CHAPTER 1

Introduction

Objectives of the Chapter

- Introduce the hierarchical approach to process automation and control.
- Introduce the role of model-based control in the overall process control hierarchy.
- Introduce the concepts of model-based control.
- Discuss the outline of the book.

The term model-based control (MBC) is used in this text to mean control systems that explicitly embed a process model in the control algorithm. In particular, we consider control algorithms such as Internal Model Control (IMC) and Model-Predictive Control (MPC) which have found applications in the process industry. Beginning in the early 1970s, the concept of using a predictive model of the process to determine the control actions to be taken has been accepted widely by industrial practitioners. The impetus for this came from the difficulties encountered with decentralized PID (proportional integral derivative) based control approaches that had been the norm in the past. The emergence of computer-based control allowed complex calculations to be performed online. At the same time, the increased cost of energy and raw materials provided greater economic incentives to push the plants to their optimal operating points.

The objective of this book is to provide an introduction to the concepts and practice of model-based process control. A prior beginning-level undergraduate course in process control is assumed.

Model-based control is not a replacement for traditional single-loop controllers. Rather, it complements the traditional methods. The theory of model-based control gives additional valuable insights into the way traditional single-loop PID controllers are tuned and operated.

We begin by considering the process control problem as a subset of the overall plant operations problem.

1.1 Nature of the Process Control Problem

The overall objective of plant operations is to achieve maximum profitability (optimum plant performance) subject to operational constraints related to safety, economics, government regulations, and equipment limitations. This complex problem is tackled by breaking it down into simpler subproblems that are tackled more easily. Figure 1.1 shows the resulting hierarchy of functions. This structure was proposed by Mesarovic et al. (1970). Popovic and Bhatkar (1990) and Williams (1983) discuss this concept in more detail. A brief discussion of each of the layers is given next.

At the lowest level we have the *instrumentation layer,* which consists of devices for acquiring data (sensors and transmitters), field display devices for displaying process variables, and hardware safety interlocks for ensuring emergency actions in case of safety violations. The devices at this level sense the process variables and transmit the data to the computer control system running the plant. Instrument engineers use the local display devices to troubleshoot the problems in the plant. With the introduction of smart sensors (computerized sensing devices) there is a trend towards creating a local area network (LAN) of the sensors and actuators. Data are collected at sampling rates on the order of one second or less. Some equipment might require smaller sampling times.

The instrumentation layer reports the data to the regulatory control layer which is implemented using control hardware known as DCS (Distributed Computer Control Systems, used primarily in large continuous production facilities) or PLCs (Programmable Logic Controllers, used primarily in discrete or batch process operations). See McMillan (1991) and Williams (1983) for a more detailed discussion of DCS and PLC control hardware.

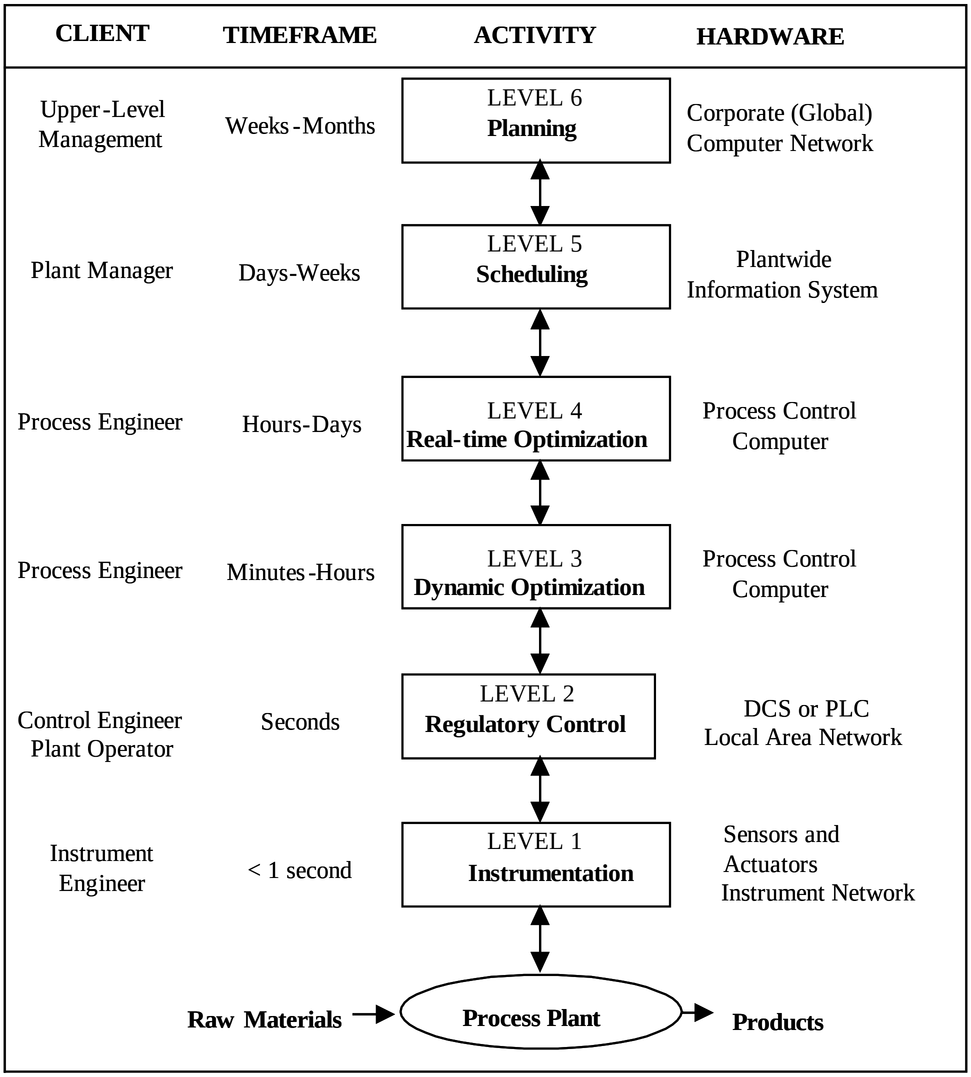

Figure 1.1 The six-layer hierarchical decomposition of control functions.

The function of the *regulatory control layer* (see Figure 1.2) is to maintain the process variables at their prescribed setpoints in spite of local disturbances that are occurring at a timescale of seconds to minutes. Such disturbances originate due to a variety of causes, such as changes in ambient conditions, changes in raw material properties, and startup and shutdown at other sections of the plant. In addition to this regulatory function, this layer allows the operator to take control of the plant in case the need arises.

The main objectives of this layer are:

1. Provide operator interfaces.
2. Provide regulatory control of process variables at their setpoints.
3. Reject local, high-frequency disturbances (disturbances on a timescale of seconds to minutes).
4. Follow the directives of the layers above.

The PID controller is widely used to implement the local single input single output (SISO) control loops. The DCS is also used to implement multiloop control strategies such as feedforward, cascade, ratio, and override control.

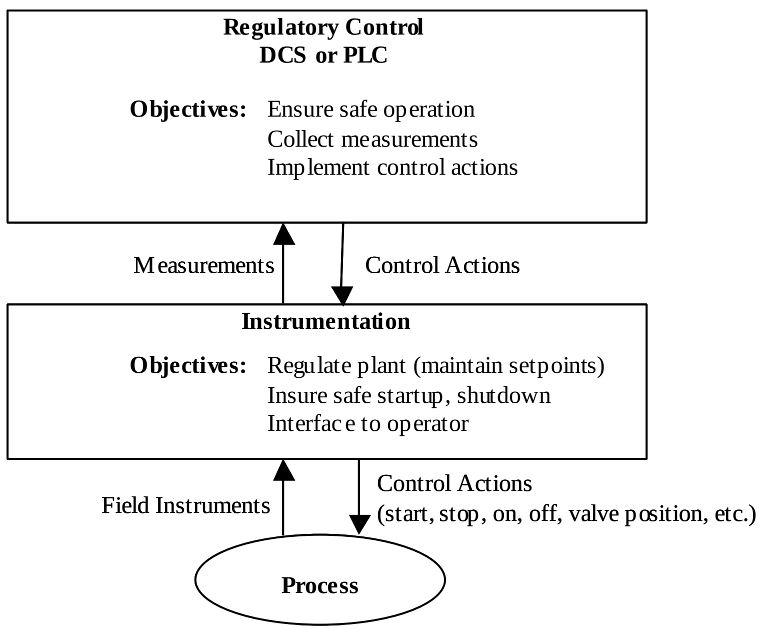

Figure 1.2 Lower levels of the control hierarchy.

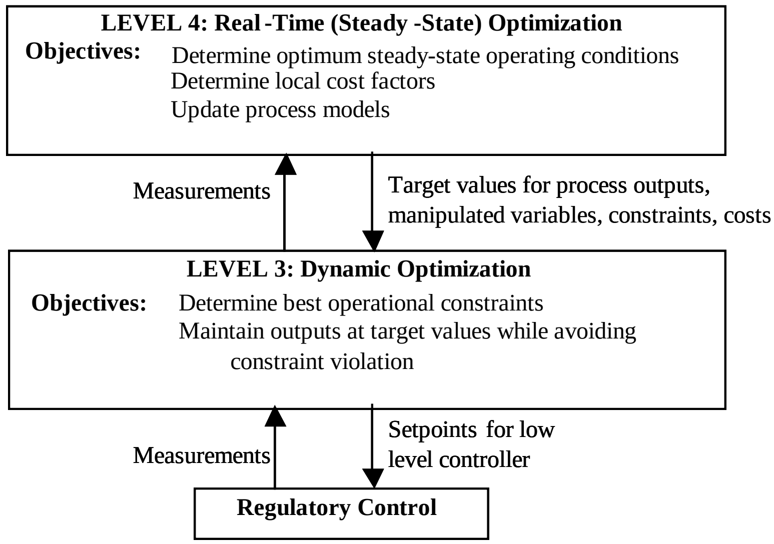

Figure 1.3 The middle layers of the control hierarchy.

The functions of the next two levels are shown in Figure 1.3. The function of the *dynamic optimization (DO)* layer is to keep the process operating near optimum efficiency by constantly adjusting the setpoints and responding to longer duration disturbances that could shift the optimum from one constraint to another. The problems here are typically multivariable and constrained in nature. Due to the possible interaction among the variables, all the control moves must be calculated simultaneously. The control actions are taken to accommodate longer duration disturbances entering the process (at a timescale on the order of minutes).

This layer uses the process model to guide its actions so that the plant operates within the constraints and moves to the most economic operating point given the current status of the disturbances. Process dynamics are important, and hence a dynamic process model is necessary. Some authors refer to this as the predictive control layer. The output of this layer is used by the DCS or PLC system as setpoints. An implicit assumption here is that the DCS or PLC is capable of responding to the changes requested by the layer before the next set of model-predictive control (MPC) calculations are initiated. The response time of the process variables is used to guide the allocation of control loops between the regulatory control layer and the MPC layer.

The *real-time optimization (RTO)* layer is charged with the responsibility of determining the optimum steady-state operating conditions for the plant given the current production requirements and factors such as material costs, utility costs, and product demand. This layer employs a detailed, first principles, steady-state model of the plant to determine the optimum operating conditions. This model is continuously updated online to reflect the changing process parameters and to account for errors in the process model. The timescale of the disturbances considered at this layer allows the plant to reach and maintain a steady-state between actions.

The cost factors, production capacity targets, raw material availability and production schedule are determined by the *scheduling layer*. For example, a refinery will optimize the operating schedule of the crude units, reforming units, cracking units, and blending units to meet the market demand for the coming weeks or months, based on the crude availability and prevailing prices. Large-scale linear programming (LP) is used at this level. This is run on a plantwide information management system, which collects and disseminates the information over all the control facilities distributed throughout the plant. Costs of utilities and other items exchanged between processing units are determined at this scheduling level (see Figure 1.4).

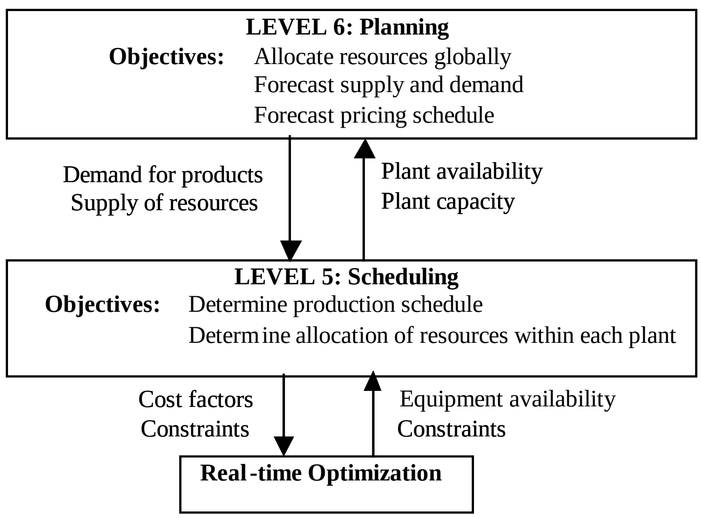

Figure 1.4 Top layers of the control hierarchy.

The *planning layer* is implemented at the corporate level. This layer would determine the allocation of resources at a global level. Because of the long timescales involved, changes in the planning layer are made over much longer periods of time, ranging from weeks to months. Planning requires forecasting supply and demand.

Another way of looking at the hierarchical decomposition is along the geographical domain of influence of each layer as illustrated in Figure 1.5. This figure shows the various layers of control hierarchy in a global oil company. The highest level of planning could cover all of the global facilities owned by the company. The scheduling level is executed locally at each plant location. The plant itself could consist of many distinct processes, each with its own set of process control computers. Dynamic optimization takes place at this level. Tightly coupled units (through mass or energy exchange) in a process are grouped together for multivariable control purposes. Individual DCSs operate for each processing unit set to enforce regulatory control. Multiloop and single-loop control strategies are applied to each unit operation individually at this level using local control units.

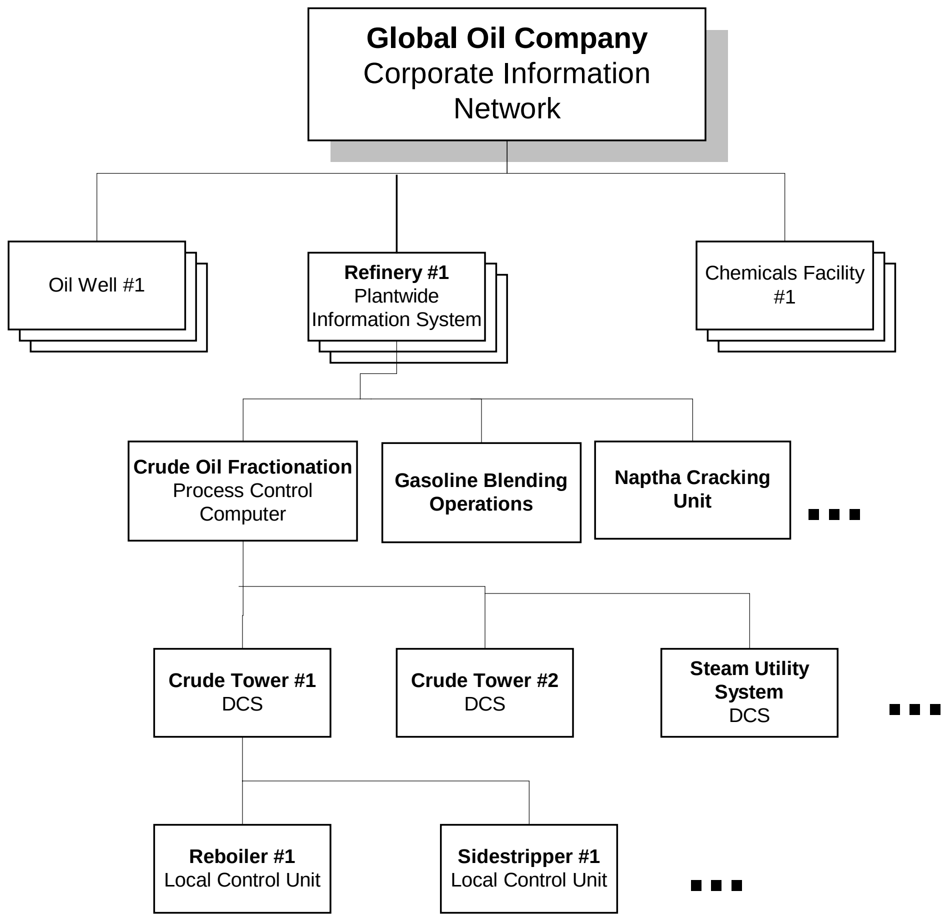

Figure 1.5 Geographical decomposition of the hierarchical control structure as applied to an oil company.

The concept of tying all the layers together to operate seamlessly (without manual intervention) is called *Computer Integrated Manufacturing* (CIM). A company that embraces CIM is able to respond to changing market conditions rapidly and hence operate more efficiently. Until recently, each of the layers tended to be supported by different vendors and computer systems, making it virtually impossible to maintain a seamless flow of information from top to bottom and vice versa. The need for CIM is now widely accepted and the trend is towards DCS and PLC manufacturers (who typically manage the bottom two layers) to provide integration with the planning and scheduling software used in higher levels of management. In an ideal CIM system, when a customer places an order, the information is immediately passed up and down the hierarchical chain so all affected parties may respond to it immediately.

The middle layers (RTO, DO) are still in a state of development. Lack of good process models is usually an impediment to the implementation of these layers. Most advanced control projects involve the development and implementation of these layers. According to industry experts, this layer can increase the profitability of a process by 7% to 10%. Payback times of six months to a year are often claimed on such projects.

Example 1.1 Application to a Microbrewery

Consider a microbrewery manufacturing different blends of beer at three different locations. Let us consider how the hierarchical control strategy applies to this firm.

Level 1. Instrumentation layer: This layer will include the sensors to measure process variables such as temperature, pressure flow, and pH, the control and solenoid valves, safety interlock devices that prevent safety violations, and local alarm devices.

Level 2. Regulatory control layer: This layer will include the PLC system that controls the brewing process. The PLC system is responsible for implementing the batch recipe for each product, regulating the process variables at their setpoints using feedback control (typically PID controllers), startup, shutdown, and emergency shutdowns. It will also create logbooks and provide operator interfaces. It will accept new recipes from the layer above.

Level 3. Dynamic optimization layer: The formation of this layer will be to monitor the process during a batch and to make midcourse corrections if necessary so that the product specification targets can be met. For example, it might decide to alter the recipe slightly to maintain desired pH level of the product at the end of the batch. This layer usually employs a dynamic process model to predict and control product quality.

Level 4. Real-time optimization layer: This layer is responsible for creating a batch recipe for a specified brand of beer that will maximize the yield or profit, given the product demand, product and raw material prices, and cost of operation. It may alter the fermentation conditions and raw material proportions so as to minimize cost while meeting specifications.

Level 5. Scheduling layer: This layer is responsible for deciding the schedule of manufacturing different brands of beer, given the capacity limits in the plant and market constraints (demand, availability, cost of products and raw materials). It must also take into account cost of inventory.

Level 6. Planning layer: This layer is responsible for making decisions such as capacity expansion, new plant construction, resource allocation, and long-term forecasting. Inputs to this layer are projected demand and supply, interest rates, past and projected government regulations, and projected growth of the company.

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1.2 OVERVIEW OF MODEL-BASED CONTROL

Process models are used in each of the layers of the hierarchical structure. In the regulatory control layer, models are employed in the tuning of PID and internal model controllers (IMCs), the design of feedforward, cascade, and override controllers, and the design of inferential controllers (control using secondary measurements). In the dynamic optimization layer, models are used to predict the behavior of the process into the future, to compute control actions, and to determine local economic optimum point given process constraints. Nonlinear steady-state models are used in the real-time optimization layer to compute steady-state optimum operating conditions. Linear models of the overall plant operating characteristics are used in the scheduling and planning layers.

In this book we will focus primarily on the use of models in regulatory and dynamic optimization layers.

Figure 1.6 shows the generic form of a model-based control strategy. There are three distinct blocks associated with a model-based control system:

1. *The process model*: This block computes predicted values of the process measurements.
2. *Disturbance estimation/model parameter adaptation*: This block makes adjustments to the disturbance estimate or model parameters so that the predicted values are brought closer to the actual measurements.
3. *Controller or optimizer*: This block computes the actions needed so that the selected outputs of the process will be driven to their desired or optimum setpoints, while avoiding constraint violations.

Implementations of the model-based control strategy vary greatly. In the simplest form, for a SISO system, the model is a linear transfer function, the adaptation is a linear correction, and the controller is an approximate inverse of the model transfer function. In such a case (we call it IMC) the strategy can be reduced to a conventional feedback control structure. An issue that arises here is the effect of model uncertainty on the controller stability and performance. We find that there is a tradeoff between performance and stability for real processes when model uncertainty is always present.

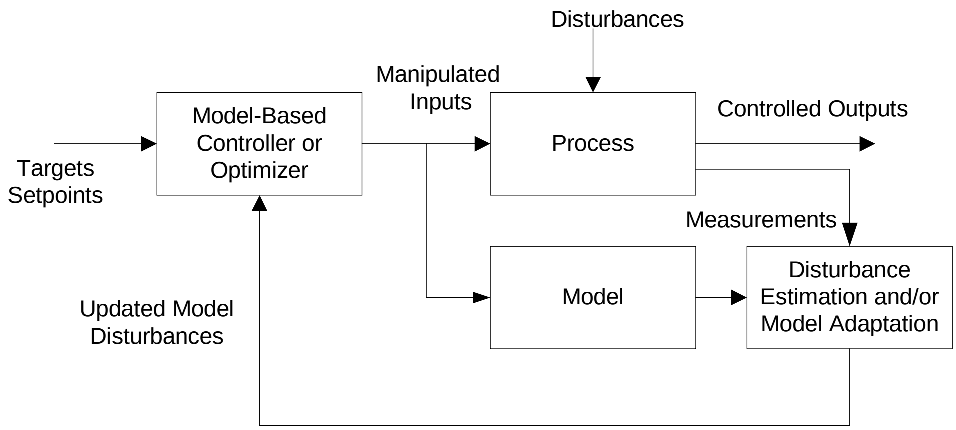

Figure 1.6 Generic form of the model-based control strategy.

In the dynamic optimization layer, a linear multiple-input multiple-output (MIMO) model is used. The controller is usually a linear least-squares calculation done at every sample time that minimizes future predicted variations of the output from their setpoints subject to process constraints. The adaptation consists of matching the model prediction and actual measurement through a linear correction to the predicted values. This layer also involves a computation of the optimum operating conditions given the estimate of the current and future values of disturbances at every sample time. Much of the economic incentive for implementing model-based control is derived from this secondary optimization of setpoints that allows the plant to follow the most economic process constraint (such as manipulated variable saturation, output limits, etc.) at any given time.

In the most general form, the model-based control consists of a nonlinear process model, a complex estimation scheme that computes process parameters to minimize plant/model mismatch, and a controller that computes an approximate inverse in an implicit form by exercising the model repeatedly (using a numerical search procedure) to achieve the economic goals of the process.

1.3 SUMMARY

In this chapter, we introduced the concept of model-based control in the context of the general process control problem. For ease of implementation, the control problem is tackled using a hierarchical decomposition of the control tasks resulting in six clearly identifiable layers:

1. Instrumentation layer
2. Regulatory control layer
3. Dynamic optimization layer
4. Real-time (steady-state) optimization layer
5. Scheduling layer
6. Planning layer

The type of models used is dependent on the application layer. The focus of this text is on the regulatory control layer and the dynamic optimization layer.

Problems

1.1 Consider the following control applications. Classify each application to one of the levels of the control hierarchy. Identify the type of control hardware where these applications will reside (DCS system, safety interlock system, process control computer, plantwide computer, etc.). Also identify whose job function it is to maintain these applications (instrument engineer, control engineer, process engineer, plant manager, etc.).

a. Temperature control in a heat exchanger
b. Safety release valve in a reactor
c. Optimum operating temperature for a reactor
d. Production rate in a crude oil distillation plant
e. The product distribution from a blending unit in an oil refinery
f. The scheduling of crude oil shipped to various refineries from a production well

1.2 Consider the operation of a continuous stirred tank reactor. Consider the following control objectives. Identify which layer of the control hierarchy will address each objective.

a. Temperature and level control
b. Feedforward compensation for variations in coolant inlet temperature
c. Keep the level in the tank from running too low
d. Keep the pressure in the tank from exceeding a certain limit
e. Adjust the reactor temperature to compensate for variations in the production rate

1.3 Apply the hierarchical decomposition of control functions to the following integrated plants. Show specific objectives of each layer as it applies to that particular plant. Give an example of the application of each level in the control hierarchy to the operation of the plant. Where applicable, discuss the hardware platform used for implementing the objectives.

a. A paper mill manufacturing paper from wood
b. A pharmaceutical plant making medical drugs
c. A steel processing plant making steel from iron ore
d. A pet food manufacturing plant making pet foods from cornmeal and meat

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