strip Mill 2. The data is divided over numerous tables, the most important sets are the Rougher Mill (RM), Finishing Mill 1 (FM1), Finishing Mill 2 (FM2) and Defect data sets. These four data sets have different sampling rates and are therefore not trivial to combine. Using timestamps, relative positions and additional meta-data, the four data sets have been combined in data views by CWI in a MonetDB database environment. There are several thousand records available per coil. Each record is in turn consisting of up to hundred signals that were used for the experiments in this research.

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2.2 BMW

In the car body parts industry, blanks of sheet metal are cut from a coil and pressed into car body parts such as side frames, roofs and structural parts like B-pillars. For different parts, different material is required and different machine settings can be used. Due to the high variation as well as high-dimensionality in both material properties and machine settings, the process is a very complex one with lots of parameters that influence the final product.

The manufacturing process consists of two main process steps and a buffer period. First, the incoming steel coils are unrolled and cut into individual blanks. The steel blanks are then stacked on top of each other and stored in the buffer. After a certain time in the buffer, the stack of blanks are moved to the press line. At the press line the blanks are pressed into a specific car body part. Depending on the body part produced, the press line consists of a number of operations, each of them controlled by a large variety of machine parameters.

2.2.1 Objectives

On-line quality optimization of the products and the prediction and avoidance of defects are the key goals of this research for BMW. More precisely, the aim is to estimate the occurrence of defects and to warn domain experts of incoming anomalously looking material and abrupt changes in material flow such that machine parameters can be adjusted in time.

To estimate the occurrence of defects, data mining techniques have to be applied at the very beginning of the production process. Anomaly detection [11] plays an important role in this early stage, since most of the machine parameters are still unknown. Using anomaly detection techniques on material properties allows for the detection of anomalous metal coils and more precisely, regions in the sheet metal that could later lead to problems in the production process. The results of anomaly detection algorithms can be presented to experts to gain additional knowledge about the process and to warn the press line controllers of risks as early as possible. However, to apply anomaly detection and other unsupervised

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techniques to the BMW data, some challenges have to be tackled. The dimensionality of the problem is large and the data consists of heterogeneous coil types and suppliers used for many different car body parts. Not all coil measurements are annotated with a supplier and final product type which makes it difficult to split the data set.

2.2.2 Data

Most of the BMW data comes from the first production step, the cutting process. At the cutting process, the following properties are measured over the complete coil length.

Impulse Magnetic Process On-line Controller (IMPOC) is an advanced measurement commonly used in steel manufacturing plants that measures the residual magnetic field strength of the material [12].

Oil Levels on the surface of the blanks are considered to be an important factor in the stamping process. The amount of lubricant affects the friction and thus plays an important role in the deep drawing process of sheet metals.

Roughness of the surface.

Thickness of the material.

Peak Count of the surface, representing the number of peaks per square meter.

The oil levels are measured by a sensor that moves over the width of the coil, all other sensors are placed at the center of the cutting machine. Additional machine parameters such as re-oiling and six cylinder forces used in the stamping process are stored and linked to the steel blanks in the database.

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The optimization of these processes is far from trivial and though they have many objectives in common, the two processes are composed of different steps, machines

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and data. A generic framework for data driven optimization of process parameters and on-line control is proposed as a solution to this problem. Each step required for the framework to work, as already given in the Introduction (Section 1.2), is covered by the proposed framework.

Both processes are so called semi-batch processes, where the products are produced in a batch fashion but the production of each individual product can be seen as a continuous process. For example, while several steel coils can be seen as a batch, the production of one steel coil is the continuous casting and reduction of roughly 2000 meters of steel. Due to the semi-batch nature of these processes, the generic framework consists of steps focused on batch processes, such as the prediction of good machine parameters for the manufacturing of the next products, and continuous processes, such as the detection of anomalous regions in the input material. The framework also has to deal with high-dimensional data coming in real-time or close to real-time. The framework needs to provide valuable feedback to the domain experts, decision makers and process controllers in limited time, about the current and possible future situation of the production process. A schematic overview of the proposed framework is shown in Figure 2.2.

The framework consists of the as-is production process on the left, where the actual production process is abstracted to one step for the sake of simplicity. The data gathered by the production process consists of three types, material measurements, process parameters and product quality measurements. All three data types are required for most of the data driven framework modules to work. In case quality measurements are absent, supervised predictive modeling would not be possible but anomaly detection and monitoring would be still fine. The first step of the data driven framework is to preprocess and clean the incoming material measurements and planned process parameters. The preprocessed data is stored in a fast database (in our setup MonetDB). Using the input data, anomaly detection and unsupervised algorithms can provide the operator with valuable insights even before the production takes place. When a trained predictive model is available, the input data can also be used to provide the operator with suggestions of near-optimal process parameters using model-driven optimization techniques. Once the product is produced, a quality inspection system can provide feedback to the operator. This data can also be used to perform supervised learning and train or

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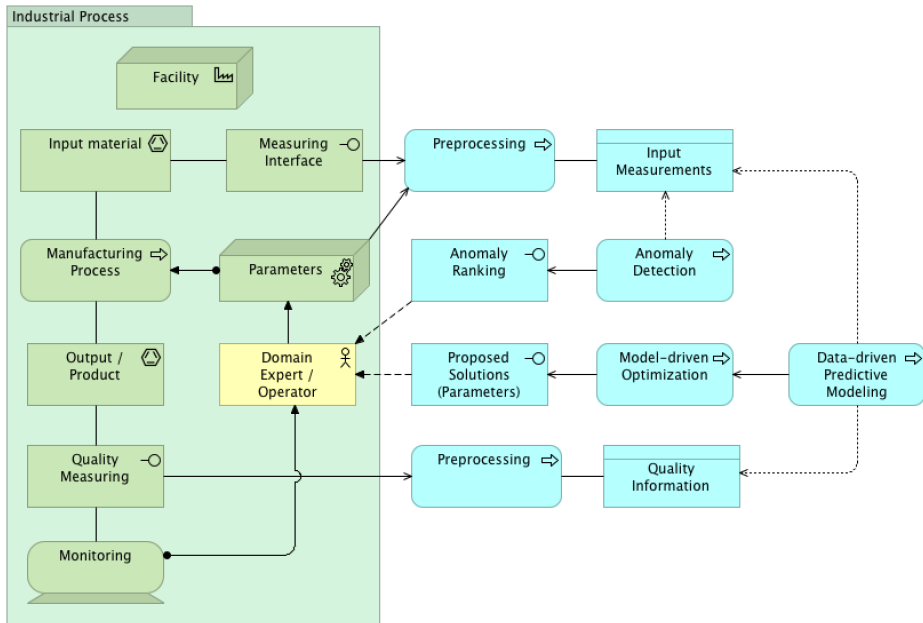


Figure 2.2: A data driven framework for optimizing and monitoring manufacturing processes.

re-train the data driven predictive models for the next iteration of the production process.

The next chapters present solutions and implementations of each step of the proposed framework. In each chapter a reference to the relevant framework step is given.

